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“Ila Sahb al asr wa zaman,
Mawlay wa Amiri,
Al Imam al Hadi al Mahdi.
Ila Sayyed al Mouqawama wa Shouhadaïha.
Ila Rouh Walidi al ghali.”
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Introduction

The field of optical fiber sensors (OFS) has attracted significant attention in the last two decades and has become more and more attractive for academic applied research and worldwide industrial development. Optical fiber sensor systems for diverse application fields have been reported, novel sensing approaches by means of advanced interrogation techniques and domain-specific technologies have been introduced, and extremely reliable monitoring systems in various engineering fields have been realized. Novel OFS measurement techniques are nowadays widely investigated for research and development, and also applied to several industrial fields including automation, aerospace, aeronautical, modern structural health monitoring, transportation, power stations, inspection of oil&gas systems, industrial plants; such wide application range of OFS systems well justifies the dedicated effort and continuously growing importance of intelligent sensing systems.

The field of optical fiber sensing is highly diverse, and this diversity is perceived as a great advantage over conventional electromechanical sensors in the ability to tailor an optical sensor to measure any one of a myriad of physical parameters with several important advantages compared to conventional approaches such as distributed measurement capability, lightweight, small size, low cost, immunity to electromagnetic interference. All these features are making OFS an attractive and smart technology in comparison to conventional sensors.

Optical fibers offers the possibility of performing distributed measurements of physical environmental variables, such as strain and temperature, representing a unique characteristics that does not have any equivalent in conventional sensing technologies. Therefore, applications such as intrusion detection or distributed temperature/strain sensors for monitoring fire/stress hazards remain the realm of the state-of-the-art distributed optical sensors.

As a part of distributed sensor arrays, the In-fiber Bragg gratings (FBGs) arguably perform better than any interferometric or electromechanical sensors. FBGs provide wavelength encoded self referencing real-time sensing capabilities and at the same time keeps system immune to high radiation environment suitable for measuring static and dynamic fields such as temperature, strain and various chemical parameters; make reproducible measurements possible as with the established and truly distributed sensing topologies based on Brillouin, Raman and Rayleigh back scattering, actually quite well with regards to spatial resolution, but the distributed sensor range cannot be matched.

After significant developments in distributed optical fiber-based sensors it is possible to realize extremely reliable and intelligent monitoring measurement & control systems for their entire operational life. Various continuously growing industrial
application fields for distributed optical fiber-based sensors have been reported to date ranging from innovative structural health monitoring to geo-technical engineering and industrial plants monitoring. With the aid of these innovations, it is become practically possible both of understanding the behaviour under anomalous conditions and improved understanding to determine the value for instance temperature/strain over the distance of several kilometres with an excellent accuracy and spatial resolution which allows for the monitoring of aircrafts, bridges, dams, tunnels, multi-story buildings, roads & railways, chemical pressure vessels, nuclear reactors, wind turbines, electrical generators, boilers, automotive, aerospace and machining tools against severe events such as environmental conditions, mechanical failures, delamination and abnormal loads. In addition, the flexibility of the optical fiber makes it relatively easy to install over the chosen measurement path and thus allows, unlike many other sensor systems, retrospective fitting.

This thesis mainly focused at the study and development of highly reliable and innovative OFS systems with improved performance, employing various novel measurement methods in the wide field of discrete and distributed OFS. In essence, the implementation of new methods for enhancing the dynamic field measurement capabilities of In-fiber grating optical sensors and advanced hybrid sensing schemes to combine discrete (FBG-based)-dynamic and distributed (Raman and Brillouin-based)-static measurements are proposed and experimentally demonstrated. The proposed techniques are based on state-of-the-art sensing methods opening new cutting-edge research directions and important application fields. In particular fundamental principles, technical aspects and various experimental results are reported concerning advanced optical pulse coding techniques and their sensing applications.

The first chapter presents an overview of fiber optic sensing technologies that comprises the historical developments, fundamental concepts & sensing principles, state-of-the-art application fields and various types of OFS. This overview provides background material needed to facilitate the understanding of the following chapters. It deals with fiber optic sensors based on Raman and Brillouin scattering as well as In-fiber grating optical sensors. In particular the principles of multiplexed and distributed sensing approaches are discussed in section 1.2. Then sections 1.3 and 1.4 respectively describe the FBG-based sensing method and the principle of distributed optical fiber sensors based on optical time-domain reflectometry (OTDR).

The second chapter reviews the detailed theoretical and mathematical background describing linear and non-linear scattering phenomenon in optical fiber. A condense but essential discussion on FBG basic physical mechanism and theory is presented. The physical nature of Rayleigh, Raman and Brillouin scattering in analysed, giving special attention to the time domain properties of the interaction between optical signals; this allows one a deep understanding of the time domain based distributed measurement techniques proposed in this theses. Then stimulated scattering effects, in particular stimulated Brillouin scattering, are described.
The following chapters thoroughly explain the most important methods and the development of novel techniques for discrete and hybrid discrete-distributed optical fiber sensors, also providing at the same time essential details regarding the basic working principle of each sensor type, as well as the experimental investigation of their improved performance. Also a great effort has been dedicated to the investigation of the several sensing applications that hybrid sensors can address especially in structural health monitoring, highlighting the area of potential growth.

The third chapter deals with FBG-based fiber optic sensors, considering mainly advanced time domain dynamic interrogation techniques based on cyclic pulse codes. Section 3.4 explains the benefits of advanced cyclic optical pulse coding technique applied to time division multiplexed (TDM)-FBG-based OFS arrays, focusing our attention to improve their dynamic strain resolution and also providing possibility for combined discrete-distributed sensing approaches. A powerful new concept is introduced, with important implications in a variety of applications including enhanced dynamic monitoring of large structures and oil&gas pipeline monitoring. In terms of improved interrogation techniques, time domain based in-fiber gratings not only have a very high sensitivity but can also be effectively combined with distributed sensing due to their common implementation of time division multiplexing.

One of the unique features of the proposed interrogation technique for in-fiber gratings arrays is their quasi-distributed sensing capability, which means that multiple points can be sensed simultaneously by a single pulse shot, with improved SNR. This capability not only reduces the cost but also makes the sensor very compact. In section 3.5 for the first time a novel time domain FBG-based sensor is proposed to significantly improve sensing measurement range, measurement time, dynamic strain resolution and sensor multiplexing capabilities by employing advance cyclic codes and unique interrogation function which also provides immunity to optical fiber spurious losses and optical source power fluctuations. The mechanism of noise reduction by quasi-periodic cyclic coding is quantitatively demonstrated, pointing out significant improvement in dynamic strain resolution with respect to single pulse TDM-FBG-based interrogation. The use of cycling pulse coding allows for the enhanced dynamic performance of real time strain measurement with respect to other coding techniques. The proposed technique can also enhance the sensing range of hybrid optical fiber sensor systems in which continuous static temperature/strain distributions and discrete dynamic strain in specific critical points, are simultaneously measured over the same sensing fiber. Experimental results point out significant improvements; while a single-pulse based measurement provides a poor dynamic strain resolution of ~1.40 με/√Hz at ~12.5 km, the use of distributed cyclic coding improves the attainable resolution down to 380 nε/√Hz, without scarifying the FBG interrogation measurement speed. Furthermore experimental results well demonstrate that by employing longer codeword with our proposed technique it is possible to practically obtain the coding gain predicted by theoretical estimation.
In the fourth chapter we investigate novel techniques for hybrid Raman-FBG sensing approach. In section 4.3 we propose a highly-integrated hybrid sensing system that effectively combines the advantages of both Raman-based distributed temperature sensor (RDTS) and TDM-FBG-based dynamic sensing, by fully exploiting their respective specific functionalities. The first proposed solution is based on two separate sensing fibers; one is a single mode fiber (SMF) for FBG-TDM-based sensing array whilst the second is multi mode graded-index fiber (MMF) for distributed temperature sensing. Experimental results show a temperature resolution better than 1 °C with 2.7 m spatial resolution at a 20 km distance as well as a dynamic strain resolution of 7.8 ne/√Hz at 0.2 kHz repetition rate (the Nyquist limit for a 20 km-long fiber is 2.5 kHz). Moreover in section 4.4 we have proposed for the first time, a novel hybrid fiber optic sensing technique that effectively combines RDTS and in-line FBG dynamic interrogation using a single common SMF sensing fiber for both point-wise and distributed measurements; the proposed solution is highly integrated and cost-effective. This new and novel highly integrated hybrid sensor employs broadband apodized low reflectivity FBGs with a single narrow band optical source (the same used for RDTS measurement) and a shared receiver block, allowing for simultaneous measurement of distributed static temperature and point-wise dynamic strain detection. The experiment results prove simultaneous distributed sensing capability with temperature resolution of 2 °C at 10.9 km and dynamic sensing with discrete FBG dynamic strain resolution of ~60 ne/√Hz at 250 Hz, enabling the use of such an efficient and effective hybrid technique. Finally section 4.5 experimentally demonstrate state-of-the-art very efficient hybrid sensing approach by using cyclic pulse coding to effectively improve the performance of hybrid RDTS/FBG-based fiber optic sensors, for simultaneous measurement of distributed-static temperature and discrete-dynamic strain over the same SMF sensing fiber. Effective noise reduction is achieved in both RDTS and dynamic interrogation TDM-FBG sensors, enhancing the sensing range-resolution and providing real-time point dynamic strain measurement capabilities. This very efficient integrated sensor scheme employs broadband apodized low reflectivity FBGs, a single narrowband optical source and a shared receiver block. We experimentally evaluate the receiver SNR improvement provided by pulse coding, verifying its capabilities to significantly enhance the sensing range, measurement time, FBG multiplexing capacity, as well as the distributed-static temperature/strain and dynamic strain resolution with respect to conventional RDTS/TDM-FBG-based sensors operating with single pulse at the same peak power level. Experimental results prove substantial achievement of 4.7 °C temperature resolution at ~21 km distance with a 1 m spatial resolution (instead 18 °C by using conventional RDTS), and a dynamic strain resolution of 77 ne/√Hz (instead of 308 ne/√Hz by using conventional TDM-FBG sensor) at the far fiber end.

Finally the fifth chapter reports the most important hybrid distributed/discrete optical fiber sensing methods we have investigated related to Brillouin time-domain analysis (BOTDA) and FBG, whilst also providing essential details regarding applications and future developments. The main characteristics, generalities and the applications of
such BOTDA-based sensors are described in section 5.1. In section 5.2, for the first time experimental demonstration of a novel hybrid BOTDA/FBG optical fiber sensor has been reported and demonstrated, pointing out its accurate and efficient performance. In particular, a highly integrated optical fiber sensor for simultaneous discrete-dynamic strain and distributed-static strain/temperature measurements is experimentally demonstrated by combining BOTDA and TDM-FBG sensor. High integration is achieved by using a single laser source, one shared receiver block and broadband, low reflectivity fiber Bragg gratings. Finally in section 5.3 we experimentally demonstrate the combined use of serially multiplexed FBG arrays and BOTDA sensor over the same SMF fiber, using a highly-integrated interrogation unit. Experimental results show concurrent distributed sensing, with temperature (strain) resolution of 2.4 °C (48 µε) throughout ~20 km fiber length, and dynamic sensing with discrete FBG dynamic strain resolution of 24.2 ne/√Hz at 0.25 kHz, enabling the use of such an effective hybrid technique in many applications where distributed static and discrete dynamic measurements are simultaneously required.
Chapter 1

Fundamentals of In-fiber Gratings and Distributed Optical Fiber Sensors

1.1 Development of Fiber Optic Sensor Technology

The field of optical sensing has undergone remarkable progress and innovations over the last two decades. The development of fiber optic sensor industry for structural health monitoring, energy sector, medical applications, oil&gas production, pipeline-integrity & flow-assurance, military & law-enforcement, transportation, robotics and other areas represents a unique confluence of electronics, photonics, mechanical and communication engineering disciplines. Additionally fiber optic sensing engineering has truly revolutionized the industry by providing more reliable, durable and high performance and cost effective measurement solutions. Fiber optic sensing R&D field has recently experienced tremendous improvement due to their numerous advantages in social and industrial fields [1]-[14]. While enormous improvements on several modern non-optical sensing technologies have been made on the other hand a significantly growing fiber optic sensing industry has also been recently observed. The measurement and sensing capabilities of optical fiber is leading to longer sensing distances, driven by the exploding demand in several industrial fields. Recently several commercial fiber optic sensor companies have squarely targeted at potential markets where traditional or electrical sensing technology was insignificant or in many circumstances non-present.

The inherent advantages of fiber optic sensors, which include their ability to be lightweight, very small size, passive, low-power, resistant to electromagnetic interference, their high sensitivity when compared to other types of sensors, their wide bandwidth, compactness, geometric versatility and their environmental ruggedness, were heavily exploited to offset their major disadvantages like higher cost and end-user unfamiliarity. Fiber optic sensors also allow for remote sensing and often do not require contact allowing access into normally inaccessible areas and finally they can be interfaced with data communication systems. Specially prepared fibers can withstand high temperatures and other harsh environments. Deployment of distributed sensors covering extensive structures and geographical locations is also feasible.

There are a variety of fiber optic sensors as well as many applications. Fiber optic sensors can be divided into a number of categories or groups; in particular they can be divided into extrinsic and intrinsic sensors [12].
Figure 1.1: Distinction between (a) Extrinsic and (b) Intrinsic fiber optic sensors used in transmission or double ended configuration.

- **Extrinsic Sensors:** An extrinsic fiber-optic sensor uses an input fiber and an output fiber and has some light modulation capability in the internal part. An external sensor head, usually based on miniature optical components, modulates the properties of laser light in response to changes in the physical perturbations of interest. Basically, the fibers merely act as light pipes transmitting and receiving the light. Some environmental parameters act on the sensitized region along the fiber and modulate the light signal. The modulation may change the light’s colour, phase, intensity, or polarization state. This modulation may occur in numerous ways. Therefore, a light source with known properties is injected into the input fiber, coupled to an optical modulator of some form, and then coupled into the output fiber, and photo detected at its output. This is an extrinsic (or external) light modulating device. This configuration represents an extrinsic fiber-optic sensor as described in Figure 1.1 (a).

- **Intrinsic Sensors:** With an intrinsic fiber sensor, the environmental signal causes some perturbation to occur on the fiber itself, locally changing the
boundary conditions. That boundary condition variation changes the fibers wave-guiding properties and therefore modulates the light in the fiber. A remarkable feature of intrinsic sensors is that they can provide distributed sensing up to sub-meter spatial resolution over longer distances. The environmental signal interacts with the fiber, hence changing the light that has propagated through it. One of the problems associated with an intrinsic fiber sensor, more than an extrinsic fiber sensor, is that the environmental signal can influence multiple parameters of the same optical field. In certain cases, complex techniques are used to localize the physical parameter to be measured. The significant advantage of an intrinsic fiber sensor over an extrinsic one is that the fiber itself is the sensing element, as shown in Figure 1.1 (b).

1.2 Multiplexed and Distributed Sensing Approach

Optical fiber sensing techniques provide additional sensing options, for instance their capabilities to perform multiplexed sensing by placing serial distribution of several discrete sensors in a single optical sensing network [11], [12], [15]-[17]. One of the most important features of fiber optic sensors is their ability of sensing many points with one fiber. These sensors use multiplexing techniques in order to use all the fiber length for sensing.

1.2.1 Discrete Sensing

![Figure 1.2: Discrete fiber optic sensor used in reflection mode or single ended configuration.](image)

Discrete fiber optic sensors as shown in Figure 1.2, measure a particular physical measurand at a particular location. Usually they are also called point sensors and correspond to way in which most sensors operate. For practical applications, the difficulty is to predict the critical points well in advance where the sensors must be located. Usually point sensors permits interrogation speed up to several KHz
allowing, for instance dynamic strain, acceleration, acoustic waves, temperature and pressure measurements.

1.2.2 Multiplexing Sensing

The primary feature of multiplexed sensor network is that the point sensors are attached to terminal points within the sensing network and interrogated individually [15]-[17]. Multiplexing is the way to use one optical source to apply light to multiple discrete sensors, the use of one fiber to access multiple sensors, the use of one photodetector to convert the optical signal from multiple sensors, the use of one electronic signal processor to compute measurand values for multiple sensors, or any combination of the above.

Figure 1.3:
Quasi-distributed / Multiplexed fiber optic sensor used in reflection mode or single ended configuration.

To provide interesting practical solutions for real field applications, it is highly desirable that sensors must be multiplexed, permitting quasi-distributed sensing at a lower cost per sensor, thus improving the cost effectiveness of the fiber systems in cases where more than one point is to be monitored. Usually they allow the measurand information to be obtained at pre-determined critical sensing points in a whole sensor network, allowing for example a continuous dynamic monitoring of complex and large building structures. Many possibilities have been implemented to arrange a set of discrete sensors in a network or array configuration, with individual sensors outputs multiplexed. In many industrial applications, the most employed techniques are time, wavelength, coherence, polarization and spatial multiplexing.

1. Time Division Multiplexing:

The reflectivity used to monitor a discrete sensor is well suited for time division multiplexing using a pulsed light source. The sensor system is efficiently using multiple times to interrogate spatially distributed in-line sensors. In such a system, launching light into an optical fiber and analyzing the arrival time of each reflected pulse in different time slots allows one to
discriminate between sensors. Fiber delay lines of different lengths are provided between transmitter and receiver. In such a system, the reflected waveforms are samples for analog-to-digital convertor (ADC) at fixed time delays and samples are averaged digitally. Figure 1.4 illustrates a time division multiplexed system that uses micro bend sensitive areas along an optical fiber [18]. As the optical fiber is stressed, micro bending loss increases and the time delay associated with these losses allows to locate faulty locations. The entire length of the fiber can be made micro bend sensitive and Rayleigh scattering loss used to support a distributed sensor that will predominantly measure strain.

The use of partial reflectors along a length of optical fiber permits in-line serial multiplexing of point sensors, such as FBG and Fabry-Perot sensors. Interrogation with the pulsed light source is practical, providing the duration of the optical pulse, is less than the round-trip delay ($2nL/c$), between reflectors separated by distance $L$ [19]. As time division multiplexing techniques produce multiple reflections, cross talk and so-called spectral shadowing effects, low-reflectivity point mirrors are placed along the sensing fiber.

Figure 1.4:
Time division multiplexing configuration can be used with fast detection electronics.

2. Wavelength Division Multiplexing:

Wavelength division multiplexing (WDM) is one of the most widely used and efficient multiplexing technique to interrogate arrays of individual sensors along a single optical fiber with high optical power efficiency, allowing to multiplex a large number of sensors with improved accuracy. WDM approach is seen to be promising solution for less complex sensing network while
increasing measurement resolution at a given interrogation speed. However the maximum number of sensors is limited by the ratio of the available system bandwidth which is less than 100 nm, over the dynamic wavelength range of an individual sensor, typically a few nanometers.

![Diagram](image)

**Figure 1.5:**
Wavelength division multiplexed configuration. A series of fiber sensors is multiplexed to reflect specific spectral bandwidths which can then be spectrally separated at the receiver onto separate detectors.

Figure 1.5 illustrates a system where a broadband light source, such as a light-emitting diode, is coupled into a series of fiber sensors that reflect signals over wavelength bands that are subsets of the light source spectrum [7]. A dispersive element, such as grating or prism, is used to separate the signals from the sensors onto separate detectors.

3. **Polarization Multiplexing:**

One of the least commonly used techniques is polarization multiplexing. In this case the idea is to launch light with particular polarization states and extract each state. A possible application is shown in Figure 1.6, where light is launched with two orthogonal polarization modes; polarization-preserving fiber and evanescent sensors are used [20]. A polarizing beam splitter allows to separate the two signals at the receiver. There is recent growing interest in using polarization-preserving fiber in combination with time domain techniques to form polarization-based distributed fiber sensors. This has the potential to offer multiple sensing parameters along a single fiber line.
Figure 1.6:
Polarization multiplexing is used to support two fiber sensors that access the cross-polarization states of polarization preserving optical fiber

4. Space Division Multiplexing

It is possible to use spatial techniques to interrogate a large number of sensor arrays using relatively few input and output optical fibers. Figure 1.7 shows a 2 by 2 array of sensors where two light sources are amplitude-modulated at different frequencies [20]. Two sensors are driven at one frequency and two more at the second. The signals from the sensors are put onto two output fibers, each carrying a sensor signal from two sensors at different frequencies. This sort of multiplexing is easily extended to $m$ input fibers and $n$ output fibers to form $m$ by $n$ arrays of sensors.

Moreover, this scheme also consists of the use of switching between different channels, each of which may contain one or several multiplexing techniques. Usually mechanical switches are employed to offer the ability to interrogate number of channels individually. It does provide a useful additional level of capacity in multiplexed sensing networks, especially in those that are not interrogated continuously.

Figure 1.7:
Spatial multiplexing of four fiber optic sensors may be accomplished by operating two light sources with different carrier frequencies.
1.2.3 Distributed Sensing

Distributed sensing offers unique and very powerful sensing capabilities which are not possible using conventional sensors, allowing the key structural measurand to be determined at any point along an optical fiber with an appropriate sensitivity and spatial resolution [16], [18], [21]-[22]. It can happen that the spatial resolution and measurement accuracy of a quasi-distributed sensing network can be superior to that of distributed sensing approach. In fact if the distance between sensors is much smaller than the scale length for change in the variable of interest, the quasi-distributed sensing can provide as much information as a distributed sensing. Practically distributed sensors are capable to spatially discriminate thousands of detecting points along the whole sensing fiber as schematically shown in Figure 1.8. A single distributed optical fiber sensor (DOFS) can replace thousands of discrete sensors; low fiber attenuation allows an uninterrupted monitoring over extremely long distances providing an impressive number of measuring points and making distributed sensing very attractive when monitoring strain and/or temperature distribution on extended infrastructure. Distributed sensing provides efficient monitoring, integrity control and improved understanding leading to significant enhancement in system design.

![Figure 1.8: Distributed fiber optic sensor configuration used in reflection mode or single ended configuration.](image)

Mostly DOFS widely exploit scattering effects, such as Brillouin or Raman non-linear effects in the fiber, to measure strain and temperature distribution.

1.3 In-fiber Grating Optical Fiber Sensor

Fiber Bragg grating (FBG) is a periodic perturbation of the refractive index along the fiber length which is formed by exposure of the core to an intense optical interference pattern [23]-[30]. The formation of permanent gratings in an optical fiber was first demonstrated by Hill et al. in 1978 at Canadian Communications Research Centre,
Canada. The index perturbation in the core is a periodic structure that acts as a stop-band filter. A narrow band of the incident optical field within the fiber is reflected by successive, coherent scattering from the index variations. Any changes in fiber properties, such as due to temperature or strain which varies the reflective index or grating pitch will change the Bragg wavelength. The basic principle of FBG sensor is to monitor the shift in the reflected wavelength of the returned “Bragg” signal with the changes in the measurand, for instance temperature and/or strain. The incident wave is coupled to a counter-propagating like mode and thus reflected. The Bragg wavelength, $\lambda_B$, is related to the effective refractive index of the fiber core at the free space center wavelength, $n_{eff}$, and the grating pitch, $\Lambda$, by the formula [24]

$$\lambda_B = 2 n_{eff} \Lambda$$  (1.3.1)

The Bragg grating wavelength, $\lambda_B$, is the free space center wavelength of the input light that will be back reflected from the Bragg grating.

FBG sensing system involving such gratings usually work by injecting light from a spectrally broadband source into the fiber, with the result that the grating reflects a narrow spectral component which is missing from the observed transmitted spectrum. Light guided along the optical fiber will be scattered by each grating plane. If the Bragg condition is not satisfied, the reflected light from each of the subsequent planes becomes progressively out of phase and will eventually cancel out. Where the Bragg condition is satisfied, the contributions of the reflected light from each grating plane add constructively in the backward direction to form a back reflected peak with the central wavelength defined by the grating parameters. Figure 1.9 shows this simply and schematically.

**Figure 1.9:**
Illustration of In-fiber grating sensors structure and spectral response used in reflection mode or single ended configuration.
The index of refractive profile of a uniform Bragg grating formed within the core of an optical fiber with an average refractive index $n_{co}$ can be expressed as [30]

$$n(z) = n_{co} \Delta n \cos \left( \frac{2\pi z}{\Lambda} \right)$$  \hspace{1cm} (1.3.2)

where $\Delta n$ is the amplitude of the induced refractive index perturbation, and $z$ is the distance along the fiber longitudinal axis.

The reflectivity increases as the induced index of refraction changes increases. Similarly, as the length of the grating increases so does the resultant reflectivity. A typical calculated reflected spectrum as a function of wavelength is shown in Figure 1.10 [30]. The side lobes of the resonance have been reduced by apodization; they are due to multiple reflections to and from opposite ends of the grating regions.

![Figure 1.10:](image)

**Figure 1.10:** Reflection spectrum of a Bragg grating as a function of wavelength.

A general expression for the approximate full width half maximum (FWHM) bandwidth of a grating is given by [30]

$$\Delta \lambda = \lambda_B s \sqrt{\left(\frac{\Delta n}{2n_{co}}\right)^2 + \left(\frac{1}{N}\right)^2}$$  \hspace{1cm} (1.3.3)

where $N$ in the number of grating planes. The parameter $s \sim 1$ for strong gratings with 100% reflection whereas $s \sim 0.5$ for weak gratings.

### 1.3.1 Sensing Principle of FBG Sensors

The built-in self-referencing capability of a FBG sensor provides a unique feature to measure absolute parameters directly encoded in wavelength, providing an output that is independent from light intensity fluctuations, spurious losses, ghost reflections and
connecting fibers thus enabling a number of important application areas ranging from structural health monitoring to medical & chemical sensing. The inherent wavelength encoded nature of FBG sensors is recognized as one of the most important advantages which allow to develop well suited and reliable sensor networks. The numbers of possible measured locations are associated with the light source bandwidth, tuning range required for each FBG and finally required measurement sensitivity & interrogation speed.

The use of fiber gratings, especially FBGs, as sensor heads has a number of advantages that make it very attractive for smart structures over the other conventional fiber optic or electrical sensors [7]:

1. The Bragg wavelength is a linear function of the measurands over large ranges.
2. The measurand information is spectrally encoded; hence, the sensor signals are basically unaffected by environmental noise or power loss.
3. FBGs have inherent advantages over fiber devices such as signal transmission capability with small loss over fiber channels.
4. FBGs can be low in price and are easily available.
5. FBGs have high reflectivity for the Bragg wavelength light, while their sizes are small (~1 cm, typically), and they can be quasi-point sensors.
6. FBGs are lightweight and because of their small diameters can be inserted into composite materials without disturbance.
7. Various types of sensor multiplexing techniques such as spatial division multiplexing (SDM), wavelength division multiplexing (WDM), time division multiplexing (TDM), and code division multiple access (CDMA), and their combinations, can be implemented to form quasi-distributed or quasi-point sensor array systems.

1.3.2 Strain and Temperature Sensing of Bragg Gratings

The sensing function of a FBG derives from the sensitivity of both the refractive index and grating period to externally applied mechanical or thermal perturbations [24], [25]. The strain field affects the response of an FBG directly, through the expansion and compression of grating pitch size and through the strain-optic effect that is the strain-induced modification of the refractive index. The temperature sensitivity of an FBG occurs principally through the effect on the induced refractive index change due to the thermal expansion coefficient of the fiber. Thus, using Eq. 1.3.1 the peak reflected wavelength shifts by an amount $\Delta \lambda_B$ in response to strain ($\Delta l$) and temperature ($\Delta T$) change as given by [30]

$$\Delta \lambda_B = 2 \left( \Lambda \frac{\partial n_{eff}}{\partial l} + n_{eff} \frac{\partial \Lambda}{\partial l} \right) \Delta l + 2 \left( \Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T} \right) \Delta T$$ \hspace{1cm} (1.3.4)
where $\Lambda$ is the grating pitch and $n_{\text{eff}}$ is the effective refractive index of the fiber core. The first term in Eq. 1.3.4 represents the strain effect on the optical fiber while the second term describes the effect due to temperature variations. Applied strain corresponds to a change in the grating spacing and the strain-optic induced change in the refractive index. The strain effect term in Eq. 1.3.4 may be expressed as [30]

$$\Delta \lambda_B = \lambda_B (1 - p_e) \varepsilon_z$$  \hspace{1cm} (1.3.5)

where $p_e$ is an effective strain optic constant defined as

$$p_e = \frac{n_{\text{eff}}^2}{2} [p_{12} - \nu (p_{11} + p_{12})]$$  \hspace{1cm} (1.3.6)

where $p_{11}$ and $p_{12}$ are components of the strain-optic tensor, and $\nu$ is the Poisson’s ratio. For a typical germanosilicate optical fiber $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.16$, and $n_{\text{eff}} = 1.482$. Experimental investigation has shown that the strain sensitivity at ~1550 nm is 1.2 pm/$\mu$e, corresponding to a change of 1.2 pm as a result of applying 1 $\mu$m to the Bragg grating. Figure 1.11 shows the Bragg center wavelength shift with applied stress on a 1548.2 nm grating.

The second term in Eq. 1.3.4 represents the effect of temperature on an optical fiber. A shift in the Bragg wavelength due to thermal expansion changes the grating spacing and the index of refraction. The fraction wavelength shift for a temperature change $\Delta T$ may be written as [30]

$$\Delta \lambda_B = \lambda_B (\alpha_\Lambda - \alpha_n) \Delta T$$  \hspace{1cm} (1.3.7)

where $\alpha_\Lambda = (1/\Lambda)(\partial \Lambda / \partial T)$ is the thermal expansion coefficient for the fiber and $\alpha_n = (1/n_{\text{eff}})(\partial n_{\text{eff}} / \partial T)$ represents the thermo-optic coefficient. Figure 1.12 shows that the sensitivity of a Bragg grating central wavelength as a function of temperature for a ~1550 nm Bragg grating is approximately 13.7 pm/$^\circ$C [30]. Now it is clear that any changes in the external perturbations to the grating are associated with a Bragg wavelength change which is the sum of strain and temperature terms. It is worth to mention here that in applications where only one physical measurand is of interest, the deconvolution of temperature and strain becomes necessarily.
1.3.3 Apodization of the Spectra Response of In-fiber Gratings

Apodization of a periodic waveguide structure like In-fiber gratings suppress the side lobes. The technique utilizes the amplitude modulation of the core refractive index which causes a reduction of the side lobe amplitude [31]. In practice apodization is accomplished by varying the amplitude of the coupling coefficient along the length of the grating. It is important to note that in some advanced sensing applications, such as for instance in hybrid distributed-discrete sensing approach, it is essential to lower and, if possible to eliminate the reflectivity of these side lobes to get very high rejection of the unnecessary back reflections. Bragg gratings with side lobes level 26 dB lower than the peak reflectivity represents a reduction of 14 dB in the side lobe levels compared to uniform gratings with the same bandwidth and reflectivity. Figure 1.13 compares the spectral reflection responses of an apodized and an unapodized In-
fiber grating reflector where a 20 dB reduction in side lobe levels is clearly shown [30].

![Reflection spectrum of fiber Bragg gratings](image)

**Figure 1.13:**
Reflection spectrum of fiber Bragg gratings with a uniform diffraction phase mask and with a phase mask Gaussian profile.

### 1.3.4 Temperature/Strain Cross Sensitivity

FBGs are most suitable elements for measuring strain/temperature in specific critical points of large infrastructures. However, one of the difficulty for most FBG sensing applications is to separate strain from temperature component which complicates the sensor design and implementation to monitor strain, as temperature variations along the optical fiber can lead to anomalous, thermal apparent strain interpretations. Several techniques have been introduced to discriminate between dual sensitivity effects [7]. It is worth to mention here that for dynamic strain measurement applications the strain/temperature cross-sensitivity is not an issue, since the thermal fluctuations occurs at lower frequencies that tend not to coincide with the resonance frequency of interest. For static measurement, temperature sensitivity of the FBG can be an issue and complicate the measurement system.

To recover temperature and strain without ambiguity, a two-grating sensing system (reference grating and sensing grating) could be used to provide the following relation between the wavelength shifts and the measurands

\[
\begin{pmatrix}
\Delta \lambda_1 \\
\Delta \lambda_2
\end{pmatrix} =
\begin{pmatrix}
K_{1\varepsilon} & K_{1T} \\
K_{2\varepsilon} & K_{1T}
\end{pmatrix}
\begin{pmatrix}
\varepsilon \\
T
\end{pmatrix}
\]

(1.3.8)
where $\Delta \lambda_1$ and $\Delta \lambda_2$ are the wavelength shifts from two grating sensors, respectively; $K_{1e}, K_{1T}$ represents the response to strain and temperature for FBG 1 and $K_{2e}, K_{2T}$ for FBG 2. Different cases can be classified as

1. Ideal case cross sensitivity occurs at $K_{1e} = K_{2T} = 0$, or $K_{2e} = K_{1T} = 0$.
2. With one of the elements in the response matrix being zero, one sensor is isolated from either of the perturbations, which can provide a reference for the other sensor.

An efficient solution involves compensating for the temperature/strain influence by using another FBG that is shielded from strain/temperature and measures only one perturbation. Several schemes have been proposed. Among them, the most effective method involves the use of strain-free temperature reference gratings that are co-located with the strain sensors, experiencing the same thermal environment. The compensation is obtained by subtracting the wavelength shift induced by the temperature excursion in the reference grating from the total wavelength shift recorded by the strain sensor [7]. Despite its effectiveness, this method is costly as extra gratings and their associated interrogation units are needed in the sensing system.

3. The two sensors have very different responses to strain and temperature so that the determinant of the response matrix is nonzero, and the eigenvalue solution for the matrix equation can therefore be obtained.

A great deal of research effort has been focused on finding possible grating sensor configuration and interrogation techniques that will allow temperature and strain to be measured simultaneously which includes.

1. Bragg gratings and fiber polarization rocking filter.
2. FBGs with different fiber diameters.
3. FBG and chirped grating in a tapered fiber.
4. Using fundamental and harmonic modes of FBG.
5. Employing polarization maintaining FBG.
6. Reference grating.

### 1.4 Distributed Optical Fiber Sensors

Distributed optical fiber sensors (DOFS) offer a unique mechanism that allows to measure key parameters such as strain and temperature at any point along the fiber optic cable with great advantages over conventional electrical sensors in terms of reliability, flexibility, cost and performance, They also offer capability of being embedded within complex structural components, to include portable demodulation system, intelligent real time processing, adequate measurand resolution and sufficient time response.
DOFSs are particularly effective for use in applications where monitoring a single measurand is required at a large number of points as for big structures. DOFSs utilize the very special properties of the optical fiber to make simultaneous measurements of both the spatial and temporal behaviour of a measurand field. As such, they provide an extra dimension in the measurement process, leading to accurate monitoring and control, and to a new level of understanding, especially useful for controlling the behaviour of large infra-structures. DOFS allow one to measure spatial distributions with a spatial resolution of 0.1-1 m over a distance of several kilometres or tens of kilometres.

The benefits of DOFS for general measurement functions are well known: they rely on the insulating, dielectric, passivity of the medium, combined with the sensitivity of its optical propagation properties to external influences. DOFS takes advantage of two additional properties of the fiber: its one-dimensional nature, and its mechanical flexibility. With the aid of these, it becomes possible, in principle, to determine the value of a wanted measurand continuously as a function of position, along the length of a suitably-configured fiber, with arbitrarily large spatial resolution; the normal temporal variation is determined simultaneously, from the time-dependence of the signal.

DOFS are considered as a perfect solution for several applications where conventional sensors such as foil strain gauges, thermocouple and vibrating wires have proven ineffective and difficult to be used in several practical conditions. Possible applications might include:

1. Chemical and bio-chemical sensing exploiting absorption and fluorescence phenomenon.
2. Monitoring structures that generate, distribute, and convert electrical power in energy sector such as for instance windmill, electrical transformers; monitoring the integrity of wind turbines, pipe line monitoring, power line plate form and downhole monitoring.
3. Applications in civil industry like, large building monitoring, bridges and roads monitoring, airport landing strip and dams monitoring.
4. Various transportation applications like railways and roadways monitoring, airplane fuel tank and ship hull monitoring.

The flexibility of the fiber makes it relatively easy to install over the chosen measurement path and thus allows, unlike many other sensor systems, retrospective fitting. Furthermore, again in contradistinction to other sensor arrangements, DOFS offers the unique feature that there are no conventional techniques for acquiring the same information. The most commonly DFOS are based on Rayleigh, Raman and Brillouin scattering. By monitoring the variation of Rayleigh back scattering signal intensity, one can measure the spatial variations in the fiber scattering coefficient providing local temporal information along the optical fiber, thus analysing the reflection trace one can sense the localized perturbation. Raman DOFS has the ability
to sense the ambient temperature along the fiber while Brillouin scattering is sensitive to both temperature and strain.

### 1.4.1 Principle of Distributed Optical Fiber Sensors

To investigate the working principle of DOFS, it is essential to understand the novel measurement technique to get spatially resolved reflectometry that enables to view inside of optical fiber with sub meter spatial resolution. For a precise and reliable measurement of physical parameters along an optical fiber it is important to study the back scattered optical power phenomenon along the fiber itself. By utilizing spatially resolved measurement technique like Optical Time Domain Reflectometry (OTDR), it becomes possible to design and visualize the sensing system for medium and long distances measurements for example to determine the temperature and/or physical stress along the optical fiber.

![Block diagram of single-pulse OTDR. PD: Photo-detector, ADC: Analog-to-digital converter.](image)

**Figure 1.14:**

The primary challenge in DOFSs is to identify the position along the optical fiber within the spatial resolution interval by exploiting backscattered light returning from the sensing cable when probing it with laser or light emitting diode (LED). This can be done either by employing OTDR by sending short optical pulses or equivalently by utilizing spectral techniques like the Optical Frequency Domain Reflectometry (OFDR). Due to inherent simplicity, performance parameters, excellent results, non-complex operating principle and for their convenience, most DOFS systems use OTDR techniques.

The backscattering impulse response of the fiber under test can be effectively measured using OTDR, providing ultimate fiber response which is the result of convolution with a finite pulse width, leading to smoother version of impulse response. OTDR measurements translate the time scale to fiber distance by using a
conversion factor which approximately equals 10 µsec/km, the round trip propagation delay of light in fiber. In this way one can evaluate the time/space distribution and magnitude of physical local induced effects along the optical fiber.

To understand the basic principle of DOFS based on OTDR approach it is very important to investigate how light propagates down the fiber. OTDR launches short duration optical pulses into the fiber and then measure the waveform of the returned optical signal as a function of time, providing the detail local loss information throughout the fiber and then this information can also be used precisely to calculate the attenuation coefficient. Due to the nonzero losses this power is gradually attenuated along the fiber and consequently the backscattered power is also attenuated. While light propagates into the fiber, optical pulses encounter Fresnel reflections and Rayleigh scattering locations resulting in a fraction of the signal being travel back in the opposite direction which is linearly proportional to the optical power pulse at that location. Since both the light source and optical detector are co-located therefore only access to single end is required also conforming a non-destructive method.

Figure 1.14 shows the block diagram of an OTDR [32]. A laser diode is driven by an electrical pulse generator that produces a train of short optical pulses. A photodiode is used to detect the backscattered optical power from the fiber through a directional coupler. The detected waveform of the optical signal is amplified and digitized through an ADC and analyzed by a digital-signal processing (DSP) unit. The timing of the DSP is synchronized with the source optical pulses so that the propagation delay of each backscattered pulse can be precisely calculated.

Figure 1.15:
Optical pulse propagation inside optical fiber and its respective backscattering round trip time in OTDR method.
In general, the loss in an optical fiber may be caused by absorption, scattering, bending and connecting. Most of these effects can be nonuniform along the fiber, especially if different fiber spools are connected together. Therefore, the fiber attenuation coefficient is a function of the location along the fiber. The power distribution along the fiber can be expressed as [32]

\[ P(z) = P(0) \exp \left\{ - \int_0^z [\alpha_0(x) + \alpha_{sc}(x)] \, dx \right\} \tag{1.4.1} \]

Where \( P(0) \) is the input optical power, \( \alpha_{sc}(x) \) is the attenuation coefficient due to Rayleigh scattering, and \( \alpha_0(x) \) is that caused by attenuation effects other than scattering along the fiber. Suppose an optical pulse is injected into the fiber at time \( t_0 \) with the pulse width \( \tau \); neglecting the effect of chromatic dispersion and fiber nonlinearity, the locations of the pulse leading edge and the trailing edge along the fiber at time \( t \) are \( z_{le} = v_g (t - t_0) \) and \( z_{tr} = v_g (t - t_0 - \tau) \), respectively, where \( v_g \) is the group velocity of the optical pulse.

Then consider the Rayleigh backscattering caused by a short fiber section of length \( dz \). According to Eq. 1.4.1, the optical power loss due to Rayleigh scattering within this short fiber section is [32]

\[ dP_{BS}(z) = P(z) \cdot \alpha_{SC}(z) \, dz. \tag{1.4.2} \]

Only a small fraction of this scattered energy is coupled to the guided mode, which can propagate back to the input side of the fiber. Therefore the reflected optical power that is originated from the location \( z \) and reaches to the input end of the fiber can be calculated as [32]

\[ dP_{BS}(z) = P(0) \cdot \eta \cdot \alpha_{SC}(z) \cdot dz \cdot \exp \left\{ -2 \int_0^z \alpha(x) \, dx \right\} \tag{1.4.3} \]

where \( \alpha(x) = \alpha_0(x) + \alpha_{SC}(x) \) is the composite attenuation coefficient of the fiber, which includes both the scattering and other attenuation effects. \( \eta = (1 - \cos \theta_1)/2 \) is the conversion efficiency from the scattered light to that captured by the fiber, and \( \theta_1 \) is the maximum trace angle of the guided mode in the fiber, which is proportional to the numerical aperture.

As illustrated in Figure 1.15, at time \( t_1 \), the backscattered optical signal that reaches the input terminal of the fiber is originated from a short fiber section of length \( \Delta z/2 = (z_{le} - z_{tr})/2 \), and the amplitude is therefore [32]

\[ P_{BS}(z) = \frac{v_g \tau}{2} \cdot P(0) \cdot \eta \cdot \alpha_{SC}(z) \cdot \exp \left\{ -2 \int_0^z \alpha(x) \, dx \right\} \tag{1.4.4} \]
Provided the pulse duration \( \tau \), the spatial localization of the point scattering center cannot be better than \( \Delta z = 0.5.\tau.v_g \), where \( \Delta z \) represents the spatial resolution of the OTDR which is the smallest distance to perform independent measurement.

OTDR direct detection method allow two possibilities to increase the energy of impulse response, either through enhance the peak power of laser pulse or by injecting pulses having long duration. This mutual competitive relation introduces the trade-off between dynamic range and spatial resolution which is the fundamental limit of OTDR based DOFS. Due to practical constraints for example fiber non-linearities, saturation of receiver by Fresnel reflection, heating etc, the output peak power of the injected pulses cannot be increased beyond pre-calculated thresholds. Ultimately by employing short duration input pulses introduces negative condition for good detection because it requires a broader bandwidth of the receiver that introduces more noise.

1.5 Performance Characteristics of Optical Fiber Sensors

It is important to remind the definition of some important parameters related to OFS:

1. **Dynamic resolution**: The minimum detectable dynamic strain is determined by the background noise level in power spectrum using spectrum analyzer. Since the magnitude of noise changes with frequency span, it is necessary to normalize all measurement to 1 Hz bandwidth. This normalized minimum detectable strain is displayed in units of \( \varepsilon/(Hz)^{1/2} \) where \( \varepsilon \) is strain.

2. **Precision of measurement**: The precision of each measurement is described in terms of repeatability which refers to the same conditions of measurement including same environment, operational parameters, constant temperature and measurement system.

3. **Cross-sensitivity of reading and sensing system**: It refers to the intrinsic response of OFSs that is dependent on more than one measurand for example on stress and temperature variations along the optical fiber at the same time which is indistinguishable. Cross-sensitivity could complicate the design and implementation of OFS.

4. **Scattering dynamic range**: It is the ratio between the backscatter signal at the OFS front panel connector and the noise floor to be measured with the required accuracy. It is often expressed in dB.

5. **Data resolution**: The interval between sample points usually expressed in samples per measuring time is known as data density. It refers to number of sample points per unit sensing distance. It is normally limited by on-board memory, signal processor and ADC speed.

6. **Measurement speed**: It is the time required by the sensor system to obtain significant results with a specified accuracy. The speed for measurement depends upon many factors for example fiber length, data-processing speed, required spatial resolution and accuracy.
7. **Sensitivity**: Sensitivity specifies the minimum measurable optical signal power before it reaches the background noise floor. OFS detection sensitivity is determined by the noise characteristics of receiver and it is given by $\mu\text{e}/\sqrt{\text{Hz}}, \%/{^\circ}\text{C}$, etc.

8. **Spatial resolution**: Spatial resolution is the smallest distance between two scatters that can be spatially resolved and it refers to the sensing system ability to detect the changes in the spatial variation of measurand over the smallest length of optical fiber. Mostly there is a trade-off between spatial resolution and sensing distance/measurement speed. Normally it is typical 1-3 meters, limited by the optical pulse duration from the laser source.

9. **Measurement range**: The measurement range is defined as the maximum optical fiber length over which measurand can be detected with given spatial and measurand resolution.

10. **Accuracy**: Represents the deviation of the measured value to the true value of the measurand.
Chapter 2

Theory of In-fiber Grating and Light Scattering in Optical Fiber

The practical implementation of hybrid distributed/discrete optical fiber sensor requires a deep understanding of the optical phenomena that give rise to the different existing mechanisms that can be exploited for sensing. As discussed previously, the hybrid sensors we are considering in this Thesis combine fiber Bragg gratings (FBGs) and OTDR-based distributed sensing techniques with given scattering process, allowing for simultaneous discrete-dynamic and distributed-static measurements of environmental variables along an optical fiber.

In this chapter, we describe the mathematical model of FBG and general aspects related to several scattering process including discussions on their origins as well as their mathematical modelling. The results from coupled-mode theory are briefly reviewed together with the common numerical techniques for computing the reflection and transmission spectra of fiber gratings. The fundamental equations required for a theoretical understanding of the different types of scattering processes in optical fibers are provided for both spontaneous and stimulated regimes. All the relevant parameters related to mode-coupling and scattering process are also defined throughout this chapter, thus providing a complete theoretical back ground of FBGs and linear/non-linear scattering processes in optical fibers.

This chapter starts with a well known coupled-mode theory used in simulating Bragg grating behaviour. Section 2.2 describes the general overview of spontaneous scattering processes, focussing our attention on the description of Rayleigh scattering, spontaneous Brillouin scattering (SpBS) and spontaneous Raman scattering (SpRS). Finally, stimulated scattering, such as stimulated Brillouin scattering (SBS) is presented, including the derivation of their mathematical model.

2.1 Coupled-mode Theory

Exposing photosensitive fiber to a spatially varying pattern of ultraviolet light produces the necessary refractive index perturbation that produces FBGs. We assume for simplicity that what results is a perturbation to the effective refractive index $n_{eff}$ of the guided modes of interest, described by
The relation between the spectral dependence of a fiber grating and the corresponding grating structure is usually described by the coupled-mode theory. Coupled-mode theory is a good tool for obtaining quantitative information about the diffraction efficiency and spectral dependence of fiber gratings. It is one of the most popular techniques utilized in describing the behavior of Bragg gratings, mainly due to its simplicity and accuracy in the modeling the optical properties of most fiber gratings of interest. Coupled-mode theory is described in a number of texts; detailed analysis can be found in [33], [34]. The derivation in this section closely follows the work by Erdogan [26]. In the ideal-mode approximation to coupled-mode theory, we assume that the transverse component of the electric field can be written as a superposition of the ideal modes labeled (i.e., the modes in an ideal waveguide with no grating perturbation). Given that the modes are labeled with index \( m \), such that

\[
E^T(x, y, z, t) = \sum_m [A_m \exp(i\beta_m z) + B_m(z)\exp(-i\beta_m z)] \bar{e}_m^T(x, y) \exp(-i\omega t)
\]

where the coefficients \( A_m(z) \) and \( B_m(z) \) are slowly varying amplitudes of the \( m \)th mode travelling in the +z and −z directions, respectively, and the propagation constant \( \beta \) is simply \( \beta = (2\pi/\lambda)n_{\text{eff}} \). The transverse mode field \( \bar{e}_m^T(x, y) \) might describe the bound-core or radiation LP modes or they might describe cladding modes. While the modes are orthogonal in an ideal waveguide and hence, do not exchange energy. However, the presence of a dielectric perturbation associated with the fiber grating forces coupling between the modes. In that case the amplitudes \( A_m \) and \( B_m \) of the \( m \)th mode evolve along the \( z \) direction according to

\[
\frac{dA_m}{dz} = i \sum_q A_q (C_{qm}^T + C_{qm}^L) \exp[i(\beta_q - \beta_m)z] + i \sum_q B_q (C_{qm}^T - C_{qm}^L) \exp[-i(\beta_q + \beta_m)z]
\]

\[
\frac{dB_m}{dz} = -i \sum_q A_q (C_{qm}^T - C_{qm}^L) \exp[i(\beta_q + \beta_m)z] - i \sum_q B_q (C_{qm}^T + C_{qm}^L) \exp[-i(\beta_q - \beta_m)z]
\]

The transverse coupling coefficient between the \( m \) and \( q \) modes in the above equation is given by the following integral:

\[
\delta n_{\text{eff}}(z) = \frac{\delta n_{\text{eff}}(z)}{z} \left[ 1 + s \cos \left( \frac{2\pi}{\Lambda} z + \phi(z) \right) \right]
\]
\[ C_{qm}^T(z) = \frac{\omega}{4} \int_{\infty}^{\infty} \Delta \varepsilon(x, y, z) e_q^T(x, y).e_m^{T*}(x, y) \, dx \, dy \]  

(2.1.5)

where \( \Delta \varepsilon(x, y, z) \) is the permittivity perturbation, which is approximately \( 2n \delta n \) for \( \delta n \) much smaller than \( n \). The longitudinal coupling coefficient \( C_{qm}^L(z) \) is defined in a similar way to the above transverse coupling coefficient \( C_{qm}^T(z) \); however for the fiber modes is analogous to , but generally for fiber modes \( C_{qm}^L(z) \) is usually neglected since \( C_{qm}^L \ll C_{qm}^T \).

In most fiber gratings, the UV-induced index changes \( \delta n(x, y, z) \) are approximately uniform across the fiber core and nonexistent outside the core. We can thus describe the core index change by an expression similar to that of Eq. 2.1.1, where \( \overline{\delta n}_{\text{eff}}(z) \) is replaced by \( \overline{\delta n}_{\text{co}}(z) \). If we define two new coefficients, the self- and cross-coupling coefficients, in the following way [26]:

\[ \zeta_{qm}(z) = \omega \frac{n_{co}}{2} \overline{\delta n}_{\text{co}}(z) \int_{\text{core}} e_q^T(x, y).e_m^{T*}(x, y) \, dx \, dy \]  

(2.1.6)

\[ \kappa_{qm}(z) = \frac{s}{2} \zeta_{qm}(z) \]  

(2.1.7)

where \( \zeta_{qm}(z) \) is a “dc” coupling coefficient and \( \kappa_{qm}(z) \) is an “ac” coupling coefficient. Thus, the general coupling coefficient may now be written as

\[ C_{qm}^T = \zeta_{qm}(z) + 2\kappa_{qm}(z) \cos \left[ \frac{2\pi z}{\Lambda} + \phi(z) \right] \]  

(2.1.8)

Equations 2.1.3 through 2.1.8 are the coupled-mode equations that can be used to describe the spectral response of fiber gratings.

### 2.1.1 Bragg Gratings

For the FBG the dominant interaction lies near the wavelength for which reflection occurs form a mode of amplitude \( A(z) \) into an identical counter-propagating mode of amplitude \( B(z) \). Under such conditions Eqs. (2.1.3) and (2.1.4) may be simplified [26], [35] to the following Eqs:

\[ \frac{dA^+}{dz} = i\zeta^+ A^+(z) + i\kappa^+ B^+(z) \]  

(2.1.9)

\[ \frac{dB^+}{dz} = -i\zeta^+ B^+(z) - i\kappa^+ A^+(z) \]  

(2.1.10)

where \( A^+(z) = A(z) \exp(i \delta_0 z - \frac{\phi}{2}) \), \( B^+(z) = B(z) \exp(-i \delta_0 z + \frac{\phi}{2}) \), and \( \zeta^+ \) is the general “dc” self-coupling coefficient defined as:
\[ \zeta^+ = \delta_d + \zeta - \frac{1}{2} \frac{d\varphi}{dz} \quad (2.1.11) \]

with \( \delta_d \) being the detuning, which is independent of \( z \) and is defined in the following way:

\[ \delta_d = \beta - \frac{\pi}{\lambda} = 2\pi n_{\text{eff}} \left[ \frac{1}{\lambda} - \frac{1}{\lambda_d} \right] \quad (2.1.12) \]

Here \( \lambda_d = 2n_{\text{eff}}A \) is the design peak reflection wavelength for an infinitesimally weak index of refraction change grating \( (n_{\text{eff}} \to 0) \). A complex coefficient \( \zeta \) can describe the absorption loss in the grating where the power loss coefficient will be given by \( a = 2\text{Im}(\zeta) \). For a single mode Bragg refraction we find the following simplified relations [26]:

\[ \zeta = \frac{2\pi}{\lambda} \delta n_{\text{eff}} \quad (2.1.13) \]
\[ \kappa = \kappa^* = \frac{\pi}{\lambda} \delta n_{\text{eff}} \quad (2.1.14) \]

If the grating is uniform along the \( z \) direction, then \( \delta n_{\text{eff}} \) is constant and \( d\varphi/dz = 0 \) (i.e. there is no grating chirp). Thus \( \kappa, \zeta, \) and \( \zeta^+ \) are constants. This simplifies Eqs. (2.1.9) and (2.1.10) into coupled first-order ordinary differential equations with constant coefficients. One may arrive at a closed-form solution to these equations given the appropriate boundary conditions. For a uniform fiber grating of length \( L \) the reflectivity can be found assuming a forward-propagating wave incident from \( z = -\infty \), while requiring that no backward-propagating wave exist for \( z \geq L/2 \). The amplitude \( \rho = B^*(-L/2) / A^*(-L/2) \) and the power reflection coefficients \( R = |\rho|^2 \) can be shown to be:

\[ \rho = \frac{-\kappa \sinh \sqrt{(\kappa L)^2 - (\zeta^+ L)^2}}{\zeta^+ \sinh \sqrt{(\kappa L)^2 - (\zeta^+ L)^2} + i\kappa^2 - \zeta^+ \cosh \sqrt{(\kappa L)^2 - (\zeta^+ L)^2}} \quad (2.1.15) \]

and

\[ R = \frac{\sinh^2 \sqrt{(\kappa L)^2 - (\zeta^+ L)^2}}{\zeta^+ \cosh \sqrt{(\kappa L)^2 - (\zeta^+ L)^2}} \quad (2.1.16) \]

Figure 2.1 shows the reflectivity of a uniform Bragg grating calculating from Eq. (2.1.16) for \( \kappa L = 2 \) and \( \kappa L = 8 \). The two curves are plotted against the normalized wavelength:

\[ \frac{\lambda}{\lambda_{\text{max}}} = \frac{1}{\zeta^+ L/\pi N} \quad (2.1.17) \]
where \( N \) is the total number of grating periods \( (N = L/\Lambda) \), and \( \lambda_{\text{max}} \) is the wavelength at which maximum reflectivity occurs. For this calculation \( N = 10,000 \). It is interesting to note that for a given \( \kappa L \) with increasing \( N \) the reflectivity bandwidth becomes narrower (i.e. longer gratings produce narrower spectral width).

Using Eq. (2.1.16), the maximum reflectivity for the Bragg grating is:

\[
R_{\text{max}} = \tanh^2 (\kappa L)
\]  

(2.1.18)

The maximum occurs when \( \zeta^+ = 0 \), or at the wavelength of

\[
\lambda_{\text{max}} = \left( 1 + \frac{\delta \tilde{n}_{\text{eff}}}{n_{\text{eff}}} \right) \lambda_d
\]

(2.1.19)

A bandwidth for the uniform Bragg grating may be defined as the width between the first zeros on either side of the maximum reflectivity [26]. Thus from Eq. (2.1.16) we find

\[
\frac{\Delta \lambda_0}{\lambda} = \frac{s \delta \tilde{n}_{\text{eff}}}{n_{\text{eff}}} \sqrt{1 + \left( \frac{\lambda_d}{s \delta \tilde{n}_{\text{eff}} L} \right)^2}
\]

(2.1.20)

For the case where the index of refraction change is weak (weak-grating limit) \( s \delta \tilde{n}_{\text{eff}} \) is very small; thus, \( s \delta \tilde{n}_{\text{eff}} \ll \lambda_d/L \) and

\[
\frac{\Delta \lambda_0}{\lambda} \xrightarrow{\lambda_d / n_{\text{eff}} L} 2 \frac{\lambda_d}{\bar{N}}
\]

(2.1.21)

which implies that the bandwidth of weak gratings is limited by their length. However, in the case of strong gratings where \( s \delta \tilde{n}_{\text{eff}} \gg \lambda_d/L \),

Figure 2.1:
Reflection spectral response versus normalized wavelength for a uniform FBG with \( \kappa L = 2 \) and \( \kappa L = 8 \).
\[
\frac{\Delta \lambda_0}{\lambda} \to \frac{s \delta n_{\text{eff}}}{n_{\text{eff}}}
\] (2.1.22)

In strong gratings, the light does not penetrate the full length of the grating, and thus the bandwidth is independent of the length and directly proportional to the induced index change. For strong gratings the bandwidth is similar whether measured at the band edges, at the first zeros, or as the full width half maximum (FWHM).

Figure 2.2: Measured (dots) and calculated (line) reflection spectra for Bragg reflection in a 1 mm long uniform grating with \( \kappa L = 1.64 \).

Figure 2.2 shows an excellent agreement of the theoretical calculation (solid line) with the experimental data (square points) from a 1 mm uniform Bragg grating. The design wavelength of the grating was approximately 1558 nm with an induced index change estimated to be approximately \( 8 \times 10^{-4} \).

2.2 Spontaneous Light Scattering

2.2.1 Features of Spontaneous Light Scattering

In spontaneous light scattering process, the optical properties of the propagating medium are unmodified by the presence of the incident light beam. This condition only occurs when the intensity of the incident light is low. Under such circumstances scattering is generated by the mechanical or thermal excitation of the medium with an intensity that is proportional to the intensity of the incident light. However the character of the light-scattering process is profoundly modified whenever the intensity of the incident light is sufficiently large to modify the optical properties of the material, and therefore, the scattering process turns to be nonlinear. In such case, the scattering is generated by the material fluctuations by the incident light [36], process that is known as stimulated scattering.
When light propagates through matter several scattering processes can occur. Actually, scattering is originated from the interaction of light with the excitation of the medium. In quantum theory, scattering can be described as the interaction of photons (quanta of light) and phonons (quanta of medium excitation). The quantum theory can adequately describe the interaction for low light intensity levels. However, when there is a strong excitation of the medium, due to the high intensity of light, the use of semi-classical wave theory turns to be more appropriate to describe scattering. Considering an inhomogeneous medium, scattering process removes some photons of incident light and produces scattered photons that might be shifted in direction, phase and frequency. As a matter of fact, scattering process can be classified into two types:

1. **Elastic scattering**: process that scatters photons maintaining their energy, so that they have the same frequency of the incident light.
2. **Inelastic scattering**: In this case incident photons give/receive energy to/from the medium, leading to scattered photons shifted in frequency. By definition, those components of the scattered light that are shifted to lower frequencies are known as *Stokes* components, and those components that are shifted to higher frequencies are known as *anti-Stokes* components.

Under the normal light conditions, the spectrum of the scattered light has the form that shown in Figure 2.3, in which Raman, Brillouin, Rayleigh, and Rayleigh-wing features are present.

![Figure 2.3](image_url)

**Figure 2.3:**
Spectral components resulting from light scattering in inhomogeneous medium.

One of these light-scattering processes is Raman scattering. Raman scattering results from the interaction of light with the vibrational modes of the molecules constituting the scattering medium. Raman scattering can equivalently be described as the scattering of light from optical phonons.
Brillouin scattering is the scattering of light from sound waves that is, from propagating pressure (and thus density) waves. Brillouin scattering can also be considered to be the scattering of light from acoustic phonons.

Rayleigh scattering (or Rayleigh-center scattering) is the scattering of light from non-propagating density fluctuations. Formally, it can be described as scattering from entropy fluctuations. It is known as quasi-elastic scattering because it induces no frequency shift.

Rayleigh-wing scattering (i.e., scattering in the wing of the Rayleigh line) is scattering from fluctuations in the orientation of anisotropic molecules. Since the molecular reorientation process is very rapid, this component is spectrally very broad.

### 2.2.2 Perturbed Wave Equation

The propagation of light through a medium can be properly described by the following perturbed wave equation derived from Maxwell’s equation [37], [38]:

\[
\nabla \mathbf{E}^2 - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2} \quad (2.2.1)
\]

where \( \mathbf{P} \) is the polarization field, \( \mathbf{E} \) is the wave electric field, \( c \) is the speed of light in vacuum, and \( \mu_0 \) is the magnetic permittivity in the vacuum. In a linear regime, the polarization \( \mathbf{P} \) is proportional to the wave electric field \( \mathbf{E} \) according to:

\[
\mathbf{P} = \varepsilon_0 \chi \cdot \mathbf{E} \quad (2.2.2)
\]

where \( \chi \) is the dielectric susceptibility of the medium and \( \varepsilon_0 \) is the vacuum dielectric permittivity. In an isotropic and homogeneous medium, the tensor \( \chi \) reduces to the scalar quantity \( \chi \), so that Eq. (2.2.1) becomes:

\[
\nabla \mathbf{E}^2 - \frac{n^2}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \quad (2.2.3)
\]

when \( n = \sqrt{\varepsilon/\varepsilon_0} = \sqrt{1 + \chi} \) is the medium refractive index and \( \varepsilon \) is the dielectric constant of the medium. Eq. (2.2.3) is actually similar to the wave equation (2.2.1) for propagation in vacuum, where the only difference is that the speed of light in the medium is \( c/n \) instead of \( c \).

It should be noted that, since variations in the dielectric susceptibility have been neglected, light described by Eq. (2.2.3) propagates not being affected by scattering. Real medium, however are neither homogeneous nor isotropic, so that the spatial and temporal fluctuations of the dielectric susceptibility (\( \Delta \chi \)) need to taken into consideration according to:

\[
\mathbf{P} = \varepsilon_0 \chi \cdot \mathbf{E} + \varepsilon_0 \Delta \chi \cdot \mathbf{E} = \mathbf{P}_0 + \mathbf{P}_d \quad (2.2.4)
\]
where \( \mathbf{P} = \varepsilon_0 \mathbf{X} \cdot \mathbf{E} \) is the linear polarization and \( \mathbf{P}_d = \varepsilon_0 \Delta \mathbf{X} \cdot \mathbf{E} = \Delta \varepsilon \cdot \mathbf{E} \) is the induced polarization. Note that, while \( \mathbf{P}, \mathbf{P}_0, \mathbf{P}_d \) and \( \mathbf{E} \) are vectors, \( \Delta \mathbf{X} \) and \( \Delta \varepsilon \) are tensor quantities that are responsible for scattering processes. Therefore, the perturbed wave equation turns to be:

\[
\nabla \mathbf{E}^2 - \frac{n^2 \partial^2 \mathbf{E}}{c^2 \partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}_d}{\partial t^2} 
\]

(2.2.5)

The right-hand side is the source term responsible for several scattering processes. In order to have a more detailed understanding of each scattering process, it is useful to analyze the element \( \Delta \varepsilon_{ij} \) of the tensor \( \Delta \varepsilon \). There are two conditions to this tensor, one is the scalar term \( \Delta \varepsilon \) and the other is the tensor component \( \Delta \varepsilon_{ij}^{(t)} \), so that:

\[
\Delta \varepsilon_{ij} = \Delta \varepsilon \delta_{ij} + \Delta \varepsilon_{ij}^{(t)} 
\]

(2.2.6)

The scalar contribution \( \Delta \varepsilon \) arises from fluctuations in the thermodynamic quantities, such as pressure, entropy, density or temperature. The scattering resulting from \( \Delta \varepsilon \) is called *scalar light scattering* [38], and is the origin of Rayleigh and Brillouin scattering. While Rayleigh scattering is induced by entropy fluctuations, Brillouin scattering is induced by density variations associated with pressure waves propagating through the medium. On the other hand, scattering coming from the tensorial contribution \( \Delta \varepsilon_{ij}^{(t)} \) is called *tensor light scattering* [38]. In fact the tensor is composed of two statistically independent tensor terms:

\[
\Delta \varepsilon_{ij}^{(t)} = \Delta \varepsilon_{ij}^{(s)} + \Delta \varepsilon_{ij}^{(a)} 
\]

(2.2.7)

where \( \Delta \varepsilon_{ij}^{(s)} \) is the symmetric part of \( \Delta \varepsilon_{ij}^{(t)} \) (i.e. \( \Delta \varepsilon_{ij}^{(s)} = \Delta \varepsilon_{ji}^{(s)} \)) and gives rise to Rayleigh-wing scattering, which is due to the fast reorientation of the asymmetric molecules under the effect of an electric field. \( \Delta \varepsilon_{ij}^{(a)} \) is the anti-symmetric part of \( \Delta \varepsilon_{ij}^{(t)} \) (i.e. \( \Delta \varepsilon_{ij}^{(a)} = -\Delta \varepsilon_{ji}^{(a)} \)) and gives rise to Raman scattering, which is due to molecular vibrations in the medium. In general, the scattering resulting from the tensorial contribution \( \Delta \varepsilon_{ij}^{(t)} \) is called *depolarized scattering* because the degree of polarization of the scattered light is typically smaller than one of the incident light [38].

### 2.2.3 Rayleigh Scattering

Considering that the density \( (\rho) \) and the temperature \( (T) \) are independent thermodynamic variables [38], the scalar changes in the dielectric constant \( (\Delta \varepsilon) \) can be expressed as:

\[
\Delta \varepsilon = \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T \Delta \rho + \left( \frac{\partial \varepsilon}{\partial T} \right)_\rho \Delta T 
\]

(2.2.8)
In spontaneous scattering regime, the contribution of temperature variations can be ignored, since it provides less than 2% of the total variations in the dielectric constant. Furthermore, temperature variations are extremely low in spontaneous regime, since the low light intensity causes a negligible increase in temperature. Thus, scalar light scattering is mainly determined by density changes rather than temperature variations, so that Eq. (2.2.8) can be reduced to:

\[
\Delta \varepsilon = \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T \Delta \rho \quad (2.2.9)
\]

Density variations (\(\Delta \rho\)), on the other hand, can also be separated into two independent thermodynamic contributions: pressure (\(p\)) and entropy (\(s\)):

\[
\Delta \rho = \left( \frac{\partial \rho}{\partial p} \right)_s \Delta p + \left( \frac{\partial \rho}{\partial s} \right)_p \Delta s \quad (2.2.10)
\]

The first term describes adiabatic density fluctuations (i.e. sound waves) that produces Brillouin scattering. The second term describes isobaric density fluctuations (i.e. entropy or temperature fluctuations at constant pressure) that give rise to Rayleigh-center scattering.

In order to describe Rayleigh scattering, the following diffusion equation for the entropy fluctuations needs to be considered [38]:

\[
\rho c_p \frac{\partial \Delta s}{\partial t} - k \nabla^2 \Delta s = 0 \quad (2.2.11)
\]

where \(c_p\) is the specific heat at constant pressure and \(k\) is the thermal conductivity. A solution to this diffusion equation is:

\[
\Delta s = \Delta s_0 \exp (-\delta t) \exp (-\mathbf{q} \cdot \mathbf{r}) \quad (2.2.12)
\]

where \(\mathbf{q}\) is the scattered wave-vector and \(\delta\) is the damping rate of the entropy disturbance, given by:

\[
\delta = \frac{k}{\rho c_p |\mathbf{q}|^2} \quad (2.2.13)
\]

Assuming a monochromatic incident wave and replacing the expression for the entropy, given by Eq. (2.2.12), into Eq. (2.2.10) and into Eq. (2.1.9), the resulting dielectric constant variation can be used in the perturbed wave equation (2.2.5) to obtain the Rayleigh scattering component. In this way it is possible to find out that, as a consequence of Rayleigh scattering, the induced polarization term \(\mathbf{P}_d\) of Eq. (2.2.5) has only a component at a frequency of the incident light, resulting in an elastic scattering process.
2.2.4 Spontaneous Brillouin Scattering

In order to describe spontaneous Brillouin scattering, the equation of motion for a pressure wave ($\Delta p$) should be analyzed. This is a well know equation from the field of acoustics [38] and is given by:

$$\frac{\partial^2 \Delta p}{\partial t^2} - \Gamma \nabla^2 \frac{\partial \Delta p}{\partial t} - v_a^2 \nabla^2 \nabla p = 0 \quad (2.2.14)$$

where $\Gamma$ is the damping parameter and $v_a$ is the acoustic velocity in the medium, which can be expressed in terms of thermodynamic variables as:

$$v_a = \sqrt{\frac{K}{\rho}} = \sqrt{\frac{1}{C_s \rho}} \quad (2.2.15)$$

where $K$ is the bulk modulus, $\rho$ is the density of the medium, and $C_s$ is the adiabatic compressibility [16]. It can be demonstrated that a solution of Eq. (2.2.14) is represented by the following propagating wave:

$$\Delta p = \Delta p_0 \exp[i(-q \cdot r - \Omega t)] + c.c., \quad (2.2.16)$$

where the dispersion relation $\Omega = v_a |q|$ is satisfied.

Considering a monochromatic incident lightwave, and using Eq. (2.2.16) in the perturbed wave equation (2.2.15), it can be demonstrated that the scattered field must obey the following wave equation [38]:

$$\nabla^2 E - \frac{n^2}{c^2} \frac{\partial^2 E}{\partial t^2} = -\frac{\gamma_e C_s}{c^2} \left[ ((\omega - \Omega)^2 E_0 \Delta p^* \exp[i(k - q) \cdot r - i(\omega - \Omega)t] 
+ (\omega + \Omega)^2 E_0 \Delta p \exp[i(k + q) \cdot r - i(\omega + \Omega)t] + c.c. \right] \quad (2.2.17)$$

where $E_0$, $\omega$ and $k$ denote the amplitude, frequency and wave-vector of the incident light, and $\gamma_e$ is the electrostrictive constant defined by:

$$\gamma_e = \left( \rho \frac{\partial \varepsilon}{\partial \rho} \right)_{\rho = \rho_0} \quad (2.2.18)$$

The first right-side term of Eq. (2.2.17) is an oscillating component with wave-vector $k' = k - q$ and frequency $\omega' = \omega - \Omega$, given rise to Brillouin Stokes scattering. The second right-side term corresponds to a component with wave-vector $k' = k + q$ and frequency $\omega' = \omega + \Omega$, leading to Brillouin anti-Stokes scattering. In both cases the frequency and the wave-vector of the incident light are related according to:

$$\omega = |k| \frac{c}{n} \quad (2.2.19)$$

On the other hand, $\Omega$ and $q$ are the frequency and the wave-vector of the acoustic wave, factors that satisfy the following relation:
This process can efficiently couple energy to the Brillouin components only if $\omega'$ and $k'$ satisfy the following dispersion relation:

$$\omega' = |k'| \frac{c}{n}$$  \hspace{1cm} (2.2.21)

Thus to generate Brillouin scattering, conservation of both momentum and energy need to be simultaneously satisfied. Therefore, the frequency and the wavevector of both the incident lightwave and the acoustic wave must have very particular values for any direction. As a matter of fact, the relation that acoustic, incident and scattered waves must satisfy in the case of Stokes and anti-Stokes scattering are illustrated in Figure 2.4 and Figure 2.5, respectively. Figure 2.4(a) and Figure 2.5(a) show the relative orientation of the wavevectors of the incident and scattered fields. Figure 2.4(b) and Figure 2.5(b) show the relation between the wavevectors of the acoustic, incident and scattered waves for both Brillouin components, respectively (i.e. $k' = k - q$ for the stokes component and $k' = k + q$ for the anti-Stokes component), as a consequence of these two interactions, the Stokes component can be considered as scattering of light from an acoustic wave propagating the same direction of the incident light (see Figure 2.4(c)). On the other hand the anti-stokes component can be considered as scattering resulting from a counter-propagating acoustic wave with respect to the direction of the incident light (Figure 2.3(c)).

From the quantum mechanical approach, Brillouin Stokes scattering results from the absorption of an incident photon followed by the emission of both an acoustic phonon and a new photon with a lower energy. On the other hand, in the Brillouin anti-Stokes scattering, an acoustic phonon is simultaneously absorbed with an incident photon, leading then to the emission of a photon with a higher energy level.

Considering that the frequency of the acoustic wave ($\Omega$) is much smaller than the optical frequencies, we can assume $|k'| \approx |k|$, for both Stokes and anti-stokes components. Then the wavevector of the acoustic wave can be written as:

$$|q| = 2|k| \sin\left(\frac{\theta}{2}\right)$$  \hspace{1cm} (2.2.22)

Thus the dispersion relation described by Eq. (2.2.20) shows that the acoustic frequency is:
Figure 2.4:
Illustration of Brillouin Stokes scattering [16].

Figure 2.5:
Illustration of Brillouin anti-Stokes scattering [38].

\[
\Omega = 2|\mathbf{k}| v_a \sin \left( \frac{\theta}{2} \right) = \frac{2n\omega v_a}{c} \sin \left( \frac{\theta}{2} \right)
\]  
(2.2.23)

Note that the acoustic frequency \( \Omega \) is equal to zero for forward scattering (\( \theta = 0 \)) and is maximum for backscattering (\( \theta = 180^\circ \)). Then the maximum frequency \( \Omega_B \), which is called Brillouin frequency shift, is given by:

\[
\Omega_B = \frac{2n\omega v_a}{c}
\]  
(2.2.24)

Even though Eq. (2.2.23) predicts that Brillouin scattering should not take place in forward direction, weak spontaneous Brillouin scattering can occur in forward direction inside an optical fiber. This phenomenon is called guided acoustic-wave
Brillouin scattering [37], and corresponds to a process which is outside the scope of this Thesis.

So far the attenuation of the acoustic wave has been ignored in the analysis. Nonetheless, taking into account this effect, acoustic waves should only propagate over a few optical wavelengths (few μm) in an optical fiber. Thus the acoustic wave intensity can be expressed as:

\[ |\Delta p(z)|^2 = |\Delta p(0)|^2 \exp(-\alpha_a z) \]  \hspace{1cm} (2.2.25)

Where \( \alpha_a \) is the acoustic absorption coefficient, which is defined by:

\[ \alpha_a = \frac{|\mathbf{q}|^2 \Gamma}{\nu_a} = \frac{\Gamma_B}{\nu_a} \]  \hspace{1cm} (2.2.26)

where \( \Gamma_B = |\mathbf{q}|^2 \Gamma \) is the phonon decay rate (also called acoustic damping coefficient), which by definition is inversely proportional to the acoustic damping time \( \tau_p \) (which in its turns corresponds to the average lifetime of the acoustic phonons in the medium). As a consequence of the acoustic wave absorption, it can be found that, in the frequency domain, the Brillouin components are not monochromatic due to the finite acoustic phonon lifetime, as shown in Figure 2.6, and exhibits a Lorentzian spectral profile given by [37].

![Spectrum showing both spontaneous Brillouin scattering and Rayleigh scattering.](image)

**Figure 2.6:**
Spectrum showing both spontaneous Brillouin scattering and Rayleigh scattering.

\[ g_B(\nu) = g_{B0} \frac{(\Delta \nu_B/2)^2}{(\nu - \nu_B)^2 + (\Delta \nu_B/2)^2} \]  \hspace{1cm} (2.2.27)

where \( \Delta \nu_B = \Gamma_B/2\pi \) is the FWHM Brillouin spectrum linewidth and \( g_{B0} = g_B(\nu_B) \) is the maximum gain coefficient at resonance (\( \nu_B = \Omega_B/2\pi \)), which is defined by:

\[ g_{B0} = \frac{8\pi^2 \gamma_e^2}{n_p \lambda_p^2 \rho_0 c \nu_a \Gamma_B} \]  \hspace{1cm} (2.2.28)

where \( \gamma_e \approx 0.902 \) is the electrostatic constant of silica, \( \rho_0 \approx 2210 \text{ kg/m}^2 \) is the density of the silica fibers, \( \lambda_p \) is the wavelength of the incident light, and \( n_p \) is the refractive index at \( \lambda_p \).
It is important to point out that, in the spontaneous regime, both Brillouin Stokes and anti-Stokes components should exhibit the same intensity and frequency shift amplitude, as depicted in the spectrum shown in Figure 2.6. As it will be discussed in section 2.4, this situation is not valid anymore in the case of stimulated Brillouin scattering (SBS), a process in which the Stokes signal results amplified while the anti-Stokes component is depleted.

### 2.2.5 Spontaneous Raman Scattering

While Brillouin scattering arises from propagating density variations in the medium, Raman scattering is generated by the interaction of light with resonant modes of the molecules in the medium. There are practically two kinds of interaction, one with vibrational modes of the molecule (giving rise to vibrational Raman scattering), and another one with rotational modes (generating rotational Raman scattering). However, the interaction with vibrational modes is much stronger and dominates the Raman scattering process. Furthermore, vibrational Raman scattering exhibits a frequency shift one order of magnitude greater than that due to rotational Raman scattering [28].

![Energy level diagrams describing (a) Raman Stokes scattering and (b) Raman anti-Stokes scattering.](image)

#### Figure 2.7:
Energy level diagrams describing (a) Raman Stokes scattering and (b) Raman anti-Stokes scattering.

Raman scattering is often described in terms of quantum energy levels. Thus, a molecule initially in a vibrational state ‘1’ (ground state) is excited by an incident photon of frequency $\omega_p$ to a vibrational state ‘2’ (with higher energy level) by means of a virtual intermediate state, as shown in Figure 2.7(a). Thus the incident photon is virtually absorbed simultaneously to the emission of a photon with frequency $\omega_s$. Considering that, due to energy conservation, $\omega_s = \omega_p - \Omega_R$ (where $\Omega_R$ is the frequency associated with the energy of the vibrational mode), such a process corresponds to Raman Stokes scattering, and is depicted in Figure 2.7(a). On the other hand, if the molecule already has some vibrational energy (in state ‘2’), the incident photon can absorb a quantum of energy from the medium, giving rise to the emission of an upshifted-frequency photon at $\omega_s = \omega_p + \Omega_R$. This process corresponds to Raman anti-Stokes scattering and is shown in Figure 2.7(b).

Due to the higher energy of the vibrational modes, the induced Raman frequency shift ($\Omega_R$) is actually a significant fraction of the optical frequency. The Raman spectrum
typically exhibits several peaks at different frequency shifts depending on the vibrational energy of the involved modes. Moreover, not every vibrational mode leads to strong Raman scattering; then, the Raman intensity is expected to vary from mode to mode [39]. In the quantum mechanical approach, vibrational modes are represented by optical phonons, which actually have much higher energy than acoustic phonons involved in Brillouin scattering. For this reason, the Raman frequency shift in optical fibers is usually three orders of magnitude higher than the Brillouin frequency shift.

Note that for each molecular vibration, two Raman components can be observed: one associated with the absorption of energy from the incident photon (Stokes process) and the other associated with the emission of a photon with energy higher than the one of the incident photon (anti-Stokes process). As a matter of fact, the Placzek model of spontaneous Raman scattering describes such a process as amplitude modulation producing lower and upper sidebands in the scattered spectrum. With this interpretation, the induced dipole moment $P$ of the molecule becomes [40]:

$$P = \beta E_p \cos(\omega_p t) = \left[ \beta_0 + \left( \frac{\partial \beta}{\partial Q} \right) Q_0 \cos(\Omega_R T) E_p \cos(\omega_p t) \right]$$

$$= \beta E_p \cos(\omega_p t) + \left( \frac{\partial \beta}{\partial Q} \right) \frac{Q_0}{2} E_p \cos[(\omega_p + \Omega_R) t]$$

$$+ \left( \frac{\partial \beta}{\partial Q} \right) \frac{Q_0}{2} E_p \cos[(\omega_p - \Omega_R) t]$$

where $\beta$ is the molecular polarizability, $\omega_p$ and $\Omega_R$ are the frequencies of the incident light (pump signal) and the molecular vibration, $E_p$ and $Q_0$ are the amplitude of the pump field and molecular vibration, respectively. While the first right-side term of Eq. (2.2.29) represents Rayleigh scattering, the second and third terms denote Raman anti-Stokes and Stokes scattering, respectively.

In typical conditions, the Raman anti-Stokes process can only occur through thermal excitation of the molecules, since optical phonons need to have a certain level of energy to be transferred to the scattered photons. Therefore the anti-Stokes component is expected to vanish at temperature $T = 0 \ K$. Since spontaneous Raman Stokes scattering can still occur at $T = 0 \ K$, it turns out that both Raman components do not exhibit the same intensity. However, according to the Placzek model, both Raman components should have the same power, even of the only molecular motion come from zero-point fluctuations at $T = 0 \ K$ [40].

The asymmetry between both Raman components can be explained by the Raman amplification of the zero-point fluctuations at the Stokes frequency [40]. In fact, modulation and amplification contributions to the Stokes component are the same at $T = 0 \ K$, leading to the cancellation of the anti-Stokes sideband due to absorption, as shown in Figure 2.8.
Figure 2.8:
Raman amplification of the “Placzek” Stokes sideband, and the simultaneous absorption of the “Placzek” anti-Stokes sideband, both at $T = 0$ K [40].

At different increasing temperatures, thermal excitation of the vibrational modes increases both Stokes and anti-Stokes intensities; however the asymmetry remains. Actually, the transition rate for the Stokes process ($W_S$) due to thermal excitation is proportional to $(1 + N_\Omega)$, while the transition rate for the anti-Stokes process ($W_{AS}$) is proportional to $N_\Omega$:

$$W_S \propto N_0(1 + N_\Omega) \quad \text{Stokes}$$

$$W_{AS} \propto N_0 N_\Omega \quad \text{anti-Stokes}$$

where $N_0$ is the incident photon number, which is proportional to the light intensity (i.e. $N_0 \propto |E_0|^2$). $N_\Omega$ is the Bose-Einstein thermal population factor, which is proportional to $Q_0^2$, where $Q_0$ is the thermal amplitude of the molecular vibration, determining the amplitudes of the second and third right-side terms of Eq. (2.2.29). The Bose-Einstein thermal population factor is given by:

$$N_\Omega = \frac{1}{\exp\left(\frac{hv_R}{k_BT}\right) - 1}$$

where $h$ is the plank constant, $k_B$ is the Boltzmann factor, $v_R = \Omega_R/2\pi$ is the vibrational frequency and $T$ is the absolute temperature (in degrees kelvin).

The ratio of the anti-Stokes to Stokes intensities is $\exp(-hv_R/k_BT)$, evidencing the fact that at high temperatures the anti-Stokes scattered intensity approaches the Stokes intensity. Furthermore, the ratio tends to zero at $T = 0$ K due to the inexistent anti-Stokes component at such a temperature.

An important feature of Raman scattering is related to the frequency dependence of the scattered light. From the Placzek model, it can be found that the electric field of the scattered light is proportional to $v_i^4 = (\omega_i/2\pi)^4$ (with $i = S, AS, R$, for the Stokes, anti-Stokes and Rayleigh components, respectively). Thus for instance, the Raman scattering cross-section for the Stokes component, defined as the ratio of the scattered Stokes power and the incident pump power, is given by:
Where \( n_0 \) and \( n_s \) are the refractive index at the pump and Stokes wavelengths, and the factor \( \left( \frac{\partial \rho}{\partial Q} \right) \) links the spontaneous Raman scattering cross-section with the Raman gain coefficient.

### 2.3 Stimulated Scattering in Optical Fibers

In the previous section our analysis was confined to the linear scattering regime, in which the induced polarization is proportional to the applied electric field. However, when the high-intensity electric field is applied to a medium, the nonlinear material response to the light should be taken into account [38]. The origin of this nonlinear response is related to an-harmonic motion of bound electrons under the influence of an intense electromagnetic field.

Therefore, scattering processes resulting from thermal or quantum-mechanical zero-point effects are said to be **spontaneous** (as discussed in section 2.2). On the other hand, scattering induced by the presence of high-intensity light is said to be **stimulated**; such processes are typically much more efficient than spontaneous light scattering. For instance, stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) processes are clearly enhanced by the use of high-intensity optical fields. Stimulated scattering is also a coherent process due to the required energy and momentum conservation, and hence, requires sufficient temporal and spatial coherence of the light source.

As a result of a high light intensity, the total polarization \( \mathbf{P} \) induced by the electric dipoles is now a nonlinear function of the electric field \( \mathbf{E} \). Then, an additional nonlinear polarization term must be considered, giving rise to a total polarization \( \mathbf{P} \) given by [37], [38]:

\[
\mathbf{P} = \varepsilon_0 (\chi_1 \mathbf{E} + \chi_2 : \mathbf{E} \mathbf{E} + \chi_3 : \mathbf{E} \mathbf{E} \mathbf{E} + \ldots),
\]

where \( \varepsilon_0 \) is the vacuum permittivity and \( \chi_j \) (with \( j = 1, 2, 3, \ldots \)) is \( j \)-th order susceptibility.

Among all terms in Eq. (2.3.1), the linear susceptibility \( \chi_1 \) represents the dominant contribution to \( \mathbf{P} \), and its effects are described through the refractive index \( n \) and the attenuation coefficient \( \alpha \), as discussed in section 2.2. The second order susceptibility \( \chi_2 \) is responsible for some nonlinear effects, such as second-harmonic generation and sum-frequency generation. However under normal conditions, optical fibers do not exhibit second-order nonlinear effects due to the molecular symmetry of silica glasses [15]. Actually, nonlinear effects in optical fibers are mainly dominated and
originated from the third order susceptibility $\chi_3$, leading to the phenomena such as kerr effect and stimulated scattering. Furthermore, effects due to higher-order susceptibilities are also negligible in optical fibers.

Thus taking into account the attenuation coefficient $\alpha$, and the nonlinear induced polarization factor $\mathbf{P}^{\text{NL}} = \chi_3 : \mathbf{EEE}$, the following perturbed nonlinear wave equation is obtained from Maxwell’s equations [36]:

$$\nabla \mathbf{E}^2 - \frac{n^2}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} - \frac{\alpha n}{c} \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \frac{\partial^2 \mathbf{P}^{\text{NL}}}{\partial t^2}$$  \hspace{1cm} (2.3.2)

Where $n$ is the refractive index of the medium, $c$ is the speed of light in vacuum and $\mu_0$ is the magnetic permittivity in the vacuum.

Nonlinear light scattering, such as stimulated Brillouin, resulting from the nonlinear polarization term in Eq. (2.3.2) will be analyzed in the following section.

### 2.4 Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) can be classically described as a nonlinear interaction between a pump wave at frequency $\omega_p$ and a Stokes wave at frequency $\omega_s$ (propagating in opposite directions) through an acoustic wave. When the frequency of the beating field, resulting from the interference of these two counter-propagating optical waves, coincides with the Brillouin frequency shift of the material (i.e. $\Omega_B = \omega_p - \omega_s$) an acoustic wave is generated through electrostriction. The acoustic wave, in its turn, modulates the refractive index of the medium, generating a pump-induced index grating that scatters the pump wave through Bragg diffraction [37]. Due to the Doppler shift associated with the induced grating moving at the acoustic velocity $v_a$, the scattered light is actually downshifted in frequency by an amount determined by the Brillouin frequency shift of the material. The scattered light adds constructively to the Stokes wave, leading to the amplification of the Stokes component, which in its turn reinforces the acoustic wave. Consequently, both acoustic and Stokes waves reinforce each other, while the anti-Stokes signal vanishes for high amplification regime (due to energy transfer to the pump signal).

Stimulated Brillouin scattering can be originated by two mechanisms; the so-called Brillouin amplifier and the Brillouin generator.

In Brillouin amplifier the Stokes wave is externally provided by injecting into the medium an optical wave, the so-called probe wave, in a counter propagating direction with respect to the propagation of the pump signal. If the frequency of the probe wave is adjusted to coincide with the Brillouin Stokes frequency, the probe signal experiences amplification while it propagates along the medium.

In Brillouin generator no Stokes signal is injected externally into the medium; however, SBS process is initialized by Stokes photons resulting from spontaneous Brillouin scattering. The generation of SBS actually takes place only when using a
high-intensity pump wave, condition in which spontaneous Brillouin scattering becomes strong enough to act as seed of the SBS process.

2.4.1 Electrostriction

Electrostriction is basically described as the tendency of materials to become compressed in the presence of an electric field. The origin of the electrostrictive force can be understood as a consequence of the maximization of the stored energy \[38\]. Considering the force acting on the molecules (as result of an applied electric field) and the energy stored in the polarization of the molecules, we can obtain the electrostrictive pressure \(p_{st}\). This parameter corresponds to the contribution to the pressure of the material resulting from the presence of an electric field, and is given by:

\[
p_{st} = - \frac{1}{2} \varepsilon_0 \rho \left( \frac{\partial \varepsilon}{\partial \rho} \right) \langle \mathbf{E}, \mathbf{E} \rangle = - \frac{1}{2} \varepsilon_0 \gamma_e \langle \mathbf{E}, \mathbf{E} \rangle \tag{2.4.1}
\]

where \(\rho\) is the density of the material and \(\gamma_e = \rho \frac{\epsilon}{\partial \rho} \) is the electrostrictive constant. Due to the negative sign in Eq. (2.1.1) the total pressure of the material is reduced in regions of high field strength. Taking into account Eq. (2.4.1), it is possible to describe the changes in the material density (\(\Delta \rho\)) as:

\[
\Delta \rho = - \left( \frac{\partial \rho}{\partial \rho} \right) \Delta \rho = - \rho \left( \frac{1}{\rho} \frac{\partial \rho}{\partial \rho} \right) p_{st} = - \rho C p_{st} \tag{2.4.2}
\]

where \(C = \rho^{-1} \frac{\partial \rho}{\partial \rho}\) is the compressibility of the material.

If we represent the changes in the susceptibility in presence of an optical field as \(\Delta \chi = \Delta \varepsilon\), where \(\Delta \varepsilon\) is calculated as \(\Delta \varepsilon = \left( \frac{\partial \varepsilon}{\partial \rho} \right) \Delta \rho\), and we use Eq. (2.4.2), the nonlinear polarization of Eq. (2.3.2) is found to be:

\[
\mathbf{P}^{NL} = \varepsilon_0 C \gamma_e^2 |\mathbf{E}|^2 \mathbf{E} \tag{2.4.3}
\]

In comparison to other types of optical nonlinearities, usually the value \(\chi^3\) resulting from electrostriction is not large; however, it can provide a significant contribution to the total nonlinearities in some materials. For instance, it has been demonstrated that electrostriction provides approximately 20% of the contribution to the third-order susceptibility in optical fibers \[38\].

Considering the nonlinear polarization resulting from the interaction of two optical waves (a pump \(\mathbf{E}_p\), and a Stokes wave \(\mathbf{E}_s\), so that \(\mathbf{E} = \mathbf{E}_p + \mathbf{E}_s\)) and an acoustic wave (characterized by a propagating density variation \(\Delta \rho\)), the following system of perturbed equations can be obtained to fully describe the SBS process:

\[
\nabla^2 \mathbf{E}_p - \frac{n^2}{c} \frac{\partial^2 \mathbf{E}_p}{\partial t^2} - \alpha_p n \frac{\partial \mathbf{E}}{c} \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \frac{\partial^2 \mathbf{P}^{NL}_p}{\partial t^2} \tag{2.4.4}
\]
\[ \nabla^2 E_S - \frac{n^2}{c^2} \frac{\partial^2 E_S}{\partial t^2} - \frac{\alpha_n}{c} \frac{\partial E}{\partial t} = \mu_0 \frac{\partial^2 P_{NL}^S}{\partial t^2} \quad (2.4.5) \]

\[ \frac{\partial^2 \Delta p}{\partial t^2} - \Gamma \nabla^2 \frac{\partial \Delta p}{\partial t} - v_d^2 \nabla^2 \Delta p = \nabla \cdot \mathbf{f} \quad (2.4.6) \]

where \( \alpha_p \) and \( \alpha_s \) are the attenuation coefficients for the pump and the Stokes wave, respectively; and \( \mathbf{f} \) is the electrostrictive force given by \( \mathbf{f} = \nabla P_{NL} \). Eqs. (2.4.4) - (2.4.6) are actually coupled through the electrostrictive force \( \mathbf{f} \) using the material constitutive relations given by:

\[ P_{ps}^{NL} = \Delta \varepsilon E_{p,s}(\mathbf{r}, t) = \frac{\gamma_e}{\rho_0} \Delta \rho (\mathbf{r}, t) E_{p,s}(\mathbf{r}, t) \quad (2.4.7) \]

\[ \nabla \cdot \mathbf{f}(\mathbf{r}, t) = \frac{1}{2} \gamma_e \nabla^2 (|E_p(\mathbf{r}, t) + E_s(\mathbf{r}, t)|^2) \quad (2.4.8) \]

**Figure 2.9:**

Generation of an acoustic wave by means of electrostriction.

It should be noted that, in unperturbed situations (i.e. when \( \mathbf{f} = 0 \)), the three waves described by Eqs. (2.4.4) - (2.4.6) propagate independently in the medium. However, in presence of electrostriction (\( \mathbf{f} \neq 0 \)), the amplitudes of the interacting waves are modified according to Eqs. (2.4.7) - (2.4.8). Considering that molecular mass displacement is a rather slow process, the response time of the material to the applied optical field is much higher than the period of the optical waves. This explains the time average over several optical periods of Eq. (2.4.8). Even though the medium cannot respond to the optical frequency, it can respond to the beat frequency between both optical fields (i.e. to the envelope of the interference pattern), as depicted in Figure 2.9. In this figure we can observe how an acoustic wave is generated by
electrostriction (represented by Eq. (2.4.8)) as result of the interference (beating) pattern between pump and Stokes signals in stimulated Brillouin scattering process.

2.4.2 Coupled-wave Equations for SBS

In order to simplify the system of equations (2.4.4) - (2.4.6), plane waves propagating in direction ±z can be assumed, so that the transverse diffraction can be neglected. If the states of polarization (SOPs) of both pump and Stokes signals are represented as \( \mathbf{e}_p \) and \( \mathbf{e}_s \), and the slowly-varying envelope approximation is used, the fields for both optical waves and acoustic wave can be expressed as:

\[
E_p(r, t) = e_p E_p(z, t) \tag{2.4.9}
\]
\[
E_s(r, t) = e_s E_s(z, t) \exp[i(k_s z - \omega_s t)] + c.c., \tag{2.4.10}
\]
\[
\Delta \rho(r, t) = A(z, t) \exp[i(qz - \Omega t)] + c.c., \tag{2.4.11}
\]

where \( E_p(z, t), E_s(z, t) \) and \( A(z, t) \) are the slowly-varying envelopes of the pump, Stokes and acoustic waves, respectively. Then, using Eqs. (2.4.9) - (2.4.11) into Eqs. (2.4.7) - (2.4.8), and maintaining only the resonant terms for each wave, it is possible to obtain:

\[
P_p^{NL}(r, t) = e_p \frac{\varepsilon_0 Y_e}{\rho_0} A(z, t) E_s(z, t) \exp[i(k_p z - \omega_p t)] + c.c., \tag{2.4.12}
\]
\[
P_s^{NL}(r, t) = e_s \frac{\varepsilon_0 Y_e}{\rho_0} A^*(z, t) E_p(z, t) \exp[i(k_s z - \omega_s t)] + c.c., \tag{2.4.13}
\]
\[
\nabla \cdot \mathbf{f}(r, t) = \varepsilon_0 Y_e q^2 \eta_P E_{p(z, t)} E_s^*(z, t) \exp[i(qz - \Omega t)] + c.c., \tag{2.4.14}
\]

where \( \eta_P = |e_p \cdot e_s| \) is the polarization mixing efficiency, which is equal to 1 for parallel polarizations and equal to 0 for orthogonal polarizations. Assuming identical states of polarization (i.e. \( \eta_P = 1 \)) and substituting Eqs. (2.4.9)-(2.4.14) into Eqs. (2.4.4) - (2.4.6), the following three coupled-wave equations are found:

\[
\left[ \frac{\partial}{\partial z} + \frac{n}{c} \frac{\partial}{\partial t} + \alpha_p \right] E_p(z, t) = \frac{i \omega_p Y_e}{2 n c \rho_0} A(z, t) E_s(z, t) \tag{2.4.15}
\]
\[
\left[ - \frac{\partial}{\partial z} + \frac{n}{c} \frac{\partial}{\partial t} + \alpha_s \right] E_s(z, t) = \frac{i \omega_s Y_e}{2 n c \rho_0} A^*(z, t) E_p(z, t) \tag{2.4.16}
\]
\[
\left[ -2 i q u_a^2 \frac{\partial}{\partial z} - 2 i \Omega \frac{\partial}{\partial t} + (\Omega_b^2 - \Omega^2 - i \Omega_b \Gamma_b) \right] A(z, t) = \varepsilon_0 Y_e q^2 E_p(z, t) Z_s(z, t) \tag{2.4.17}
\]

The system of coupled-wave equations (2.4.15) - (2.4.17) fully describes stimulated Brillouin scattering in optical fibers, in time and space, on the assumption of plane-wave interaction. Unfortunately, this system of equations does not have an analytical
solution; therefore, in order to find a proper solution, it is necessary to use numerical methods.

2.4.3 Steady-state Solution

Whenever the interaction of the three waves takes place during a period of time longer than the acoustic-wave damping time (~10 ns in silica fibers), the steady-state approach can be used. In such a situation, all time derivatives in Eqs. (2.4.15) - (2.4.17) can be neglected. Moreover, considering that the acoustic wave vanishes after propagating over few optical wavelengths (distance over which any change of the optical field is negligible), the spatial derivative of Eq. (2.4.17) can also be dropped. As a consequence, Eq. (2.4.17) can be substantially simplified, so that the amplitude of the acoustic wave can be analytically found as:

\[ A(z) = \varepsilon_0 q^2 \frac{E_p(z)E_s^*(z)}{\Omega_B^2 - \Omega^2 - i\Omega_B} \]  \hspace{1cm} (2.4.18)

Assuming \( \omega = \omega_p \approx \omega_s \) (and hence \( \alpha = \alpha_p \approx \alpha_s \)), and substituting Eq. (2.4.18) into Eqs. (2.4.15) - (2.4.16), the two following coupled-wave equations relating pump and Stokes fields can be found:

\[ \frac{d}{dz} E_p(z) = \frac{i\varepsilon_0 q^2}{2n_0 c} \left| E_s(z) \right|^2 E_p(z) \left( \frac{1}{\Omega_B^2 - \Omega^2 + i\Omega_B} \right) - \alpha E_p(z) \]  \hspace{1cm} (2.4.19)

\[ \frac{d}{dz} E_s(z) = \frac{-i\varepsilon_0 q^2}{2n_0 c} \left| E_p(z) \right|^2 E_s(z) \left( \frac{1}{\Omega_B^2 - \Omega^2 + i\Omega_B} \right) - \alpha E_s(z) \]  \hspace{1cm} (2.4.20)

The real part of the right-side terms of both equations represents the energy transfer, while the imaginary part denotes the phase propagation induced by stimulated Brillouin scattering. In order to obtain the spatial behavior of the optical intensities, the relation \( I(z) = 2n_0 c |E(z)|^2 \) can be used for both pump and Stokes fields. Thus, the following steady-state propagation equations are found:

\[ \frac{d}{dz} I_p(z) = -g_B(v)I_p(z)I_s(z) - \alpha I_p(z) \]  \hspace{1cm} (2.4.21)

\[ \frac{d}{dz} I_s(z) = -g_B(v)I_p(z)I_s(z) - \alpha I_s(z) \]  \hspace{1cm} (2.4.22)

where \( g_B(v) \) is the Brillouin gain defined by Eq. (2.2.27).

In order to analytically solve this system of equations, pump depletion has to be neglected. Leading to a pump wave that decay exponentially along the fiber as \( I_p(z) = I_p(0)\exp(-\alpha z) \). Using this expression in Eq. (2.4.22), the following analytical solution for the Stokes wave can be found:

\[ I_s(z) = I_s(L)\exp \left[ g_B(v)I_p(0) \exp(-\alpha L) - \alpha (L - z) \right] \]  \hspace{1cm} (2.4.23)
Where $I_s(L)$ is the intensity of the Stokes wave launches at $z = L$, $I_p(0)$ is the input pump intensity (at $z = 0$), and $L_{\text{eff}}$ is the effective interaction length, which in this case is given by:

$$L_{\text{eff}} = \frac{1}{\alpha} \left[ 1 - \exp \left( -\alpha (L - z) \right) \right] \quad (2.4.24)$$

As a matter of fact, the effective length is a parameter that takes into account the whole interaction length in an optical fiber considering its total attenuation; therefore, it is usually evaluated at $z = 0$ (in the case of backscattering), giving rise to the well-known expression [37]:

$$L_{\text{eff}} = \frac{1}{\alpha} \left[ 1 - \exp \left( -\alpha L \right) \right] \quad (2.4.25)$$

Eq. (2.4.23) clearly points out that the Stokes intensity grows exponentially with distance while it propagates in backward ($-z$) direction.

It is worth mentioning that even though the mathematical description of SBS process has been presented for the Brillouin Stokes component, similar mathematical representation can be carried out to describe stimulated Brillouin anti-Stokes process. The only difference is that for the anti-Stokes process the sign of the Brillouin gain results negative and the involved optical frequencies are swapped ($v_{\text{AS}} > v_p$) giving rise to the following coupled-wave equations:

$$\frac{d}{dz} I_p(z) = -g_B(v) I_p(z) I_{\text{AS}}(z) - \alpha I_p(z) \quad (2.4.26)$$

$$\frac{d}{dz} I_{\text{AS}}(z) = +g_B(v) I_p(z) I_{\text{AS}}(z) - \alpha I_{\text{AS}}(z) \quad (2.4.27)$$

Consequently, the anti-Stokes component undergoes attenuation (instead of gain as the Stokes component) while it propagates along the fiber.

### 2.4.4 SBS Threshold

As previously mentioned, the intensity of the Brillouin Stokes wave grows exponentially in the backward direction according to Eq. (2.4.23). Such an equation actually shows how a Stokes signal launched into the fiber at $z = L$ in backward direction is amplified by stimulated Brillouin scattering. However, if no Stokes signal is injected into the fiber, SBS might occur from noise generated from spontaneous Brillouin scattering when a high pump power is used. The pump power at which the Stokes component at $z = 0$ is equal to the output pump power at $z = L$ is defined as the Brillouin threshold. In fact, the SBS threshold corresponds to a critical pump power ($P_{\text{th}}^{\text{SBS}}$), which can be expressed as [37].
where $A_{\text{eff}}$ is the effective core area, $g_B$ is the Brillouin gain coefficient (Eq. (2.2.28)), and $L_{\text{eff}}$ is the effective length for a continuous pump wave (Eq. (2.4.25)).

However, due to the counter-propagating nature of SBS, when a pulsed pump signal is used, the maximum interaction length is given by the pulse width according to [31]:

$$L_{\text{eff}} = \frac{v_g W_0}{2}$$

(2.4.29)

where $v_g$ is the pulse duration. Therefore, the SBS threshold power is expected to drastically change with the pump pulse duration.
Chapter 3

Advanced Interrogation Techniques for In-fiber Grating Optical Sensors

3.1 Principles of Interrogation Techniques

FBG interrogators are the measurand reading units that extract measurand information from the light signal coming from sensor heads. The measurand is typically encoded spectrally, and hence the interrogators are usually meant to measure the Bragg wavelength (FBG reflected light in the narrow wavelength range centered at the so-called Bragg wavelength) shifts by employing unique interrogation techniques that efficiently converts the results to measurand data [7]. Thus FBG interrogation means to convert wavelength-shift into a variation of an electrical signal with adequate characteristics to obtain the information about the measurand, therefore the primary work for FBG sensor lies in the wavelength interrogation of the Bragg reflection.

Research on FBG high-resolution interrogation schemes has been a very active topic in recent years. Various FBG demodulation techniques have been conceived over the last years, most of which involved some form of optical filtering. The Bragg wavelength serves as an absolute parameter which can be related to the measurand at unique sensor position and is relatively insensitive to source power fluctuations as well as spurious losses along the sensing fiber. This feature allows for an uncomplicated determination of the stress, pressure or temperature exerted on the FBG by means of a simple measurement of the wavelength-shift reflected by the sensing grating element. In the laboratory, this wavelength-shift can be consistently detected using conventional monochromators or optical spectrum analyzers (OSA) which are indispensable in monitoring FBG reflection or transmission spectra, although their measurement rates are somewhat limited and it is not always appropriate for real sensing systems to use such instruments for the majority of practical applications because of their bulk optical-nature, size, slow scanning speed, high cost, ruggedness, weight penalty, the frequent need for recalibration and lack of robustness [41].

Precise detection of the FBG wavelength shift induced by the measurand has been a challenging problem since the early stage of FBG sensing work and is essential for achieving good sensing performance. The ideal interrogation schemes provide high-resolution with large measurement range (typically a wavelength-shift detection
resolution ranging from sub-picometers to few picometers), cost effectiveness compared with conventional electrical or optical sensors and compatibility with several multiplexing topologies which can make the whole sensing system cost effective [28]. Conventional spectrometers have a typical resolution of tens of picometers consequently they are typically used for characterizing the optical properties of FBGs during fabrication procedures rather than for precise wavelength-shift detection. A number of interrogation schemes have been implemented in the past for high-resolution wavelength-shift detection that allows measurements of quasi-static and dynamic measurands.

In principle, the action of a particular measurand on a FBG can affect one or more of the characteristics of the device spectral signature, i.e., its resonance wavelength, the spectral width or the reflectivity. However, in most of the cases reported up to now the focus has been on the resonance wavelength direct modulation and, therefore, the subject known as FBG interrogation method addresses the problem of transforming this wavelength modulation into an optical intensity modulation [42]. Usually, the wavelength measurement is not very straightforward; thus, the general principle is to convert the wavelength-shift to some easily measured parameter, such as amplitude, phase, or frequency and later into a corresponding electrical signal compatible with the common standards of instrumentation [7]. Desirably, this transformation is accurate in the determination of the absolute Bragg wavelength shifts, a perspective that in practice needs to be balanced by the factors complexity and cost in a particular FBG interrogation configuration.

Table 3.1 groups and classifies the FBG interrogation techniques that have been proposed along the years. The underlying physical principles are diverse, which is also reflected in the performances achievable with each particular configuration. Independently of the specificities of each FBG interrogation approach, some general goals can be indicated. First of all, an appropriated interrogation technique must provide a reproducible transduction of the Bragg wavelength. Additional merit factors will be high sensitivity, large measurement range, immunity to optical power fluctuations, low environmental susceptibility, amenability to sensor multiplexing, simplicity and low cost. Certainly, some of these characteristics do not coexist and therefore, for any particular demodulation solution a compromise is required [42].

This chapter addresses the features and functionalities of several interrogation techniques of fiber optic sensors based on FBGs. The first part reviews state-of-the-art interrogation concepts developed so far, emphasizing their core characteristics, performance and requirements while in the second part we propose a new and novel dynamic FBG demodulation technique exploiting advanced optical cyclic coding scheme to measure FBG back-reflected power induced by dynamic strain variations along the sensing fiber at particular location. The configuration of the proposed sensor is greatly simplified by employing TDM method and using direct detection technique. This novel interrogation scheme thus enables a compact, cost-effective and accurate
FBG sensing method that can be constructed to provide high resolution dynamic measurements without sacrificing demodulation speed.

Table 3.1: Interrogation techniques of FBG based sensors.

<table>
<thead>
<tr>
<th>Group</th>
<th>Principle</th>
<th>Configuration</th>
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</thead>
<tbody>
<tr>
<td><strong>Bulk Optics</strong></td>
<td>Diffraction</td>
<td>Monochomator</td>
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<td></td>
<td></td>
<td>OSA</td>
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<td></td>
<td>Diffraction Grating + CCD</td>
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<td></td>
<td></td>
<td>Volume Hologram + CCD</td>
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<tr>
<td><strong>Passive Edge Filtering</strong></td>
<td>Bulk Filter</td>
<td>Tranmissive</td>
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<tr>
<td></td>
<td>Integrated Optic Filter</td>
<td>Arrayed Waveguide Grating</td>
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<td></td>
<td>Optical Fiber Filters</td>
<td>Biconical Filter</td>
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<tr>
<td></td>
<td>Source/Detectors</td>
<td>Long-Period Grating</td>
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<td></td>
<td></td>
<td>Fused Coupler</td>
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<td></td>
<td></td>
<td>Chirped Bragg Grating</td>
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<td></td>
<td></td>
<td>Sagnac Loop</td>
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<td></td>
<td></td>
<td>Source Spectrum</td>
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<td></td>
<td></td>
<td>Detector Spectral Responsivity</td>
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<td><strong>Active Bandpass Filtering</strong></td>
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<td>Optical Fiber Filters</td>
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<td></td>
<td>Optical Sources</td>
<td>Hybrid Optical MEMS</td>
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<td></td>
<td>Optical Fiber Filters</td>
<td>Receiving Optical Bragg Grating</td>
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<tr>
<td></td>
<td>Optical Sources</td>
<td>WDM Coupler</td>
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<td></td>
<td>Carrier Generation</td>
<td>Dynamic Long-Period Grating</td>
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<td></td>
<td></td>
<td>Singlemode Laser Diode</td>
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<tr>
<td></td>
<td></td>
<td>Multimode Laser Diode</td>
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<tr>
<td></td>
<td></td>
<td>Receiving Bragg Grating</td>
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<tr>
<td></td>
<td></td>
<td>Multimode Laser Diode</td>
</tr>
<tr>
<td><strong>Interferometric</strong></td>
<td>Passive</td>
<td>Chirped Grating + Sagnac loop</td>
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<td></td>
<td>Homodyne</td>
<td>Mach-Zehnder</td>
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<td></td>
<td>Carrier Generation</td>
<td>Mach-Zehnder</td>
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<td>Fourier Domain</td>
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<td>Optical Coherence Function</td>
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<td><strong>Laser Sensing</strong></td>
<td>FBG Laser Cavity</td>
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<td><strong>Miscellaneous</strong></td>
<td>Angular Dispersion</td>
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<td>OTDR</td>
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<td>Wavelet Processing</td>
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<td>Receiving Blazed FBG + CCD</td>
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</table>
3.2 FBG Passive Interrogation Schemes

Passive detection interrogator schemes refer to those that do not use any electrical, mechanical, or optical active devices. Interrogators using linearly wavelength-dependent devices, performing measurand monitoring by detecting optical power, using identical chirped grating pairs and matched fiber grating filters are discussed in this section.

3.2.1 Linearly Wavelength-dependent Optical Filters

The simplest way of measuring the wavelength change of light reflected from an FBG is to use a linear wavelength-dependent optical filter. Indeed, this method was one of the first proposed for the practical wavelength change interrogation system of FBG sensors [7], [43].

Figure 3.1(a) shows the concept of the wavelength demodulator. The light transmittance of the filter is linearly dependent on the wavelength-shift. According to the linear response range, this type of filter is sometimes called an edge filter (which has a narrow linear range with a sharp slope, as a sharp edge of a bandpass filter) or a broadband filter (which has a wide range with a less sharp slope, as a boundary of a broadband filter). There is a trade-off between the measurable range and the sensitivity [7].

![Figure 3.1](image)

**Figure 3.1:**
(a) Transmittance of the linearity wavelength-dependent optical filter interrogator. The dashed peak shows the spectrum of light reflected by a FBG. (b) FBG sensor interrogation system.
This wavelength-change interrogator is based on intensity measurement; that is, information relative to wavelength change is obtained by the intensity monitoring of the light at the detector. For the intensity-based demodulators, the use of intensity referencing is necessary because the light intensity might be changed due to not only the reflection wavelength (Bragg wavelength) change of the FBG but also due to the power fluctuation of the light source, the disturbance in the light-guiding path, or the dependency of light source intensity on the wavelength. In a sense, although the intensity-based measurement has the advantage of being a simple structure, it does not use a key advantage of an FBG sensor that is the information of the measurand is contained in the reflection light wavelength, and not in its intensity.

Figure 3.1(b) shows the schematic diagram of the FBG sensor system adopting the wavelength-dependent optical filter demodulator, where the light reflected from the FBG splits into two directions; one of them passes through the wavelength-dependent filter, while the other is used as a reference. The intensity ratio at the two detectors is given by

\[ \frac{I_S}{I_R} = A(\lambda_B - \lambda_0 + B) \]  

(3.2.1)

where \( A \) is a constant determined by the slope of the filter and \( B \) is a constant arising from the nonzero reflection bandwidth of the FBG. Eq. 3.2.1 is linearly dependent on the Bragg wavelength change, but independent of light intensity variation due to the source fluctuation, etc. That is because the intensity variations are cancelled out by comparing the signal \( I_S \) with the reference \( I_R \).

### 3.2.2 Linearly Wavelength-dependent Couplers

The linearly wavelength-dependent optical filter interrogator deteriorates the SNR because the filter decreases optical power. An alternative interrogator has also been proposed which uses a wavelength division multiplexer coupler (usually called WDM coupler), which has a linear and opposite change in the coupling ratios between the input and two output ports \([7]\).

A wavelength demodulation scheme using a WDM coupler is shown in Figure 3.2. A WDM coupler shows a monotonic change in the coupling ratio between the two output fiber ports. Taking the ratio of the difference and sum of the two outputs of the WDM coupler gives drift-compensated output for wavelength shift detection. The spectral slope steepness of the WDM coupler determines the sensitivity and minimum detectable wavelength shift.
Figure 3.2:
Sensor system adopting the linearly wavelength-dependent coupler interrogator. $P$, $P_1$ and $P_2$ indicate optical power at each port.

3.2.3 Power Detection

In some applications of fiber grating sensors, a simple detection of reflected or transmitted power is sufficient for the measurand interrogation. Instead of using a linearly wavelength-dependent optical filter, we can use a light source that has intensity linearly dependent on wavelength. It is possible to use for example the amplified spontaneous emission (ASE) profile of an erbium-doped fiber amplifier (EDFA) [7], [44]. As shown in Figure 3.3, the Bragg wavelength of a sensor grating is located in the linear region of the ASE spectrum. The change in the Bragg wavelength results in a power change at the photodiode. Primitive dynamic tests up to 1 kHz for a strain range up to 2700 με with 50 με resolution were performed.

Figure 3.3:
Sensor system using the linear region of ASE of EDFA. The dashed lines indicate the ASE spectrum and the solid peaks show the reflected spectra by an FBG. The piezoelectric (PZT) is used to apply dynamic strain.

Several groups have investigated TDM network of FBGs based on power detection schemes. Recently a serial TDM network based on identical ultra weak FBGs is proposed for static measurements and demonstrated with experimental results [19]. The tiny crosstalk between the ultra weak FBGs allows over 1000 FBGs multiplexed in series; the TDM structure enables the simultaneous measurement of all the sensors.
and the identity of the FBGs simplifies the sensing link and makes the mass production of the sensing array affordable. In addition this method is not limited in its sensing span by the source coherence and further eliminates the polarization fading problem.

Figure 3.4:
FBG Interrogation system of a serial TDM sensor array.

Figure 3.4 illustrates TDM-based interrogation system detecting the reflected power from serially connected FBGs. CW light from a tunable laser is modulated into train of pulses by a modulator. Two EDFAs are used to amplify the optical power. Pulses are launched into a serial FBG array and reflected pulses intensities are converted to electrical signal by photo-detector.

3.2.4 Matched Fiber Grating Filter

The basic concept of the interrogation scheme using matched fiber gratings is shown in Figure 3.5 [7], [45]-[46]. Light from a broadband source is fed to the sensor grating via the fiber coupler. This propagates back to the receiving grating, which is mounted on a piezoelectric stretcher. The receiving grating is fabricated so that its central reflecting wavelength is identical to the sensor grating. The central reflecting wavelength of the sensor grating will vary in direct proportion to the measurand and generally will not match that of the receiving grating. If the central wavelength of the receiving grating is swept over a defined wavelength range by driving the piezoelectric transducer (PZT), then at one point in the sweep the reflecting wavelengths of both the sensor grating and the receiving grating will exactly match. In this condition a strong signal will be back-reflected from the receiving grating and detected by the photodiode. Providing that the relationship between the driving voltage and the wavelength of the receiving grating is known, the instantaneous wavelength value of the sensor grating can be determined. A closed-loop servo is used to maintain the matched condition and thus track the wavelength shift to the sensor grating. The resolution is dictated by line-width of the gratings.
Another approach has been proposed in which two identical chirped-fiber gratings are employed, but the receiving grating works in transmission mode [7], [47]. Two identical chirped gratings with a quasi square reflection spectrum are used as a sensor head and an interrogating filter, as shown in Figure 3.6. If the profiles of these two gratings are identical then the receiving grating will block the reflection from the sensing grating and the light received at the photodiode will be minimized. When the sensing grating is stretched or heated, its spectral profile is linearly shifted. This leads to a fraction of the light reflected from the sensing grating falling outside the reflection band of the receiving grating and being transmitted to the photodiode. The quasi square reflection profiles of the two chirped gratings permit a linear relationship between wavelength change and the light intensity transmitted by the receiving grating. This enables direct measurement of wavelength-encoded reflection, eliminating the need for a piezoelectric tracking system. This system can be extended to a multiplexing scheme where multiple sensors are arranged in a serial or parallel or a combination of both [48].
3.3 FBG Active Interrogation Schemes

Active detection schemes interrogators usually involve tracking, scanning or modulating mechanism to monitor Bragg wavelength shifts from single or multiple FBGs. Although active detection schemes require more complex sensor systems compared to passive detection schemes, the active schemes show better resolution [7].

3.3.1 Matched FBG Pair Interrogator

The interrogation technique by the matched FBG pairs is based on matching a receiving grating to a corresponding sensor grating [7], [49]. The basic concept of the sensor-receiver grating pair is that the Bragg wavelength of the sensor grating is monitored by filtering the light reflected from the sensor grating with a receiver grating that is nearly identical to the sensor grating at rest. When a strain or a temperature variation is applied to the sensor grating, the matched condition of the Bragg wavelength between the grating pair is not satisfied. But the condition can be easily recovered by tuning the receiver grating with a suitable method. It is possible to utilize a piezoelectric stretcher, to tune the receiver grating [49]. This technique can be readily applied to the simultaneous interrogation of a multiplexed arrayed sensor system with a large number of gratings if all the matched gratings can be provided at the receiver end.

![Schematic diagram of a matched FBG pair interrogator in parallel configuration.](image)

**Figure 3.7(a):**
Schematic diagram of a matched FBG pair interrogator in parallel configuration. The FBGs $G_{iR}$ and $G_{iS}$ ($i = 1, 2, 3, 4$) are matched pairs.

The matched FBGs can be positioned both in parallel and in series at the receiver end. In the parallel configuration as shown in Figure 3.7(a), the light filtered by each matched grating is monitored with a separate detector. This has the advantage of simple detection (all matched gratings can be simultaneously tuned with a piezoelectric stretcher) with low cross-talk, but the number of detectors should be
increased with the number of sensors in an array. The minimum resolution of the measured quasi-static strain was 4.16 με [49].

In series configurations as shown in Figure 3.7(b), each matched grating is tracked by a different piezoelectric stretcher with a different dithering frequency [7]. The signal is detected by feedback electronics, and hence the lock-in signals can be detected separately with a single receiver. Therefore, the single receiver can afford to interrogate the multiplexed sensors simultaneously. Both the transmissive and reflective configurations can be applied to this technique.

![Figure 3.7(b): Schematic diagram of a matched FBG pair interrogator in series configuration.](image)

Many configurations have been reported concerning interrogation systems for the multiplexed arrayed sensors, including broadband sources and appropriate filtering devices for detecting the spectral change in reflected light from the sensor gratings. However, most of the broadband sources are not high-power devices, and the receivable optical powers are reduced considerably after the broadband lights are reflected from the narrow-band sensor gratings. The low power leads to low SNRs, which might reduce the reliability of the interrogation and increase the interrogation time. Furthermore the Bragg wavelength shift is subject to both strain and temperature, and the discrimination of the two physical values is not possible by one wavelength shift measurement from a single grating sensor. In quasi-static strain measurement, wavelength shift by temperature variation can seriously affect the accuracy of strain measurement.

### 3.4 Simplex Codes

Simplex codes correspond to a coding technique in which pulse sequences are derived from the Hadamard matrix [35]-[51], which is a bipolar matrix with particular orthogonal properties. Such a matrix has been widely used in spectroscopy [51]-[52], providing an efficient method to improve the SNR of the measurements. However due to its bipolar elements (i.e. -1’s and 1’s), it is impossible to use Hadamard matrix
directly in OTDR applications based on direct detection. Thus, in order to obtain
suitable pulse sequences, Simplex codes require Hadamard transform [51], which
allows for the calculation of an S-matrix (Simplex-matrix) containing unipolar
elements and orthogonal rows. As a matter of fact, each row of the S-matrix defines a
Simplex codeword [35].

Note that Simplex coding techniques can be very effective to improve the
performance of both distributed and discrete optical fiber sensors.

S-matrix can be constructed using methods involving quadratic residues, maximal
length shift-register sequences and twin primes [35]. It has been demonstrated that the
optimum S-matrix, which minimizes the standard deviation of the decoded signal, can
be derived from the Hadamard matrix by deleting the first row and first column, and
then replacing 1’s by 0’s and -1’s by 1’s [52]. Thus, simplex coding can be easily
implemented in OTDR applications by turning the laser ON and OFF, according to
the sequences of 1’s and 0’s defined by the S-matrix [53].

Figure 3.8:
Example of Simplex coding technique for OTDR applications using an S-matrix.
(a) Probe pulse and respective fiber response for different time delays. (b) Linear
combination of pulses, confirming 3-bit Simplex codes [54].

The basic working principle of the Simplex coding can be better understood with the
following example based on an S-matrix of order 3 (see Figure 3.8). If we define \( \psi_1 (t) \)
as the OTDR trace resulting from a single probe pulse \( P_1 (t) \), and \( \psi_2 (t) \) and \( \psi_3 (t) \) as
the traces resulting from the time delayed probe pulses \( P_2 (t) = P_1 (t - \tau) \) and \( P_3 (t) = P_1 (t - 2\tau) \), as depicted in Figure 3.8 (a), with \( \tau \) being the pulse duration of \( P_1 (t) \), the following relationships are satisfied [53]-[54]:

\[
P_2 (t) = P_1 (t - \tau) \quad (3.4.1)
\]

\[
\psi_2 (t) = \psi_1 (t - \tau) \quad (3.4.2)
\]

\[
P_3 (t) = P_1 (t - 2\tau) \quad (3.4.3)
\]

\[
\psi_3 (t) = \psi_1 (t - 2\tau) \quad (3.4.4)
\]

Under linear conditions, the Simplex coded OTDR traces \( \eta_1 (t), \eta_2 (t), \) and \( \eta_3 (t) \) can be measured by launching into the fiber three different Simplex sequences according to (see Fig 3.8(b)):

\[
P_1 (t) + P_3 (t) = \eta_1 (t) = \psi_1 (t) + \psi_3 (t) + e_1 (t) \quad (3.4.5)
\]

\[
P_2 (t) + P_3 (t) = \eta_2 (t) = \psi_2 (t) + \psi_3 (t) + e_2 (t) \quad (3.4.6)
\]

\[
P_1 (t) + P_2 (t) = \eta_3 (t) = \psi_1 (t) + \psi_2 (t) + e_3 (t) \quad (3.4.7)
\]

which in the matrix notation can be written as:

\[
\begin{pmatrix}
\eta_1 (t) \\
\eta_2 (t) \\
\eta_3 (t)
\end{pmatrix} = S_3 \begin{pmatrix}
\psi_1 (t) \\
\psi_2 (t) \\
\psi_3 (t)
\end{pmatrix} + \begin{pmatrix}
e_1 (t) \\
e_2 (t) \\
e_3 (t)
\end{pmatrix} \quad (3.4.8)
\]

where \( e_1 (t), e_2 (t) \) and \( e_3 (t) \) represent the noise amplitude of each measurement and \( S_3 \) is the S-matrix of order 3, given by:

\[
S_3 = \begin{pmatrix}
1 & 0 & 1 \\
0 & 1 & 1 \\
1 & 1 & 0
\end{pmatrix} \quad (3.4.9)
\]

In order to recover the single-pulse OTDR trace \( \psi_1 (t) \), Hadamard transform has to be applied to the measured coded traces, according to [53]-[54]:

\[
\begin{pmatrix}
\hat{\eta}_1 (t) \\
\hat{\eta}_2 (t) \\
\hat{\eta}_3 (t)
\end{pmatrix} = S_3^{-1} \begin{pmatrix}
\eta_1 (t) \\
\eta_2 (t) \\
\eta_3 (t)
\end{pmatrix} = \begin{pmatrix}
\psi_1 (t) \\
\psi_2 (t) \\
\psi_3 (t)
\end{pmatrix} + S_3^{-1} \begin{pmatrix}
e_1 (t) \\
e_2 (t) \\
e_3 (t)
\end{pmatrix} \quad (3.4.10)
\]

\[
= \frac{1}{2} \begin{pmatrix}
1 & -1 & 1 \\
-1 & 1 & 1 \\
1 & 1 & -1
\end{pmatrix} \begin{pmatrix}
\eta_1 (t) \\
\eta_2 (t) \\
\eta_3 (t)
\end{pmatrix}
\]
where $\tilde{Y}_i(t)$ (with $i = 1, 2, 3$) corresponds to the estimated signal $\psi_i(t)$. Consequently, we can obtain three different decoded traces, which can be inversely time shifted with multiple of $\tau$, and then averaged to give rise to a single decoded-OTDR trace with improved SNR. Noise analysis demonstrates that in this case (i.e. Simplex codes of order 3) an SNR enhancement of $2/\sqrt{3}$ can be achieved in comparison to single pulse OTDR measurements with the same measurement time [53]-[54].

The previous example can be extended to the generalized case of code length equal to $L$, where coded-OTDR traces measured at the fiber input ($z = 0$) can be represented by the following expression:

$$
\begin{pmatrix}
\eta_1(t) \\
\vdots \\
\eta_L(t)
\end{pmatrix} = S_L \begin{pmatrix}
\psi_1(t) \\
\vdots \\
\psi_L(t)
\end{pmatrix} + \begin{pmatrix}
e_1(t) \\
\vdots \\
e_L(t)
\end{pmatrix}
$$

(3.4.11)

where $\eta_i(t)$ is the $i$-th coded-OTDR trace (with $i \in [1, L]$), $\psi_i(t)$, and $e_i(t)$ is the amplitude of the uncorrelated zero-mean noise added to the measurement of the $i$-th coded trace.

The decoding process can be carried out by the linear processing (Hadamard transform) of the traces as follows:

$$
\begin{pmatrix}
\tilde{Y}_1(t) \\
\vdots \\
\tilde{Y}_L(t)
\end{pmatrix} = S_L^{-1} \begin{pmatrix}
\eta_1(t) \\
\vdots \\
\eta_L(t)
\end{pmatrix} = S_L^{-1} \begin{pmatrix}
\psi_1(t) \\
\vdots \\
\psi_L(t)
\end{pmatrix} + S_L^{-1} \begin{pmatrix}
e_1(t) \\
\vdots \\
e_L(t)
\end{pmatrix}
$$

(3.4.12)

where $\tilde{Y}_i(t)$ is the estimated single pulse OTDR trace $\psi_i(t)$. Now, if every row is inversely time-shifted by multiples of pulse duration $\tau$, and introducing the matrix $T_L$ (corresponding to the normalized matrix of $S_L^{-1}$) we obtain:
It is worth pointing out that an interesting property of the matrix $T_L$ is that the sum of elements of each row is always -1, so that [53]-[54]:

$$T_L = \frac{L + 1}{2} S_L^{-1}, \quad T_{i,k} \in \{1,-1\}. \quad (3.4.14)$$

Considering that $\psi_i(t + (i - 1)\tau) = \psi_1(t)$ for every $i \in [1,L]$, each row of the left-side term of Eq. (3.4.13) actually corresponds to different estimation of $\psi_1(t)$, so that:

$$\tilde{Y}_1(t) = \psi_1(t) + \frac{2}{L + 1} \sum_{k=1}^{L} T_{1,k} e_k(t)$$

$$\vdots$$

$$\tilde{Y}_i(t + (i - 1)\tau) = \psi_1(t) + \frac{2}{L + 1} \sum_{k=1}^{L} T_{i,k} e_k(t + (i - 1)\tau)$$

$$\vdots$$

$$\tilde{Y}_L(t + (L - 1)\tau) = \psi_1(t) + \frac{2}{L + 1} \sum_{k=1}^{L} T_{L,k} e_k(t + (L - 1)\tau) \quad (3.4.16)$$

Thus all these traces can then be averaged according to:

$$\frac{1}{L} \sum_{i=1}^{L} \tilde{Y}_i(t + (i - 1)\tau) = \psi_1(t) + \frac{2}{L(L + 1)} \sum_{i=1}^{L} \sum_{k=1}^{L} T_{i,k} e_k(t + (i - 1)\tau)$$

Hence, the noise of the final decoded trace can be estimated as [54]-[55]:

\[ \text{Here the equation would be written in mathematical notation.} \]
\[ \text{Noise} = E \left\{ \left( \frac{1}{L} \sum_{i=1}^{L} Y_i (t + (i - 1)\tau) - \psi_1 (t) \right)^2 \right\} \]
\[ = \frac{4}{L^2 (L + 1)^2} E \left\{ \left( \sum_{i=1}^{L} \sum_{k=1}^{L} T_{i,k} e_k (t + (i - 1)\tau) \right)^2 \right\} \]
\[ = \frac{4}{(L + 1)^2} \left( \sigma^2 - \frac{1}{L^2} \sum_{i=1}^{L} (L - i) R_N (i\tau) \right) \]  \hspace{1cm} (3.4.17)

where \( E[x^2] \) represents the variance of \( x \). In this case the noise of the receiver has been considered to be an independent identically distributed (i.i.d.) and a wide sense stationary (w.s.s.) random process with zero mean and variance \( \sigma^2 \), leading to:

\[ E[e_i (t + \zeta)] = 0, \] \hspace{1cm} (3.4.18)
\[ E[e_i^2 (t + \zeta)] = \sigma^2, \] \hspace{1cm} (3.4.19)
\[ E[e_i (t) e_j (t + \zeta)] = 0, \quad \forall i \neq j, \] \hspace{1cm} (3.4.20)
\[ E[e_i (t) e_i (t + \zeta)] = R_i (\zeta) = R_N (\zeta), \quad \forall i = 1, 2, \ldots, L. \] \hspace{1cm} (3.4.21)

Note that in the case of an ideal receiver (with infinite bandwidth) \( R_N (\zeta) = 0 \) for any \( \zeta \neq 0 \), so that Eq. (3.4.17) can be simplifies to [54]:

\[ E \left\{ \left( \frac{1}{L} \sum_{i=1}^{L} Y_i (t + (i - 1)\tau) - \psi_1 (t) \right)^2 \right\} = \frac{4\sigma^2}{(L + 1)^2} \]  \hspace{1cm} (3.4.22)

Consider that, during the time required to perform the \( L \) measurements (one for each Simplex codeword), the single-pulse OTDR can averaged \( L \) traces reducing the noise in the factor of \( \sqrt{L} \); therefore the SNR enhancement provided by simples coding (i.e. its coding gain) can be expressed as [54]:

\[ \text{Gain}_{\text{Simplex}} = \frac{\text{SNR}_{\text{Simplex}}}{\text{SNR}_{\text{Pulsed}}} = \frac{\sqrt{\frac{\sigma^2}{L}}}{\sqrt{\frac{4\sigma^2}{(L + 1)^2}}} = \frac{L + 1}{2\sqrt{L}} \]  \hspace{1cm} (3.4.23)

3.4.1 Pulsed Simplex Cyclic Coding

Measurement performance is strongly dependent on employing coding techniques. The implementation of a standard Simplex codes, may provide a good SNR improvement especially if the code-words length is extended (e.g. 127 bits). However, such coding technique implies that before being able to decode all the N sent code-
words, the system has to wait for N times the transit time in the fiber. For fibers as long as 20 km or more, such an idle time would make the interrogation of FBG almost static. Therefore, while during static conditions this was not a crucial importance since only static measurements i.e. temperature/stress was carried out. To perform dynamic interrogation of TDM-based FBG sensors, the use of cyclic pulse coding scheme has been implemented as it “saves” time by a factor N (number of code-words sent) ensuring a sufficiently fast response of the sensor system in order to dynamically interrogate the FBGs while providing the same SNR gain as standard Simplex codes [50].

The key advantages of the employed cyclic codes are their ability to be used with integrated hybrid sensing scheme using high power lasers, compatibility with the use of low repetition rate pulsed lasers, exhibiting very low duty cycle values and providing strong side-lobes suppression; these features make this coding technique excellent for both simultaneously distributed and discrete sensing approaches. In the proposed cyclic coding technique, a suitable optical pulse sequence is continuously generated by modulating a high power pulsed laser source, according to a Simplex M-bit binary pattern \( P = \{p_0, ..., p_{M-1}\} \), where \( p_j = 0 \) or 1 (with \( j = 0, ..., M-1 \)), with a proper pulse repetition rate in order to divide the fiber round trip time into \( M \) consecutive intervals using a suitable pulse-width to attain a meter scale spatial resolution. In this way, the pattern results in a code spread along the whole fiber length, spaced in \( M \) time slots, increasing both the distributed (discrete) backscattered (back-reflected) power and the ultimate obtained SNR at the receiver. This feature greatly enhances the FBG dynamic interrogation sensing capabilities, resulting in a more suitable solution for high performance and long range discrete-dynamic measurements. Since the decoding process can be performed in real time using for example multi-core architectures [58], the performance in terms of dynamic detection of the proposed coding technique is fundamentally related to fiber transit time, providing then attractive features for real time FBG interrogation.

In such a scheme, the detected trace \( y \) at a given sampling instant results from the sum of many contributions linked to the single-pulse fiber response \( x \) and the pulse pattern \( P \) can be written as [59]:

\[
y(i + jH) = \sum_{k=0}^{M-1} p_{j-k|M} x(i + kH)
\]  

(3.4.24)

where \( i \) and \( j \) are integer indexes associated with a given sampling instant \( T \), \( H \) is the number of sampling points within one interval and \( k \) (index of summation) is used to index the given bits into the code word. Since the cyclic coding exploiting the Simplex pattern offers a coding gain (or SNR improvement) equal to \( (L+1)/2\sqrt{L} \) (\( L \) is the code word length), the use of this technique yields to a substantial enhancement of the dynamic strain resolution of a conventional FBG-based sensor, to extend its
sensing range and simultaneously to improve the SNR without impairing the dynamic detection capabilities. This enhancement is confirmed by direct experimental comparison between single pulse and decoded traces obtained with equal total measurement times.

3.5 High Performance Time-domain FBG Dynamic Interrogation Technique Based on Cyclic Pulse Coding

In this section a novel method to improve measurement range, resolution and multiplexing capability of TDM-FBG-based sensors, based on advanced cyclic pulse coding, is proposed and experimentally demonstrated. The mechanism of noise reduction by quasi-periodic cyclic coding is quantitatively demonstrated, pointing out significant improvement in dynamic strain resolution with respect to single pulse TDM FBG interrogation. The use of cycling pulse coding allows for the enhanced dynamic performance of real time strain measurement with respect to other coding techniques. The proposed technique can also enhance the sensing range of hybrid optical fiber sensor systems in which continuous static temperature/strain distributions and discrete dynamic strain in specific critical points, are simultaneously measured over the same sensing fiber.

FBG-based optical fiber sensors have attracted great attention in recent years and they are now becoming an industrial standard [5]-[55] for a wide range of applications in strategic sectors such as transport, energy, safety, security and medical. They offer unique features and advantages over conventional sensors, in terms of immunity to electromagnetic interference, dynamic response, multiplexing and embedding capabilities, making them suitable for smart structures and structural health monitoring [1]. WDM and TDM techniques have been extensively applied to FBG arrays, showing, however specific limitations in terms of available optical bandwidth and low signal to noise ratio (SNR), reducing in this way multiplexing and measurement resolution capabilities respectively. Other multiplexing techniques, such as code division multiplexing (CDM), have been proposed [50], being however characterized by rather high complexity and cost. In many industrial applications, such as nuclear plants, transportation, oil&gas and structural health monitoring, a sensor network should be implemented to measure physical parameters such as temperature, strain, pressure and vibration, ensuring an extended sensing distance, high resolution, as well as real time measurement capabilities. In this contest, the use of coding techniques has been proven to provide enhanced capabilities, mainly in the static distributed measurement of strain [50] and temperature [56].

Recent developments in optical fiber sensor technologies have also dealt with hybrid sensors for simultaneous distributed static temperature/strain measurement and dynamic interrogation of TDM-FBG-based point sensors. In such systems highly compact solutions, using a single pulsed laser and one sensing fiber only, can be developed, however with rather limited performances in terms of sensing distances.
and resolutions. In this context pulse coding can play a key role to improve the sensing capabilities of such hybrid sensor systems. When dealing with FBGs interrogation for dynamic strain measurement, it is however extremely important to properly select the pulse coding technique, without impacting on the dynamic detection capabilities of the interrogation technique. In particular standard Simplex [35] and correlation [57] based coding techniques are not suited to this end, as they would require the subsequent use of several different code-words before decoding, with a consequent serious degradation of the dynamic response.

To the best of our knowledge, we experimentally demonstrate for the first time, the possibility of improving the dynamic sensing performance of FBG based sensors, combining TDM and Simplex based cyclic pulse coding techniques. Cycling pulse coding applied to time domain FBG interrogation provides a significant SNR enhancement (up to 7 dB in our experiment) without impairing the measurement time hence attaining a detection technique with high frequency response. A suitable bit sequence is continuously generated from a narrowband pulsed source and, due to the quasi-periodic feature of the cyclic code, decoding can be effectively implemented in real time in just one fiber round trip time. This ensures dynamic strain measurement, with an upper bandwidth limitation related fundamentally to fiber transit time. Experimental results confirm that using quasi-periodic cyclic coding significantly improves the dynamic strain resolution with respect to foregoing single pulse TDM interrogation techniques. This feature confirms that the proposed technique becomes very attractive also for enhancing the performance of hybrid sensing, in which Brillouin and Raman-based long-range distributed static measurements are efficiently combined with FBG dynamic interrogation in specific critical points of the structures.

Although previously successfully applied for static distributed temperature measurement [56], the idea of using Simplex cyclic codes for TDM FBG dynamic interrogation is new. The specific choice of Simplex cyclic coding is extremely important for our application, as it guarantees both zero side lobes characteristics and full compatibility with existing long-range distributed static sensors, without affecting dynamic FBG interrogation rate. Since the proposed technique uses a single Simplex codeword which periodically sense the fiber, rather than a large number of different codewords, the coding/decoding-time overhead is kept very low (fundamentally related to the fiber round trip time), ensuring then dynamic measurement capabilities.

3.5.1 Discrete Time-domain FBG Interrogation Technique

TDM-FBG-based sensing is a well-known technique that exploit the time of flight of the back-reflected intensities from FBGs located along the structures to be monitored to distinguish their signals. An effective point dynamic strain measurement requires distinguishing the reflected power variations caused by dynamic strain from the one caused by static effects, also correcting detrimental effects due to spurious losses or laser power fluctuations.
The operating principle of the proposed FBG interrogation technique for dynamic strain measurement is based on the use of a pulsed narrowband pump and a pair of closely spaced low reflectivity Gaussian-shaped and apodized FBGs in each sensing point illustrated in Figure 3.9. The coded light from the narrow-band pulsed laser source is employed to interrogate, at each sensing point, a pair of FBGs that should be closely spaced and spatially separated by a few meter fiber spool within a small form-factor packaged coiling in order for them to be subjected to the same temperature. Each left and right FBG (L-FBG and R-FBG) is characterized by low peak reflectivity and broadband spectrum, allowing for low level crosstalk between different sensing points and a large measurement span respectively. Both FBGs at each sensing point are symmetrically shifted with respect to the centered wavelength of the employed pulsed laser source as shown in Figure 3.9. 

**Figure 3.9:**
Discrete FBG time-domain interrogation scheme. $\Delta T$ & $\Delta \varepsilon$ are temperature and strain changes respectively, $\lambda_{c1}$ & $\lambda_{c2}$ are the Bragg wavelength of L-FBG & R-FBG.

The performance of such a TDM point sensor array in terms of maximum acceptable crosstalk level, sensor resolution and measurement range are mainly dictated by FBG reflectivity, FBG bandwidth and the number of discrete sensing points. Regarding this, the value of FBG reflectivity involves a trade-off between sensor point number and performance, since, while low-reflectivity FBGs results in lower back-reflected power levels and then lower SNR levels, employing high-reflectivity FBGs (especially when many sensing points are needed) can induce significant penalties arising from multiple FBG reflection effects, thus hindering the sensor performance. In our experiment scheme, we could ensure adequate SNR levels and sensor performance in terms, e.g., of strain resolution even with low-reflectivity FBGs. Thus, by employing low-reflectivity FBGs and high input power pulsed laser source, a dense array of many serial discrete sensing points can be successfully placed along the fiber.

Since the FBGs reflectivity spectrum within the same sensing point are symmetrically shifted with respect to the central wavelength of the laser source, any strain or temperature perturbation experienced by the FBGs results in a differential variation of
the back reflected pulse intensities. The amount of light reflected by the $i$th pair of FBGs is given by [19]:

$$I_{L-FBG(j-1)} = I_0 R_{L-FBG(j-1)} \left( 1 - R_{L-FBG(j-1)} \right)^2 (j-2)$$  \hspace{1cm} (3.5.1)$$

$$I_{R-FBG(j)} = I_0 R_{R-FBG(j)} \left( 1 - R_{R-FBG(j)} \right)^2 (j-1)$$  \hspace{1cm} (3.5.2)$$

where $I_0$ is the source power, $R_{L-FBG}$ and $R_{R-FBG}$ are the L-FBG and R-FBG reflectivity profile, $I_{L-FBG}$ and $I_{R-FBG}$ are the returned power from L-FBG and R-FBG, and $j$ is index equals to $i$ times 2.

The spectral reflectance of the used apodized FBGs is well approximated by the following profile [7]:

$$R_{FBG}(\lambda) = R_i \exp \left[ -4 \ln(2) \cdot \frac{(\lambda - \lambda_{FBG})^2}{\Delta \lambda_{FBG}^2} \right]$$  \hspace{1cm} (3.5.3)$$

where $R_i$, $\lambda_{FBG}$, and $\Delta \lambda_{FBG}$ are the peak reflectivity, the central wavelength and the FWHM, respectively.

Since the employed FBG interrogation technique uses the discrete sensors as a linear filter to translate wavelength shift into amplitude variations, the maximum effective measurement range for point temperature and strain depends on both the spectral separation between the central wavelengths of the FBG pair and the FBG bandwidth. In order to obtain good linearity over a large sensing range, as well as immunity against spurious losses and laser power fluctuations, a unique interrogation function $\rho(\Delta \lambda_B)$ has been defined, that exploits the direct proportionality between FBG back-reflected pulse intensities and applied dynamic strain/temperature variations:

$$\rho(\Delta \lambda_B) = \ln \left( \frac{Z_{L-FBG} + \Delta Z}{Z_{L-FBG}} \int_{Z_{L-FBG}}^{Z_{L-FBG} + \Delta Z} I_{L-FBG}(\Delta \lambda_B, \xi) d\xi \right)$$

$$- \ln \left( \frac{Z_{R-FBG} + \Delta Z}{Z_{R-FBG}} \int_{Z_{R-FBG}}^{Z_{R-FBG} + \Delta Z} I_{R-FBG}(\Delta \lambda_B, \xi) d\xi \right)$$  \hspace{1cm} (3.5.4)$$

where $I_{LR-FBG}(\Delta \lambda_B, \xi)$ is the spatial domain back-reflected signals from the FBGs, $Z_{L-FBG}$ and $Z_{R-FBG}$ are the longitudinal positions of left and right FBGs and $\Delta Z$ is the spatial extension of the FBGs response. It is worth mentioning that static and dynamic effects can be distinguished in frequency domain using a suitable signal processing, providing an effective dynamic strain measurement which is robust to fiber losses and laser power fluctuations.
3.5.2 Experimental Setup for Proposed Interrogation Method

![Experimental setup](image)

**Figure 3.10:**
Experimental setup for improved TDM-FBG-based dynamic interrogation technique.

The experimental setup is rather simple and is schematically shown in Figure 3.10. A narrow line-width (~100 kHz) continuous wave (CW) laser centered at 1550.4 nm is amplified by an erbium-doped fiber amplifier (EDFA) to obtain 18 dBm peak power and an optical band pass filter (OBPF) is used to filter out the unwanted amplified spontaneous emission (ASE) noise. A Mach-Zehnder modulator (MZM), driven by a pattern generator, is used to generate the Simplex codeword to be sent into the fiber providing a 10 ns pulse only if the corresponding bit within the codeword is ‘1’. A multi-pulse pattern are then sent into the 12.5 km-long standard single mode fiber (SMF) using a circulator, which also allows for extracting back-reflected coded pulses. Two sensing points (SP$_1$ and SP$_2$) respectively at ~2.5 km and ~12.5 km are considered; each of them consists of a pair of Gaussian-shaped apodized FBGs with a peak reflectivity 2.5 % and 5%, bandwidth 2.5 nm, centered at 1549.35 nm (L-FBG) and 1551.4 nm (R-FBG) and separated by ~3 m of coiled fiber. The receiver section consists of a low noise PIN, trans-impedance amplifier and an analog-to-digital converter (ADC) which is connected to a computer for data processing. In order to validate our measurement technique, SP$_1$ and SP$_2$ are placed inside a temperature controlled chamber (TCC) for static measurements and a piezo-electric actuator system (PZT) is also used to apply a dynamic sinusoidal strain to SP$_2$ (which has lower SNR).

3.5.3 Experimental Validation: Results and Discussion

To estimate the SNR improvement provided by the proposed cyclic code, Simplex coded time domain traces are compared to the ones obtained by the conventional single pulse technique, using the same acquisition time and laser peak power. Figure 3.11(a)-(b) report 100 single pulse traces acquired from SP$_1$ and SP$_2$ while Figure 3.11(c)-(d) illustrates 100 decoded traces from SP$_1$ and SP$_2$ using a 63-bit cyclic code at a repetition rate of ~438 kHz respectively.
Figure 3.11:
Back-reflected 100-traces of single-pulse and 63-bit cyclic decoded at room temperature. (a)-(b) Single pulse time-domain traces of SP₁ and SP₂ (c)-(d) decoded traces of SP₁ and SP₂.

The horizontal axis corresponds to the distance between the interrogation unit and FBG locations in the fiber. Because TDM-FBG-based sensors can only measure time, it translates the time scale to fiber distance by using a conversion factor which approximately equals 10 nsec / m. It is evident from Figure 3.11 that the distance between L-FBG and R-FBG in SP₂ is ~3 m (corresponds to ~30 nsec) located at ~12.5 km and the obtained spatial location of back-reflected FBGs traces using single-pulse and 63-bit cyclic code (decoded trace) are similar.

Figure 3.12:
Coding gain of interrogation function (Eq. (3.5.4)) for SP₁ and SP₂ against several codeword lengths.

The SNR enhancement provided by cyclic Simplex coding is quantified by computing the standard deviation of the interrogation function reported in Eq. (3.5.4). Figure 3.12
compares the experimentally achieved coding gain and its theoretical value as a function of the codeword length; good agreement can be noticed with a maximum measured coding gain of ~7 dB with a 127-bit codeword.

To confirm the linear behaviour of the used interrogation function we have first characterized the FBGs response in static condition by varying the temperature inside the TCC from 5 °C to 45 °C; Figure 3.13(a) and 3.13(b) show the back reflected traces obtained from SP2 by using conventional single-pulse and 63-bit codeword. We can clearly see the significant reduction of noise by implementing coding as well as the counteracting temperature effect on both FBGs. Since the reflectivity profile of L-FBG and R-FBG in each sensing point is symmetrically shifted with respect to the central wavelength of laser, any temperature changes impact differently on the reflected power from L-FBG and R-FBG (i.e. reflectivity of L-FBG increases with temperature while decreases in R-FBG and vice versa). Figure 3.13 (c) shows the measured interrogation function, confirming a highly linear behavior and significant noise reduction up to ~6 dB with the same measurement time by using cyclic pulse coding.

**Figure 3.13:**
FBG reflected pulses at different temperatures. (a) Time-domain traces at around SP2 with single pulse (b) and decoded traces with 63-bit codeword (c) Characterization of the interrogation function against temperature.

We have finally investigated the dynamic strain measurement performance by applying a sinusoidal strain waveform (506 µε peak-to-peak) to the PZT. It is worth noticing that the coding/decoding process, consisting in a simplex matrix to vector multiplication, can be performed in real time with negligible overhead-time, by exploiting for example a multi-core architecture [58]. Figure 3.14 illustrates the obtained real time reflected traces at different applied dynamic strain values around
Again we can clearly see the significant improvement of SNR and enhanced dynamic strain measurement capability by implementing coding as well as counteracting applied dynamic strain effect on both FBGs.

**Figure 3.14:**
FBGs real-time reflected pulses at different applied dynamic strain. (a) Time-domain traces at around SP$_2$ with single pulse (b) and decoded traces with 63-bit codeword.

Figure 3.15(a) and 3.15(b) illustrates the acquired sinusoidal time-domain dynamic strain reconstruction based on Eq. (3.5.4). Actually, we can clearly observe that single-pulse provides a poor sinusoidal waveform reconstruction as compared to the cyclic pulse coding technique. The normalized fast Fourier transforms (FFT) of the measured traces are shown in Figure 3.15(c) and 3.15(d), pointing out that the fundamental component at 250 Hz can only be clearly identified when using pulse coding. While the single-pulse measurement provides a poor dynamic strain resolution of $\sim 1.40 \mu \varepsilon/\sqrt{\text{Hz}}$ at $\sim 12.5$ km, the use of distributed cyclic coding improves the attainable resolution down to $380 \text{ n\varepsilon}/\sqrt{\text{Hz}}$.

**Figure 3.15:**
Dynamic strain measurements at 0.25 kHz. (a) Sinusoidal reconstruction with single-pulse. (b) Sinusoidal reconstruction with 63-bit code. (c) Normalized FFT of single pulse. (d) Normalized FFT with 63-bit code.
Chapter 4

Novel Techniques for Hybrid Raman/FBG Based Fiber Optic Sensors

During the last decade, optical fiber optic sensors have emerged as a promising industrial technology with respect to conventional electrical/mechanical sensors, due to their unique advantages such as electromagnetic interference immunity, high sensitivity to measurand variations, environmental ruggedness as well as the possibility of integration within smart structures and materials, allowing their effective use in many industrial applications. In particular distributed fiber optic sensors based on Raman scattering have been attracting a great attention over the last years as they provide unique features that have no counterpart in conventional sensing techniques in terms of integrity, safety, maintenance cost, sensing distance, complexity and performance. The ability of Raman-based distributed temperature sensor (RDTS) to measure temperature at thousands of points along the sensing fiber is particularly interesting for the monitoring of large structures, mostly including monitoring of oil&gas pipelines, oil wells, storage vessels, reservoir monitoring, steam flow monitoring, geophysical measurement, process industry, nuclear reactors, power cables, transport infrastructure protection, tunnels, dams and power grid stations.

Several industrial applications require however the simultaneous measurement of static temperature profiles over long distances and static or dynamic strain in fixed critical points of the infrastructures to be monitored.

This chapter is primarily focused on time-division multiplexed (TDM) advance techniques for combining RDTS-based temperature measurements and FBG-based dynamic strain measurements by employing cyclic pulse coding schemes, enabling the use of such an efficient and effective hybrid system. Furthermore, the basic characteristics of FBG and Raman scattering in optical fibers is presented, and the configurations of hybrid sensors based on Raman scattering and FBG reflection are introduced.
4.1 Distributed Sensors Based on Spontaneous Raman Scattering

Distributed fiber optic temperature sensing using the temperature dependence of Raman scattering was proposed and first demonstrated in the mid 1980s; Raman scattering in optical fibers has then been exploited to develop distributed sensors, especially for temperature sensing [7]. In this section, the basic characteristics of Raman scattering in optical fibers is presented, and the configurations of temperature sensors based on Raman scattering are introduced.

4.1.1 Spontaneous Raman Scattering in Fiber

It is well known that the Raman scattering frequency shift in materials provides a good characterization of the composition and structure of the material itself. The Raman scattering process produces spectral components at both Stokes (lower photon energy) and anti-Stokes (higher photon energy) frequencies [60]. Since Raman spectroscopy has been used to analyze composition and impurities in optical fibers, thus optical fiber devices based on Raman effect have also been developed [7]. Figure 4.1 illustrates the measured Raman spectrum obtained in a silica fiber pumped at 532 nm [61]-[62]. The Raman spectrum is sufficiently displaced from the incident light wavelength as a result it can readily be separated by means of standard optical filters.

Figure 4.1:
Raman gain spectrum for vitreous silica.

The peak wave number shift of Raman scattering of vitreous silica is 420 cm\(^{-1}\) measured by a pump laser beam at 532 nm, corresponding to a peak frequency shift of 13 THz. The line-width is quite large, about 9 THz and it is attributed to the molecular structure of vitreous silica. Note that the effective Raman cross-section depends on the specific fiber structure; this is due to the different mode distributions between step-index and gradient-index fibers, and between single-mode optical fiber (SMF) and
multi-mode optical fiber (MMF). As a consequence, the scattering capture fraction depends on both effective refractive index \( (n) \) and fiber numerical aperture (NA) \([7]\):

\[
S = \frac{3}{2n^2} (NA)^2
\]  

(4.1.1)

For condense matter, the scattering cross-section per unit volume for the Raman Stokes component is only of the order of \(10^{-6} \text{ cm}^{-1}\)\([38]\). For a 50/125 graded-index MMFs the scattering cross-section is even lower, as a result only \(2.5 \times 10^{-9}\) of an incoming optical pulse power is backscattered in 1 m of fiber at the anti-Stokes Raman line \([63]\). This value is further reduced for SMFs due to their lower capture factor.

In a typical system the shorter-wavelength Raman band (the anti-Stokes band) is used to obtain the temperature information since it has a far higher temperature sensitivity (0.8% °C\(^{-1}\) at room temperature) than the longer wavelength (the Stokes, band). The temperature dependence of the anti-Stokes band measured in a germanium-doped silica fiber is shown in Fig 4.2 \([38]\).

**Figure 4.2:**
Raman anti-Stokes backscatter signal measured as a function of temperature. The vertical axis has been normalized at room temperature.

The temperature dependent properties of the Raman scattering are exploited to develop temperature sensors. It is shown that Stokes and anti-Stokes scatterings occur simultaneously in the materials, but with very different intensities. The basic factor physically explaining the difference is related to the populations at the ground state and the exited state, which obey the Bose-Einstein distribution law or its approximation, the Maxwell-Boltzmann distribution law \([7]\). In step-index fibers, a homogeneous distribution of the light over the effective cross section \((A)\) of the core can be assumed. Thus if we consider a small volume of fiber \(Adz\), there should exist \(NAdz\) molecules inside it, where \(N\) is the molecule density of the fiber core \([64]\). Therefore, considering both Raman Stokes and Raman anti-Stokes components, the
power propagation equations due to thermal excitation of these molecules can be written as:

\[ dP_S = (1 + N_\Omega) \Gamma_S P_0 \, dz \]  
\[ dP_{AS} = N_\Omega \Gamma_{AS} P_0 \, dz \]

where \( N_\Omega \) is the Bose-Einstein thermal population factor, \( \Gamma_S \) and \( \Gamma_{AS} \) are the Raman Stokes and anti-Stokes coefficients, and \( P_0 \) is the power of the incident light [64]. Equations (4.1.2) and (4.1.3) point out that, since both Stokes and anti-Stokes powers depend on the Bose-Einstein probability distribution of phonons, the spontaneous Raman scattering results to be a temperature dependent process caused by thermally driven molecular vibrations. Ultimately this temperature dependence provides a mechanism to perform distributed temperature sensing based on spontaneous Raman scattering using an optical fiber [60]. Note that the intensity of backward Raman scatterings is surely proportional to the pump laser power and that the fiber loss leads to attenuations of both pump and Raman signals. However, the ratio of anti-Stokes to Stokes scattering intensities provides a function of temperature which is independent on the fiber loss and pump power variations; this ratio can then be effectively used to develop RDTS systems. Finally it is worth noting that the sensitivity of the Raman scattering to the sensing fiber strain is very low, providing then the possibility to measure distributed temperature along the sensing fiber without any temperature-strain cross-sensitivity issue [7].

### 4.1.2 Raman OTDR-based Distributed Temperature Sensing

Optical time-domain reflectometry (OTDR) techniques are often exploited to realize RDTS temperature sensors in which the temperature estimation is usually obtained by measuring the Stokes and anti-Stokes spontaneous Raman backscattering intensities generated by optical pulses propagating along the sensing fiber [64]. A distributed Raman-OTDR-based temperature sensor provides a practical solution to a number of measurement problems by implementing the conventional OTDR principle to detect backscattered spontaneous Raman signals at both Stokes and anti-Stokes wavelengths in time-domain [7], [65]-[64]. One of its key advantages is that it can be effectively implemented using standard MMF telecommunication fibers which is relatively inexpensive and commonly available.

A typical configuration of a Raman-OTDR-based sensor system is shown in Figure 4.3, which consists of a pulsed pump laser to perform OTDR measurements with pulse duration proportional to the required spatial resolution, an optical circulator (or optical coupler) to deliver optical pulses to a long sensing fiber, which is usually an MMF to transmit higher peak-power optical pulses and to pick-up the returned weak signal. Optical narrow band pass filters are used to allow the Stokes and anti-Stokes components to be detected separately with high isolation from the backscattered Rayleigh component. Either a single avalanche photodiode (APD) or a double APD receiver scheme can be used for measuring the anti-Stokes signal and either the
Stokes or the Rayleigh component, used for normalization of the Raman anti-Stokes power.

![Diagram](image)

**Figure 4.3:**
A typical configuration of single-ended Raman OTDR-based RDTS temperature sensor.

Although the Raman frequency shift of 13THz is quite large, about 100nm at around 1550nm, the side lobe suppression ratio of the filters must be high enough because the Raman scattering intensity is much lower than that of Rayleigh scattering, typically 30 dB lower. Moreover, the intensity of anti-Stokes components is much weaker than that of Stokes components; therefore, an effective receiver must be based on high sensitivity APDs followed by a high-gain transimpedance amplifier and an optional low-noise voltage amplifier connected to a signal processor. The wavelength dependence of Raman scattering has been analyzed and it was demonstrate that long wavelength lasers (preferably in 1550 nm band) are beneficial for lower optical loss and longer sensing fibers [68].

Similar to the OTDR technique, several specifications can be defined for practical applications of RDTS-based temperature sensors: working distance, precision of localization, precision and range of measured temperature, and measurement time. The basic technical issue for better performance is to enhance the signal-to-noise ratio (SNR), as higher SNR means longer working fiber length, fast response of sensor data readout, higher spatial resolution and higher precision of temperature measurement [7]. There is however a fundamental trade off between sensing distance and spatial resolution. To enhance the SNR, multiple data collection and averaging are necessary and as a result longer measurement times are required to obtain the final temperature profile. The spatial resolution of RDTS-based temperature sensor is another important feature which is basically determined by the laser pulse duration and the photo-receiver response. The definite method to enhance the spatial resolution is to shorten...
the pulse width of the employed laser source. However, a short pulse means fewer photons to be integrated leading consequently to longer data processing times and/or to lower sensing distances.

While the intensity of the anti-Stokes component exhibits a strong dependence on the fiber temperature, the Stokes component is only slightly temperature dependent; however the OTDR traces of the anti-Stokes component only are not commonly used for temperature sensing, since these traces also depend on fiber losses, whose variations might be easily interpreted as a temperature change, inducing errors in the measurement. In order to overcome this problem, the anti-Stokes intensity trace has to be normalized by a temperature independent trace, such as the Stokes or Rayleigh component, so that local fiber loss effects are effectively cancelled out [69]-[70].

In RDTS a pump pulse propagates along an optical fiber and generates spontaneous Raman scattering depending on the pulse position along the fiber at each particular time. Thus, the Stokes Raman power reaching the photodiode at the near fiber-end ($z = 0$) and backscattered from a region of extension $\Delta L$ which is equal to half of the pulse width at a position $z$, is given by [71]:

$$P_S(Z)_{z=0} = (1 + N_\Omega)\Gamma_S P_0 \Delta L \exp[-(\alpha_S + \alpha_P)z]$$  \hspace{1cm} (4.1.4)

where $P_0$ is the input pump power and, $\alpha_S$ and $\alpha_P$ are the fiber loss coefficients at the Stokes and pump wavelengths. Equivalently, the anti-Stokes Raman power reaching the fiber input ($z = 0$) is:

$$P_{AS}(Z)_{z=0} = N_\Omega \Gamma_S P_0 \Delta L \exp[-(\alpha_{AS} + \alpha_P)z]$$  \hspace{1cm} (4.1.5)

where $\alpha_{AS}$ is the fiber loss coefficient at the anti-Stokes wavelength.

After calculating the ration of the anti-Stokes to Stokes power, we obtain [66]:

$$R(z) = \frac{P_{AS}(z)}{P_S(z)}$$

$$= C_R \exp[-(\alpha_{AS} + \alpha_S)z] \left( \frac{N_\Omega}{1 + N_\Omega} \right)$$

$$= C_R \exp[-(\alpha_{AS} + \alpha_S)z] \exp\left[\frac{-h\Delta\nu}{k_B T(z)}\right]$$  \hspace{1cm} (4.1.6)

where $C_R$ is a constant that takes into account the differences in the Raman capture factor and in the response of the receiver at the Stokes and anti-stokes wavelengths; $\alpha_S$ and $\alpha_{AS}$ are the fiber attenuation coefficients at the Stokes and anti-Stokes wavelengths, respectively; $\Delta\nu$ is the frequency separation between the Raman and pump signals, $h$ is the plank constant, $k_B$ is the Boltzmann constant, and $T(z)$ is the fiber temperature.
The ratio $R(z)$ depends on the differential wavelength-dependent losses of the fiber $(\alpha_{AS} - \alpha_S)$. If this factor is properly characterized as a function of the distance, it can be corrected from Eq. (4.1.6), leading to the following expression, which is independent of the launching conditions [66]:

$$R(z) = C_R e^{\frac{-h\Delta \nu}{k_B T(z)}} \quad (4.1.7)$$

It is difficult to measure the absolute temperature using Eq. (4.1.7), mainly because the possible inaccuracies when determining the coefficients $C_R$, value that can differ from fiber to fiber. However if a reference measurement is used at a known temperature ($T_{ref}$), the obtained reference ratio $R_{ref}(z)$ can be used for calibration, allowing for an accurate estimation of the temperature along the fiber according to [66]:

$$T(z) = \left\{ \frac{1}{T_{ref}(z)} - \frac{k_B}{h\Delta \nu} \ln \left[ \frac{R(z,T)}{R_{ref}(z,T_{ref})} \right] \right\}^{-1} \quad (4.1.8)$$

Note that Eq. (4.1.8) is obtained taking the ratio $R(z,T) / R_{ref}(z,T_{ref})$ and using Eq. (4.1.7). Note that, in order to neglect the local fiber losses and laser power fluctuations, the ratio of anti-Stokes to Rayleigh can also be used [71]-[72]: thus the Rayleigh backscattered signal reaching the fiber input ($z = 0$) can be expressed as [73]:

$$P_R(Z)_{z=0} = S A_S P_0 \Delta \text{exp}[\alpha_{\nu} z] \quad (4.1.9)$$

where $S$ is fiber capture factor which depends on the type of fiber and $A_S$ is the fraction of absorption coefficient due to Rayleigh scattering ($\sim \lambda^{-4}$). The anti-Stokes to Rayleigh intensities ratio is obtained as:

$$R(z) = \frac{P_{AS}(z)}{P_R(z)}$$

$$= C_R e^{\left[-(\alpha_{AS} + \alpha_{\nu}) z\right]} \left\{ e^{\frac{h\Delta \nu}{k_B T(z)}} - 1 \right\}^{-1} \quad (4.1.10)$$

When Eq. (4.1.10) is properly compensated for the differential wavelength-dependent losses, the absolute temperature measurement can be estimated as:

$$T(z) = \frac{h\Delta \nu}{k_B} \ln^{-1} \left[ \frac{C_R}{R(z,T)} + 1 \right] \quad (4.1.11)$$

Note that, $C_R$ can also be obtained using a reference trace at the known temperature, similarly to the previous case when the anti-Stokes to Stokes ratio was used.
4.2 Distributed Pulsed Cyclic Coding Technique for Hybrid Static and Dynamic Measurements

A fundamental limitation for RDTS temperature sensor is the trade-off between spatial resolution and SNR due to the weakness of the Stokes and anti-Stokes traces. Increasing the SNR of a RDTS temperature measurement by averaging of acquired anti-Stokes and Stokes traces results in increased dynamic range in a given measurement time. However the greater the number of averages, the longer the measurement time, which might become inappropriate for several applications requiring a dynamic response time.

Coding techniques based on Simplex or complementary correlation codes exploit a set of code-words of short optical pulses to increase the launched energy without degrading spatial resolution [35], [54], [57], [74]-[76]. However the required repetition rate of the laser pulses is not achievable when using high peak power laser, such as rare-earth doped fiber which can effectively operate at a maximum repetition rate of some hundreds of kHz [76]. Additionally the implementation of such coding scheme implies that before being able to decode all the N sent code-words, the system has to wait for N times the transit time in the fiber. For fibers as long as 20 km or more, such an idle time would make the measurements almost static. Therefore, while during static conditions this was not of crucial importance since only static measurements i.e. temperature was carried out, it can become a serious limitation when a dynamic measurement is required.

In this section, a novel coding technique adapted for simultaneous static and dynamic field measurands has been proposed. The basic idea is to periodically sense an optical fiber with a multi-pulse pattern, corresponding to a code distributed along the sensing fiber with a repetition period equal to the fiber round-trip time. The code pattern is spread along the whole sensing fiber, with a bit time inversely proportional to the code length. A 10 ns pulse width guarantees a meter-scale resolution and the laser peak power can be set to be below the threshold of nonlinear effects.

4.2.1 Pulsed Simplex Cyclic Coding Technique

Let us consider a $M$-bit binary pattern $P = \{p_0, \ldots, p_{M-1}\}$, with $p_j = 0,1$ for $j = 0, \ldots, M-1$. Suppose that the acquisition of the backscattered trace is divided into $M$ consecutive intervals, corresponding to $M$-bit pattern (codeword), and that an optical pulse is sent into the sensing fiber at the beginning of each interval if the relevant pattern bit is equal to 1. Suppose also that this triggering scheme is periodically repeated. According to $P$, some delayed backscattered traces overlap along the fiber, as shown in Figure 4.4 for $M = 7$ and $P = \{0,1,1,0,1,0\}$ [59].
Figure 4.4:
Distributed optical coding technique with $M = 7$ and $P = \{0,1,1,1,0,1,0\}$, (overlapped trace).

Given the system sampling period $T_s$, the length of backscattered trace can be expressed as the number $L$ of its samples. Now let $H$ be the number of samples within each of the $M$ intervals, so that $L = HM$. By defining a further index $i = 0,\ldots,(H - 1)$, we indicate with $y[i + jH]$ the array of the acquired samples, and with $x[i + jH]$ the array of the single-pulse response samples to be recovered. In this way, while $j$ scans the intervals, the index $i$ scans the samples within the $j$-th interval. It can be observed from Figure 4.4 that each $y[i + jH]$ is due the contribution of the backscattered traces originated by the pulses launched in the $j$-th interval and in the $M - 1$ previous ones. Hence the following relationship holds for $y$ and $x$ samples:

$$y[i + jH] = \sum_{k=0}^{M-1} p_{j-k|M} x[i + kH] \quad (4.2.1)$$

In particular, for a given $i$, Eq. (4.2.1) turns into a linear system of $M$ equations (one for each $j$ value) with a cyclic coefficient matrix [78]. In fact, its first row ($j = 0$) is $\{p_0, p_{M-1}, \ldots, p_2, p_1\}$ and any other row is a right-shifted copy of the previous one.

From a noise point of view, $y$ and $x$ samples can be reasonably considered as uncorrelated random variables. The noise affecting the recovered $x$ samples is determined by the linear system itself, i.e. by the inverse of the system coefficient matrix [59]. Hence, $P$ should be chosen so that a good noise reduction can be achieved. To this end, as the coefficient matrix is cyclic by construction, it is sufficient to use a matrix derived from the cyclic code theory and chose the pattern $P$ accordingly.

Considering the cyclic simplex codes, a cyclic binary coefficient matrix of order $M = 4n - 1$ (with $n = 1, 2, 3,\ldots$) can be built using the method reported in [78]. Being $\sigma_y$ and $\sigma_x$ the standard deviation of any $y$ and $x$ sample, respectively, the achieved SNR
enhancement, i.e. the coding gain $C_{\text{gain}}$, is given by the following well-known relation [35]:

$$C_{\text{gain}} = \frac{\sigma_y}{\sigma_x} = \frac{(M + 1)}{2\sqrt{M}} \quad (4.2.2)$$

### 4.3 Implementation of Hybrid RDTS/FBG Sensor for Temperature and Point Dynamic Strain Measurements

In principle, optical fiber sensors can be fundamentally classified into two categories: distributed and point (or discrete) sensors. Distributed sensing technology is based on scattering effects, such as Raman or Brillouin scattering, in which the measurand is continuously monitored along an optical fiber, which acts itself as the sensing element. The second type of sensors involves the use of point fiber sensing elements, such as fiber Bragg gratings (FBGs), in which the measurement takes place at particular spatial location along the fiber.

In order to overcome the limitations imposed by the cost and interrogation complexity of many point sensors, quasi-distributed sensing can be implemented based on array of FBGs employing different multiplexing techniques. Among all multiplexing methods, Time Division Multiplexing (TDM) is one of the most promising techniques, since it makes efficient use of the optical spectrum, allowing for several FBG sensors to be employed in the same wavelength window, and providing at the same time measurements with a good dynamic range.

While RDTS-based distributed temperature sensors constitute to-date the most successful and widely adopted technology for distributed sensing [12], allowing for quasi-static measurements with typical timescales of tens of seconds or few minutes, FBG-based sensing is the most commonly employed technique for point measurements, allowing for multiplexed discrete sensing with dynamic measurement capabilities up to several kHz; the range of their application fields spans from transportation to industrial power plants monitoring and oil&gas leakage detection in wells and pipelines.

#### 4.3.1 Benefits of Hybrid RDTS/FBG Sensing System

In many applications simultaneous point-dynamic and distributed measurements would be highly desired, as for example, in petrochemical industrial plants monitoring where a slow temperature profiling throughout the plant, useful for process control, can be effectively associated to dynamic strain information at specific critical points, useful to early detect possible cracks in pipelines. For such applications, an efficient sensor system should be devised combining distributed (static) temperature measurements and discrete (dynamic) strain sensing, thus providing detection of anomalous operating conditions (i.e. overheating, leakages and fire along a pipeline or
within a plant) and a simultaneous dynamic monitoring of the structure (i.e. vibrations in proximity of critical locations such as joints along a pipeline or a plant).

It must be considered that in most industrial applications, due to significant thermal inertia of the fiber cabling (often involving polymer sheaths, rodent protection and external armoring in addition to coated optical fiber itself), local temperature exhibits significant variations only on timescales extending over the second scale (often being as slow as many tens of sec at least). To this extent, monitoring with Raman distributed temperature sensing with a temporal response of a few seconds would provide a calibration on local temperature which can be effectively used to accurately perform the dynamic FBG strain measurement.

Both RDTS and FBG-based sensing provide stable and reliable measurements when exploited in time domain, and therefore, they can be good candidates to be integrated in a hybrid sensor that utilizes all functionalities of both sensing technologies simultaneously.

In this section, a new highly-integrated hybrid sensing system is proposed that effectively combines the advantages of both RDTS and TDM-FBG-based dynamic sensing by fully exploiting their respective specific functionalities.

An integrated sensing unit based on a shared laser source and receiver block has been developed, allowing for distributed measurements up to 20 km distance as well as dynamic strain sensing with a Nyquist limit up to 2.5 kHz. Additionally the technique provides a multi-functional and cost-effective solution in several industrial sectors such as in transportation, pipelines and industrial plant monitoring.

4.3.2 Description of Integrated Sensing Approach

In conventional RDTS systems, optical pulses are launched into a sensing fiber, so that using optical time-domain reflectometry (OTDR) techniques the spontaneous Raman scattering (SpRS) light that is back-scattered along the fiber is measured as a function of the distance. The forward propagating light pulse generates two SpRS components; the so-called Stokes and anti-Stokes lights. Although only the intensity of the anti-Stokes SpRS component strongly depends on the fiber temperature, a normalization with a temperature-independent OTDR trace, such as the Stokes SpRS or Rayleigh component, must be carried out in order to distinguish real temperature changes from local fiber loss variations. In our implemented RDTS system, trace normalization has been carried out by using Stokes light; in such schemes the anti-Stokes over Stokes intensity ratio is employed, providing a temperature sensitivity which can be expressed as:

\[
R(z, T) = C \left( \frac{\lambda_S}{\lambda_{AS}} \right)^4 \exp \left[ -\frac{h \Delta \nu}{k_B T(z)} \right] \tag{4.3.1}
\]
where $T(z)$ is the fiber temperature, $C$ is a constant dependent on fiber differential loss and receiver conditions, $\lambda_S$ and $\lambda_{AS}$ are the Stokes and anti-Stokes wavelengths respectively, $h$ is the Planck constant, $\Delta\nu$ is the frequency separation, and $k_B$ is the Boltzmann constant.

The absolute temperature profile $T(z)$ is found through a reference temperature profile $T_0(z)$ obtained from an initial calibration procedure involving an off-field calibration of fiber response at known temperature conditions, and a subsequent in-field calibration is then performed, requiring external measurement of temperature only at some fixed points (typically 2 points) in order to apply suitable corrections on fiber response impacting the ratio which might arise during deployment (mainly impacting slope of reference ratio). The absolute temperature is then found using the following equation:

$$T(z)^{-1} = T_0(z)^{-1} - \frac{k_B}{h\Delta\nu} \ln \left[ \frac{R(z,T)}{R(z,T_0)} \right] \quad (4.3.2)$$

Eq. (4.3.2) provides a $T(z)$ profile which is highly robust with respect to variations in opto-electronic parameters of the receiver stage, fiber conditions and losses, as well as laser power fluctuations.

On the other hand, FBGs are point fiber-sensors acting as band-reflect optical filters; the reflection bandwidth, centered at the Bragg wavelength $\lambda_B$, due to changes in the effective index and grating pitch linked to strain and temperature, exhibits a linear dependence on temperature ($\Delta T$) and strain variations ($\Delta \varepsilon$) [7], according to the formula:

$$\Delta \lambda_B = \lambda_B \left[ (\alpha + \varsigma) \Delta T + (1 - p_e) \Delta \varepsilon \right] \quad (4.3.3)$$

In Eq. (4.3.3), $\Delta \lambda_B$ is the variation of Bragg wavelength, $\alpha$ and $\varsigma$ are the thermal expansion and thermo-optic coefficients respectively, and $p_e$ is the effective photo-elastic constant of the fiber material.

The proposed integrated hybrid sensing approach makes use of a single pulsed laser which is simultaneously employed for both distributed Raman sensing and point dynamic FBG interrogation. Specifically the system requires the use of two optical fibers (possibly within the same duplex cable): a graded-index multimode fiber (MMF) for Raman-based temperature measurements and, a single-mode fiber (SMF) for FBG-based sensing. Even though a unique SMF could be used for both distributed and discrete sensing, the larger effective area of MMFs allows higher peak power to be launched into the fiber before the onset of nonlinearities, increasing both the Raman backscattered power and the SNR at the receiver. This feature greatly enhances the RDTS sensing capabilities, resulting in a more suitable solution for high-performance, long-range distributed temperature measurements.

In addition, the proposed method employs a time-domain approach for interrogating a pair of FBGs, which are placed close to each other in cascade along the same SMF at
each discrete sensing point. The performance of the multiplexed discrete sensor in terms of maximum acceptable crosstalk level, sensor resolution and measurement range are mainly dictated by FBGs reflectivity, FBGs bandwidth and number of discrete sensing points [19]. Regarding this, the choice of the FBG reflectivity should consider the existing trade-off between sensor point number and performance; while low-reflectivity FBGs results in lower back-reflected power levels and then lower SNR levels, employing high reflectivity FBGS (especially when many sensing points are needed) can induce significant penalties arising from multiple FBGs reflection effects, thus hindering the sensor performance.

In our experimental scheme, we could ensured adequate SNR levels and sensor performance in terms of strain resolution even with low reflectivity FBGs. Thus, by employing low reflectivity FBGs and high input peak power pulsed from a rare-earth-doped pulsed laser source, a dense array of many serial discrete sensing points can be placed along the fiber.

4.3.3 Validation of Efficient Interrogation Technique for TDM-FBG-based Sensor Array

The basic principle of the FBG interrogation technique is illustrated in Figure 4.5. The light from a narrowband pulsed laser source (the same source is also used for distributed Raman sensing) is employed to interrogate, at each sensing point, a pair of low-reflectivity Gaussian-apodized FBGs, whose reflection spectra have to be symmetrically shifted with respect to the central wavelength of the laser source. Both FBGs at each specific sensing point should be closely spaced and spatially separated by a few meters fiber spool within a small form-factor packaged coiling, in order for them to be subjected to the same temperature. Only one FBG of the FBG pair should be attached to the structure of interest (the so-called sensing FBG, S-FBG), and therefore made sensitive to both strain and temperature simultaneously. The other grating, named as reference FBG (R-FBG), should be loose and subjected to temperature only, allowing for a strain-independent reference to compensate for optical power variations resulting from changes in local losses or from laser power fluctuations. Since the employed FBG interrogation technique uses the discrete sensors as linear filter to translate wavelength shift into amplitude variations, the maximum effective measurement range for point temperature and strain depends on both the spectral separation between the central wavelengths of the FBG pair and the FBGs bandwidth.
Figure 4.5:
FBG dynamic strain measurement interrogation technique (Gaussian shaped apodized FBGs provide linear interrogation function).

In order to take into account the Gaussian shape of the FBG reflectivity spectrum, we have defined a temperature- and strain-dependent interrogation function \( \rho(\Delta \lambda_B) \) as the logarithm of the ratio between the integral of the reflected pulses from each FBG:

\[
\rho(\Delta \lambda_B) = K \cdot \ln \left( \frac{\int_{Z_{R-FBG}}^{Z_{R-FBG}+\Delta Z} I_{RS-FBG} (\Delta \lambda_B, \xi) d\xi}{\int_{Z_{S-FBG}}^{Z_{S-FBG}+\Delta Z} I_{RS-FBG} (\Delta \lambda_B, \xi) d\xi} \right) \tag{4.3.4}
\]

where \( I_{RS-FBG}(\Delta \lambda_B, \xi) \) is the intensity of the back-reflected pulses from FBG pair and depends upon the Bragg wavelength shift \( \Delta \lambda_B \), \( Z_{R-FBG} \) and \( Z_{S-FBG} \) are the longitudinal positions of FBGs along the fiber, \( \Delta Z \) is the spatial extent of the FBG response for given pulse conditions in the RDTS pump and, \( K \) is a correction factor that allows for sensor calibration and takes into account any static variation of \( \Delta \lambda_B \) affecting both R-FBG and S-FBG simultaneously.

It is important to notice that, in this configuration, the impact of strain on the FBGs response is different than the impact of temperature. Actually, small or moderate changes of temperature are expected to shift linearly the Gaussian-shaped spectrum of both FBGs as from Eq. (4.3.3); hence, the logarithm of interrogation function in Eq. (4.3.4) is expected to exhibit a linear behavior with temperature. This linear behavior should only occur within a particular range of temperature, which depends on the spectral separation between the central wavelengths of each FBG. On the other hand, if strain is applied, only the spectrum of S-FBG is expected to be shifted; in any case, the value given by Eq. (4.3.4) also depends on the spectral position of both FBGs, which is determined by the local temperature affecting both FBGs. This issue leads to a linear strain dependence of the interrogation function with a slightly different slope for every temperature, as reported by the dashed lines in Figure 4.6, showing the slope dependence of interrogation function versus applied strain for different temperature values.
Figure 4.6:
Characterization of interrogation function $\rho$ vs applied strain $\varepsilon - \varepsilon_0$ at different temperatures (dashed line: before slope correction, straight line: after slope correction).

In order to compensate for such effect and obtain a reliable point strain measurement at all operating temperatures, a calibration process has been carried out; in such a process, the temperature-dependent factor $K$ (with $K=1$ at room temperature, 25°C in our case) in Eq. (4.3.4) is characterized, using the information obtained from the RDTS, to compensate the impact of temperature on the interrogation function. We can observe in Figure 4.6 (solid lines) that the temperature-dependent slope of the interrogation function can be easily corrected with a proper characterization of the factor $K$, leading to approximately linear traces with similar slopes, and only affected by an offset at different temperature. It is worth noticing that since Raman-based distributed temperature measurements are carried out in a (graded-index) multimode fiber, the spatial resolution of the temperature profile is affected by the pulse broadening during light propagating resulting from modal dispersion (increasing along the fiber from the initial value determined by the pulse duration, from 1 m at fiber input to about 1.4 m after 20 km fibre propagation considering the employed standard graded-index fiber). On the other hand, point dynamic strain measurements employ a single-mode fiber, and therefore the impact of chromatic dispersion on the pulses and the respective reflected light (from the FBGs) can be considered to be negligible.
4.3.4 Experimental Setup: Sensor Implementation

Figure 4.7:
Experimental setup showing the sensor reading unit & the sensing fibers (Inset: picture of piezoelectric actuation system used to apply dynamic strain to the S-FBG).

The experimental setup is shown schematically in Figure 4.7. In order to implement the low-cost integrated hybrid sensor system, a shared sensor reading/interrogation unit (within the dashed block in Figure 4.7) has been developed. The sensor interrogation unit exploits a commercial single rare-earth-doped fiber pulsed laser, centered at 1550.5 nm, and provides 10 ns pulses with a maximum peak power of ~50 W at a repetition rate of 5 kHz. A couple of variable optical attenuators (VOAs) is placed before the fibers to reduce the peak power input level, thus avoiding the onset of fiber nonlinearities. In addition, an optical splitter is used to couple the pulsed light from the sensing unit into both sensing optical fibers. The routing and filtering stage is composed of an optical circulator along the SMF branch (employed for coupling light into the time-multiplexed FBG pairs and for routing the respective back-reflected light onto receiver stage) and a 4-port optical filter (coupling the pulsed pump light into the MMF used in distributed sensing and extracting the backscattered Stokes and anti-Stokes components before the receiver stage).

The integrated receiver block consists of an amplified photodiode array which is composed of a couple of avalanche photodiodes for Stokes and anti-Stokes light detection and a PIN diode for FBG-back-reflected light detection. In addition, a multi-channel analog-to-digital converter (ADC) enables simultaneous acquisition of the analog waveforms with 1 GS/s sampling frequency and subsequent processing by a PC-controlled FPGA-based board. While the laser pulsewidth and the receiver bandwidth up to 125 MHz in principle allow for a spatial resolution of 1 m, the maximum FBGs interrogation rate is limited by the laser repetition rate (5 kHz imposed by the fiber length) leading to a maximum FBG dynamic strain reconstruction down to 2.5 kHz (Nyquist limit).
The output light from the pulsed laser is coupled into two 20 km fibers (within the same duplex cable), i.e. an SMF for dynamic strain sensing, and an MMF for distributed temperature sensing. Along the MMF branch, the laser light (single-mode pigtail) is coupled into the filtering block and then into the MMF by an SMF-MMF fiber-mode coupler in order to reduce higher-order mode leakage. Along the SMF branch for point sensing, we employed an FBG pair with the two FBGs centered at 1549.35 nm (S-FBG) and 1551.4 nm (R-FBG), and showing the same nominal peak reflectivity (5%) and bandwidth (2.5 nm). This allows for an expected full-scale temperature measurement range of 170°C (when no strain is applied) and a strain measurement range of \( \sim 1700 \mu \varepsilon \) (at room temperature). In case of simultaneous strain and temperature measurements, the total measurement range for both temperature and strain is reduced, so that for instance, in order to realize the strain sensing up to 800 \( \mu \varepsilon \), the temperature range results to be from -15°C to 65°C. Both gratings have been placed at 15.2 km distance and have been spatially separated by 2.5 m coiled single-mode fiber (small form factor).

### 4.3.5 Experimental Validation: Results and Discussion

In order to analyze and validate the capability of our approach to discriminate temperature and strain, we placed 200 m of MMF and both FBGs inside a temperature-controlled chamber (TCC). Strain was applied only to the S-FBG along the longitudinal direction using a piezoelectric (PZT)-action system (inset in Figure 4.7 shows all the components that have been placed inside the TCC in order to apply strain together with temperature variations). The S-FBG was actually pre-strained in order to apply dynamic strain effectively and increase the grating compression sensitivity.

![Figure 4.7](image.png)

**Figure 4.7:**
A schematic diagram showing the components placed inside the TCC for dynamic strain and temperature measurements.

**Figure 4.8:**
S-FBG and R-FBG reflected pulses at room temperature.

We applied a dynamic sinusoidal strain along longitudinal direction to the S-FBG through a piezoelectric (PZT) actuator driven by a waveform-generator (120 \( \mu \varepsilon \) peak-to-peak amplitude). Figure 4.8 shows a single photo-detected time-waveform from the FBG pair, in which the integrals of each reflected pulse are used in Eq. (4.3.4) to infer the temperature and/or strain values. Note that temperature data from the RDTS
sensing fiber has been employed to compensate the FBG strain-temperature cross-sensitivity. Although the receiver bandwidth and the ADC sampling frequency would allow photo-detection up to a 200 MHz, the laser repetition rate limits the maximum FBG interrogation rate down to 2.5 kHz (Nyquist limit).

**Figure 4.9:**
Time-domain traces of FBG reflected pulses (a) at different temperatures $T$, and (b) at different values of applied strain $\varepsilon - \varepsilon_0$ and temperature $T$.

In order to obtain the temperature dependence of the interrogation function in Eq. (4.3.4), both gratings have been placed into the TCC at a temperature which was varied from 15°C up to 45°C, shifting the reflectivity spectrum of both S-FBG and R-FBG. Figure 4.9(a) shows the time-domain traces of the back-reflected pulses from both gratings, confirming the counteracting effect of temperature on each of them. To further characterize the strain interrogation function, a static-strain ($\Delta \varepsilon$) has also been applied to the S-FBG by varying the PZT from -44 $\mu$e up to +44 $\mu$e at two different temperatures (25°C and 35°C). Figure 4.9(b) shows the time-domain traces at different strain and temperature values, pointing out the significant strain-temperature cross-sensitivity affecting the measurements.
In order to compensate for temperature variations and obtain the real dynamic strain, a slope characterization of the interrogation function versus strain was carried out at different temperatures. The experimental results reported in Figure 4.10 show the temperature dependence of the interrogation function according to Eq. (4.3.4) (with $K=1$). The figure clearly shows a linear behavior of the interrogation function against temperature in the presence of a constant applied pre-strain ($\varepsilon_0$) on S-FBG. Simulations have also been carried out using the spectra of the used FBGs and their sensitivity on temperature, resulting in good agreement with the experimental data as shown in Figure 4.10.

By analyzing Eq. (4.3.4) it is possible to find out that, when strain has to be measured, the local temperature introduces an offset in the interrogation function (due to the linear behavior of Figure 4.10), but also changes the slope of the characterization versus strain. As explained in Section (4.3.3), in order to provide a practical and temperature-independent strain estimation algorithm, the temperature-dependent factor $K$ in Eq. (4.3.4) has been calibrated, so that the strain dependence becomes temperature-insensitive, with a linear behavior which is characterized by the same slope at different temperatures (as previously explained and shown in Figure 4.6).

To provide $K$ factor calibration, the correction factor $K$ has been obtained as a function of temperature by increasing the temperature in both gratings and keeping a constant strain; the behavior is reported in Figure 4.11(a) (where the local temperature information has been obtained by Raman sensing). We also verified that the correction factor $K$ does not change appreciably if the initial (residual) strain applied to S-FBG varies, thus allowing for a unique calibration for any initial strain value applied to S-FBG. Figure 4.11(b) shows the corrected interrogation function versus strain at different temperature values, where we can observe a constant slope of the function for different temperatures. Using such a characterization (i.e. a linear
behavior with constant slope), the temperature-independent strain value can be easily estimated once the local temperature information obtained by Raman sensing is used to compensate for the temperature-induced offsets shown in Figure 4.11(b).

**Figure 4.11:**
(a) Slope correction factor $K$ for interrogation function vs temperature.
(b) Characterization of interrogation function vs applied strain at different temperatures (symbols: experimental data, dotted line: simulations).

In order to verify the capabilities of the system to perform at the same time distributed temperature sensing and reliable temperature-compensated dynamic strain measurements, the TCC temperature (affecting both gratings) was varied from 15° C up to 45° C and a sinusoidal dynamic strain (88 με peak-to-peak amplitude) was simultaneously applied to S-FBG.
Figure 4.12:
(a) Anti-Stokes and (b) Stokes traces at different TCC temperatures (blue: 15° C, green: 25° C, black: 35° C, red: 45° C).

The anti-Stokes and Stokes intensity traces resulting from Raman-DTS (using above-mentioned measurement set-up with 100k averages and 30 s total measurement time) are reported in Figure 4.12(a) and 4.12(b) respectively (reporting for clarity the time-domain traces around a 15 km fiber distance where the TCC is placed).

Figure 4.13:
Temperature profile along 20 km fiber at different TCC values (red: 15° C, black: 25° C, green: 35° C, and blue: 45° C).

The RDTS calibration procedure (discussed in Section 4.3.3) has been carried out in order to take into account all possible effects impacting on acquired traces, such as receiver gain, fiber Raman cross-section, wavelength-dependent- and local losses (at the unit input/output or near fusion splices). Using the Raman back-scattered intensity traces, the distributed temperature profile has been obtained along 20 km MMF. Temperature traces at different TCC temperatures are reported in Figure 4.13, clearly showing the temperature variations and the increased noise near the far fiber end. The spatial resolution (10% - 90% temperature step response) was estimated to be 2.7 m at
the far fiber end, mainly due to the temporal broadening of pulse and backscattered light components induced by modal dispersion throughout the 20 km fiber length. The temperature resolution has been estimated as the standard deviation of noise in the temperature trace, attaining $1^\circ$C resolution at 20 km distance.

**Figure 4.14:**
(a) Normalized time-domain trace and (b) FFT spectrum of S-FBG (0.2 kHz modulation) at 25 °C (c) Time-domain trace and (d) FFT of S-FBG at 45 °C.

Regarding simultaneous strain measurements, the acquired sinusoidal traces induced by the applied dynamic strain to S-FBG (sinusoidal waveform, 0.2 kHz) are reported in the Figure 4.14(a) and Figure 4.14(c); such figures report the dynamic strain reconstruction (at 25 °C and 45 °C), obtained with the interrogation function described by Eq. (4.3.4) and using the temperature information from the RDTS. As it is evident from the figure, the final reconstructed dynamic strain trace shows a very good agreement with the known strain waveform applied to the PZT. Moreover, the dynamic strain acquired with the proposed technique clearly appears to be independent on environmental temperature; actually Figure 4.14 reports about two different strain measurements (Figure 4.14(a-b) and Figure 4.14(c-d)) obtained with the same strain conditions (same applied strain waveform at PZT) but under different temperature conditions (i.e. TCC at 25 °C for Figure 4.14(a)-(b), at 45 °C for Figure 4.14(c)-(d). The Fast Fourier Transform (FFT) of the measured strain traces with FBG temperature of 25 °C and 45 °C is also reported in Figure 4.14(b) and Figure 4.14(d) respectively. Based on strain measurements, the dynamic strain resolution of our system was estimated to be about 7.8 $\text{nm}/(\text{Hz})^{1/2}$. Harmonic components are clearly visible in the amplitude spectrum, and a slight non-linear behavior of the interrogation technique can be also observed due to the presence of (significantly smaller) spurious spectral components in addition to the fundamental one (the crosstalk from harmonic components is in any case smaller than -20 dB).
The experimental results clearly show the useful implementation of a hybrid sensor scheme, integrating spontaneous Raman scattering and FBG-based discrete sensing employing a single interrogation unit. Moreover the system is able to simultaneously perform distributed temperature evaluation and dynamic discrete strain measurements using an integrated reading unit with shared source and receiver stages. Experimental results show a temperature resolution better than 1 °C with 2.7 m spatial resolution at a 20 km distance as well as a dynamic strain resolution of 7.8 nε/√Hz at 0.2 kHz repetition rate (the Nyquist limit for a 20 km long fiber is 2.5 kHz). The planned technique provides a high-performance solution for many applications where both dynamic and distributed measurements are simultaneously required.

4.4 Highly Integrated Hybrid Raman/FBG Sensor Using Single Sensing Fiber for Distributed Temperature and Point-wise Dynamic Strain Measurements

4.4.1 Description of the Sensing System

In the previous section, a new implementation of hybrid RDTS/FBG-based sensing system was proposed by using two different sensing fibers (SMF and MMF).

In this section a novel highly-integrated hybrid sensing system is proposed using only one single sensing cable leading to simpler, reliable and cost-effective system that effectively combines the advantages of both RDTS and FBG-based dynamic sensing; the system allows for simultaneous distributed temperature sensing and dynamic discrete strain measurements using a single mode optical fiber, a common pulsed narrowband optical source and a shared receiver unit. The highly integrated proposed scheme employs broadband apodized low reflectivity FBGs, allowing for simultaneous measurements of distributed static temperature and discrete dynamic strain, over the same sensing fiber.

In the proposed RDTS/FBG integrated technique, a single pulsed laser source for both Raman and FBG sensing are employed, light pulses are launched into the sensing fiber generating SpRS which is measured using the OTDR technique. The intensity of the anti-Stokes SpRS light component strongly depends on the fiber temperature. In order to distinguish real temperature changes from local fiber loss variations or laser source power fluctuations, a normalization with a temperature-independent OTDR trace, such as Stokes SpRS or Rayleigh must be performed. For dynamic strain measurements, FBGs are placed along the fiber acting as band-reflect filters whose Bragg wavelength ($\lambda_B$) shifts linearly with local temperature and strain, due to changes in the effective index and grating pitch.

Interrogation technique for dynamic strain measurement is similar as the one described in previous section and illustrated in Figure 4.5. A single pulsed narrowband pump laser is used to interrogate a pair of Gaussian apodized FBGs,
placed close to each other in each sensing point, both characterized by low reflectivity and broadband spectrum. As schematically shown in Figure 4.5, the two reflected spectra from the FBGs within the same sensing point are symmetrically shifted with respect to the central wavelength of the laser source. The proposed interrogation technique exploits the FBG pair as reflective linear filters to translate wavelength shift into amplitude variation. In particular, considering the Gaussian reflectivity profiles of the employed FBGs, the following interrogation function $\rho(\Delta \lambda_B)$ is defined:

$$
\rho(\Delta \lambda_B) = \ln \left( \frac{Z_{L-FBG} + \Delta Z}{Z_{L-FBG}} \int_{Z_{L-FBG}}^{Z_{R-FBG} + \Delta Z} I_{LR-FBG}(\Delta \lambda_B, \xi) d\xi \right) - \ln \left( \frac{Z_{R-FBG} + \Delta Z}{Z_{R-FBG}} \int_{Z_{R-FBG}}^{Z_{LR-FBG} + \Delta Z} I_{LR-FBG}(\Delta \lambda_B, \xi) d\xi \right)
$$

(4.4.1)

where $L-FBG$ and $R-FBG$ stand for left and right FBGs in the pair. $I_{LR-FBG}(\Delta \lambda_B, \xi)$ is the back-reflected intensity trace from the two FBGs and depends on the Bragg wavelength shift $\Delta \lambda_B$; $Z_{L-FBG}$ and $Z_{R-FBG}$ are the longitudinal positions of the FBGs, and $\Delta Z$ is the spatial extension of the FBGs response. It is worth noting that using the ratio of back-reflected intensities from both FBGs, we can provide immunity to fiber losses and laser power fluctuations as well as good linearity over a large sensing range (depending on the spectral separation between $L-FBG$ and $R-FBG$).

### 4.4.2 Hybrid Raman/FBG on Step-index SMF: Experimental Setup

![Figure 4.15: Experimental setup for highly-integrated hybrid Raman/FBG sensor.](image)

The experimental setup of the proposed highly-integrated Raman-FBG sensor is schematically shown in Figure 4.15. A narrow-band pulsed laser operating at 1550.50 nm, followed by a variable optical attenuator (VOA), is used to generate, at a repetition rate of 8.33 kHz, pump pulses of 33 dBm peak power and a pulse-width of 10 ns, providing 1 m spatial resolution considering that chromatic dispersion in SMFs is negligible. The generated pulses are launched into the sensing fiber through an
optical circulator, which also couples the back-reflected light to a 4-port filter used to separate the Raman anti-Stokes, Raman Stokes and Rayleigh bands.

The receiver block consists of two avalanche photodiodes (APD) for anti-Stokes and Stokes light detection and a PIN photodiode for the FBG back-reflected light intensity measurement. The detected lights are then sent to a multi-channel 8-bit analog to digital converter (ADC) with 1 GS/s sampling frequency (to ensure an accurate reconstruction of the FBGs shape) for simultaneously acquiring the analog waveforms. For a 10 ns pulse a 1GS/s ADC sampling rate is indeed oversized since 250MS/s would be enough for the anti-Stokes and Stokes signals. However, to be able to accurately reconstruct the shape of the FBGs such a higher sampling rate is needed. The fiber under test is composed by a 10.9 km of single mode fiber and two sensing points located at 0.5 km and 10.7 km respectively. Each sensing point consists of a pair of FBGs with 1% nominal reflectivity and 2.5 nm line-width centered at different wavelengths (L-FBG at 1549.50 nm and R-FBG at 1551.50 nm).

### 4.4.3 Simultaneous Dynamic Strain and Distributed Temperature Measurement: Experimental Results and Validation

Figure 4.16 shows an example of acquired anti-Stokes trace at room temperature, from where we can clearly observe the peaks at the spatial locations corresponding to the position of the gratings (the insets in Figure 4.16 clearly show two peaks corresponding to the two FBGs in each sensing point). Each peak is generated by the corresponding FBG which creates a reflected pump pulse at 1550.5 nm back-propagating to the fiber input while generating anti-Stokes scattering. The forward component of this scattering co-propagates with the reflected pulse to the fiber input while accumulating energy which finally results in energy peaks at the corresponding FBG positions. These peaks are superimposed to the standard back-scattered Raman anti-Stokes trace. Similar peaks are also present in the Stokes spontaneous Raman scattering trace, being generated at each position of the fiber by the same mechanism. As can be clearly seen in Figure 4.16, the second sensing point returns higher power peaks, since the forward scattering, induced by FBGs reflection in the counter-propagating direction with respect to the pump, is summed over a much longer distance. Nevertheless these peaks do not affect the distributed temperature measurement, which can be accurately performed along the whole sensing fiber, obviously except in the close proximity of the FBGs, where we are only interested in dynamic strain measurement.
Figure 4.16:
Raman anti-Stokes trace at room temperature.

In order to analyze and validate the capability of our sensor to perform static distributed temperature and discrete dynamic strain measurements simultaneously, we placed the FBGs of both sensing points together with 200 m of SMF (preceding the second sensing point) inside a temperature-controlled chamber (TCC). In addition, the two FBGs of the sensing point located at 10.7 km have been glued to a piezoelectric actuator (PZT) driven by a waveform generator.

The FBG responses of both sensing points have been first statistically characterized as a function of temperature, by setting the TCC at different values and acquiring the time-domain traces of the back-reflected signals. For a complete FBG characterization, 100 traces have been averaged for each TCC temperature, and the interrogation function has then been calculated. As expected, comparing the linear fitting (solid line) with the experimental data (square dots) in Figure 4.17(a), confirms a linear behavior of the interrogation function versus temperature. The amplitude variations of the back reflected pulses from L-FBG and R FBG due to temperature changes are reported in Figure 4.17(b). It is worth noting that, although the interrogation function is used to map both strain and temperature values, dynamic strain variations can be extracted using high-pass filtering, thus removing the static component of the signal.
In order to study the influence of the FBG based sensing points on the distributed temperature measurements, Raman based temperature measurements have been carried out setting the TCC temperature at three different values 5 °C, 28 °C and 45 °C respectively. The temperature profiles, estimated at each different temperature and reported in Figure 4.18 clearly appear undistorted.

We can evidently note that the FBGs at the two sensing points, at ~ 0.5 km and ~ 10.7 km distances, have no influence on the Raman temperature measurement. To fully demonstrate the robustness of our hybrid sensor system, excluding possible spurious effects of the FBGs on the RDTS performance, distributed temperature measurements at 28 °C have been repeated under the same conditions and using the same optical fiber spools, without splicing the FBG-point sensors. The corresponding temperature resolutions with and without FBGs have been calculated from the standard deviation of the measured temperatures and are shown in Figure 4.19. We can see consistent results in both cases, with a similar trend in the resolution versus distance, fully demonstrating that FBG sensing points have no impact on the Raman temperature.
measurements. The worst temperature resolution (at ~ 10.8 km distance) is calculated to be ~ 2 °C.

![Graph showing temperature resolution along fiber with and without FBGs.](image)

**Figure 4.19:**
Temperature resolution along the fiber for the setup with (green) and without (blue) FBGs.

Finally, dynamic strain measurements have been carried out by applying a sinusoidal strain waveform (~410 με peak-to-peak) to the PZT actuator on the sensing point, at ~10.7 km distance. The waveform frequency and the TCC temperature have been changed to evaluate the dynamic sensing capabilities of the system under different conditions.

![Graph showing dynamic strain measurements at 250 Hz.](image)

**Figure 4.20:**
Dynamic strain measurements at 250 Hz. (a) Time-domain trace and (b) normalized fast Fourier transform.

Figure 4.20(a) shows a dynamic strain acquisition at room temperature with a 250 Hz sinusoidal waveform as input of the PZT actuator; the acquired time-domain dynamic strain trace is in good agreement with the (known) applied strain waveform. The normalized fast Fourier transform of the measured trace is shown in Figure 4.20(b); as we can see, the fundamental component is easily identified among other spurious spectral components, with a power lower than 10 dB. Similar traces were obtained at
different TCC temperatures and frequencies. The dynamic strain resolution was estimated to be $\sim60 \text{ nε}/(\text{Hz})^{1/2}$ at 250 Hz.

Dynamic strain measurements at different temperatures have been performed giving the same results as shown in Figure 4.20(a)-(b) and therefore demonstrating that temperature variations do not affect the correct identification of the fundamental frequency component of the applied strain. It is worth mentioning that, as it is shown in Figure 4.17(a), the interrogation function has a highly linear behavior with respect to temperature in the range between 0 °C and 45 °C, also demonstrating that temperature variations do not influence dynamic strain measurements.

The dynamic range of the RDTS/FBG-based hybrid sensing system is strongly dependent on the minimum SNR (threshold for performing temperature measurements) at the receiver and therefore depends on the kind of receiver which is used. The number of FBG sensing points used is also affecting the dynamic range as each sensing point introduces losses (due to the FBG reflectivity and of splices). Therefore, what can be said is that for the same receiver stage, the more FBG sensing points we will have, the shorter the dynamic range will be. A very simple but plausible calculation is that assuming that if each sensing point introduces a 0.1 dB loss, by having 10 sensing points we would have 1 dB lower SNR at the receiver meaning that, referring to Figure 4.19, the wanted temperature resolution of 2°C could be achieved only around 7 km and not almost 11 km as with only two FBG sensing points as demonstrated in the experiment.

The experimental results clearly show that a hybrid Raman/FBG sensing system using a highly integrated interrogation unit (sharing a narrowband pulsed source, the sensing fiber and the receiver stage) has been implemented. The experimental results prove simultaneous distributed sensing capability with temperature resolution of 2 °C at 10.9 km and dynamic sensing with discrete FBG dynamic strain resolution of $\sim60 \text{ nε}/(\text{Hz})^{1/2}$ at 250 Hz, enabling the use of such a simple and effective hybrid technique in many applications where distributed temperature and discrete dynamic strain measurements are simultaneously required.

**4.5 Highly Efficient Raman/FBG Hybrid Sensor Utilizing Advanced Cyclic Coding Technique**

**4.5.1 Combined use of Cyclic Coding and Hybrid Sensing Scheme**

For more sensitive and accurate measurements we need to move to a higher level of sophistication, and this normally requires the introduction of coding techniques. To alleviate the trade-off between spatial resolution and sensing range, the use of several coding techniques has been successfully demonstrated in the past. In particular for hybrid distributed-static/point-dynamic measurements, the proper selection of coding technique and pulse modulation format is extremely important in order to obtain high
performance and to avoid distortions. Considering that the dynamic range of RDTS sensor is ultimately determined by the receiver sensitivity, other techniques have to be employed to further extend the sensing distance. For instance, the use of correlation-based codes has been proposed for distributed sensors to improve the performance. The basic idea behind correlation techniques applied to RDTS-based sensor is to spread the signal in time-domain and to reconstruct the fiber impulse response by correlating the detected signal with pump pulses used for sensing. It is then possible to improve the attained SNR, avoiding the same time the onset of nonlinear effects. However, correlation-based coding schemes are not suitable for hybrid RDTS/FBG sensors due to occurrence of $N$ code-words limiting the interrogation speed for dynamic point measurements. In addition correlation coding can potentially give rise to serious multi-path interference when interrogating time-division multiplexed FBGs.

The highly efficient hybrid sensing system proposed here is based on cyclic pulse codes; the coding gain is exploited at the same time to overcome the limitations imposed by the low level of Raman scattering and low multiplexing capacity of FBG sensor array. The SNR enhancement provided by the coding is quantified by the coding gain, which is defined as the SNR improvement provided by coding with respect to single-pulse case, considering the same measurement time.

The noise reduction in cyclic coding scheme can be exploited i) to obtain simultaneously a distributed temperature and discrete dynamic strain accuracy higher than the one achieved by a single pulse hybrid RDTS/FBG sensor with the same measurement time, or ii) to provide the same static-temperature / dynamic-strain accuracy as in single pulse hybrid RDTS/FBG sensor, but in shorter measurement time, or iii) to achieve the improved sensing range (FBG multiplexing capacity) with similar measurement time.

In this section we propose and experimentally demonstrate a novel method with the specificity to employ advance pulsed cyclic coding technique to significantly improve the performance of highly-integrated hybrid RDTS/FBG optical fiber sensor using single optical narrow band source / sensing cable and a shared receiver block. The high accuracy and long term inherent stability for simultaneous measurements of distributed-static temperature and discrete-dynamic strain over the same SMF sensing fiber make it attractive and suitable for accurate measurement and synchronization of sensing data. In the employed sensing system effective SNR improvement is achieved in both Raman OTDR and dynamic interrogation of TDM-based broadband Gaussian-shape apodized low reflectivity FBG sensors, confirms the effectiveness of the proposed approach plus permitting its stability against spurious losses. Such a noise minimization is effectively performed, enhancing the sensing range-resolution / multiplexing capability and providing real-time point dynamic strain measurement without sacrificing the dynamic interrogation speed.
The unique possibility of measuring simultaneously different measurand for instance distributed static temperature and discrete dynamic strain at some specific critical points is opening new research directions and numerous industrial application fields in optical fiber sensing. It is necessary to realize simultaneous measurement of static and vibrant variations ensuring an accurate and complete structural health monitoring as well as enabling extended sensing distances, high resolution and keep real time measurement capabilities. Consequently as mentioned in previous section, in many industrial fields simultaneous point dynamic and static distributed measurements would be highly desire.

Highly integrated hybrid Raman/FBG sensor has been demonstrated in the previous section for simultaneous distributed temperature sensing and dynamic discrete strain measurements on the same SMF, using a single pulsed narrowband optical source and a shared receiver unit. This scheme, although very attractive in terms of compactness and cost-effectiveness, is however limited in the sensing range (distance) due to the rather poor performance of Raman distributed temperature sensor (RDTS) employing SMF (as compared to MMF-based RDTS). In this contest, the use of coding techniques has been proved to provide enhanced capabilities, mainly in static distributed measurement of strain and temperature. Such coding schemes are used in peak power limited systems where increases in the transmitted energy would otherwise result in degraded resolution. When dealing with FBGs interrogation for dynamic vibration measurements, it is however extremely important to properly select the employed pulse coding technique, effectively avoiding the impact on dynamic detection capabilities of the time-domain interrogation technique. In particular, as described above standard simplex and correlation based coding schemes are unsuitable to this end, as they employ subsequent use of several different code-words to obtain ultimate useful information, with a consequent serious degradation of the sensor dynamic response.

We have investigated a thorough analysis of the benefits of a new long-range high performance hybrid sensing scheme for simultaneously accurate measurement of distributed temperature and discrete dynamic strain employing advance pulsed cyclic coding techniques, using a single narrow band laser source, a common sensing cable and a shared receiver block plus avoiding any possible detrimental effects like spurious losses and source power fluctuation problems. The Raman scattering signal and FBG back-reflected peaks can be efficiently improved in optical time-domain by employing such a precisely selected coding technique hence substantial improvement in both static-distributed and dynamic-discrete SNR; the effective choice of quasi-periodic pulse coding is of key importance to guarantee significantly improved sensing distance-resolution without affecting the dynamic interrogation response of the hybrid sensor. It is worth noticing that, since Raman-based distributed temperature measurements are carried out in a common SMF sensing cable along with dynamic strain measurements, the spatial resolution of the temperature profile is unaffected by the pulse broadening (due to modal dispersion) during light propagation. These
features make the proposed system attractive and give a practical way of sensing the distributed temperature and point dynamic strain simultaneously while facilitate cost effective real-time high interrogation speed and excellent throughput.

4.5.2 Integrated Coded Hybrid RDTS/FBG Sensing Method

For RDTS measurements, one is particularly interested in measuring an impulse response which is essentially exponential, although distributed temperature decoded traces also contains discrete reflections exactly from FBG sensing locations, superimposed on the exponentially decay stokes and anti-stokes traces. However after FPGA-based signal processing discrete peaks could be effectively filtered out, yielding perfect reconstruction of the original impulse response temperature distribution along the fiber with maximum improvement in SNR. These peaks are generated by the coded pump light components back-reflected from the FBG sensors; due to the bi-directional propagation nature of the Raman scattering, the anti-Stokes spontaneous Raman forward component, generated along the fiber by the cyclic coded pump pulses reflected from the FBG sensing points placed along the fiber, add to each other giving rise to energy peaks at the corresponding FBG positions, which are superimposed to the standard back-scattered Raman anti-Stokes trace. Similar coded peaks are also present in the Stokes spontaneous Raman scattering trace, being generated at each position along the fiber by the same mechanism. Nevertheless these peaks do not affect the distributed temperature measurement, which can be accurately performed along the whole sensing fiber, obviously except in the close proximity of the FBGs sensing points, where we are only interested in dynamic strain measurements.

Distributed temperature measurement does not require real time acquisition; on the other hand the FBG interrogation requires an optimized procedure in order not to affect the dynamic response of the system. In particular when using single pulse OTDR techniques, the limited achieved SNR requires several averages, significantly affecting the system bandwidth. The proposed Simplex cyclic coding (see section 4.2.1) allows us to perform real time decoding in less than one transit time, using for example multi-core architectures to effectively implement the decoding algorithm, without any significant overhead time.

In dynamic strain signal detection, dynamic strain resolution is a useful parameter to compute the performance of dynamic strain sensor. In particular, the normalized minimum detectable strain depends on the amount of noise magnitude which affects the detected signal. Since the magnitude of the noise depends on frequency span, to allow measurement with different frequency span to be compared it is necessary to normalize all the measurement to 1 Hz bandwidth. Therefore the dynamic strain resolution is calculated taking the ratio between the applied dynamic strain root-mean-square and the SNR of the detected signal normalized to 1 Hz bandwidth. Since the dynamic strain resolution is related to the SNR, our proposed coding technique
can be effectively used to improve the measurement resolution of the OTDR-based FBG sensing technique without impairing on the measurement time.

4.5.3 Experimental Setup: Implementation using Cyclic Codes

The experimental setup of the proposed low-cost integrated hybrid Raman/FBG sensor is schematically shown in Figure 4.21. The pulsed light source is a narrow band high-power rare-earth doped fiber laser (~47 dBm peak-power) centered at 1550.40 nm, with 10 ns pulse width and a repetition rate of ~300 kHz, allowing a maximum of 63 bits cyclic coded pulse sequence. The real periodic sequence of the Simplex cyclic code is achieved by a FPGA-controlled acousto-optic modulator, which acts as a chopper cancelling out laser pulses when a bit ‘0’ is generated, and letting pulses through when a bit ‘1’ is expected. The threshold for nonlinear effects along the sensing fiber, found to be ~37 dBm, is not exceeded by controlling the laser output through a variable optical attenuator (VOA).

![Figure 4.21](image)

**Figure 4.21:**
Experimental setup for an integrated hybrid RDTS/FBG sensor using single 21.4 km long SMF and simples cyclic coding.

The generated pulses are launched into the sensing fiber through an optical circulator, which also couples the back-reflected light to a 4-port filter used to separate the Raman anti-Stokes (AS), Raman Stokes (S) and Rayleigh (R) bands. The receiver block consists of two highly sensitive avalanche photodiodes (APDs) with 200 MHz bandwidth for anti-Stokes and Stokes trace detection and a low noise PIN photodiode for the FBG back-reflected light intensity measurement. To ensure the accurate reconstruction of FBGs dynamic strain response signature, the detected lights are then sent to a multi-channel 8 bit analog to digital converter (ADC) with 1 GS/s sampling frequency for simultaneously acquiring the analog signals and subsequent processing by PC-controlled field programmable gate array-based board. The total gain of the receiver is of 60-70 dBΩ. While the laser pulse width and receiver bandwidth up to 125 MHz in principle allow for spatial resolution of 1 m, the maximum FBG
interrogation speed is limited by the round trip time of the launched pulses (~4.5 kHz imposed by the fiber length) leading to a maximum FBG dynamic strain reconstruction down to ~2.3 kHz (Nyquist limit). The fiber under test is composed of ~21 km of SMF and two sensing points located at ~10 km and ~20 km respectively. Each sensing point consists of a pair of FBGs (separated by ~3 m of coiled fiber) with 1% nominal peak reflectivity and 2.5 nm line-width centered at different wavelengths (L-FBG at ~1549.50 nm and R-FBG at ~1551.50 nm). This allow for an expected full-scale temperature measurement range of ~170 °C (when no strain is applied) and a strain measurement range of ~1700 με (at room temperature). In case of simultaneous strain and temperature measurements, the total measurement range for both temperature and strain is reduced so that for instance, to realize the strain sensing up to 800 με, the temperature range results to be from -15 °C to 65 °C. In order to validate our dynamic FBG measurement technique, the two sensing points at the middle (SP1) and far end (SP2) of the sensing fiber are placed inside a temperature controlled chamber (TCC) for static temperature measurements; a piezo-electric actuator system (PZT) is also used to apply a dynamic sinusoidal strain to the far sensing point SP2 which has lower SNR.

4.5.4 Benefits of Coding on Hybrid Sensor: Results and Discussions

In order to analyze and validate the capability of our integrated hybrid sensor to perform static distributed temperature and discrete dynamic strain measurements simultaneously; first we have experimentally measured the threshold for nonlinear effects along the sensing SMF, a value that was found to be 37 dBm. To estimate the SNR improvement provided by the proposed cyclic pulse codes, measurement with coding are compared to the ones obtained by the conventional technique, using the same acquisition time and laser peak power.

The repetition rate of the laser has been set to ~300 kHz, and hence 63 bits have been allocated along the ~21 km long SMF. Figure 4.22(a) and 4.22(b) shows the acquired coded anti-Stokes and Stokes traces, where we can observe the repetition period of the bits corresponding to a ~340m fiber distance, which is linked to the laser repetition rate (~300 kHz). The phenomenon of coded backscattered anti-stokes and stokes peaks in RDTS traces is already explained in the section 4.3.3. Simultaneously the real time obtained coded FBGs traces extract from the Rayleigh port at around 1550.5 nm are shown in Fig 4.22(c) where we can clearly observe the back-reflected peaks from L-FBG and R-FBG nearby SP1 and SP2.
Figure 4.22:
63-bit fiber response of coded traces (a) Back-scattered anti-Stokes trace (b) Back-scattered Stokes trace and (c) Back-reflected trace from FBGs.
The SNR enhancement of FBGs measurements provided by the cyclic Simplex coding is quantified by computing the standard deviation of the interrogation function reported in Eq. 4.4.1. Figure 4.23(a) and 4.23(c) report 100 single pulse traces acquired from SP1 and SP2 respectively and Figure 4.23(b) and 4.23(d) indicate their 100 decoded traces using a 63-bit cyclic code at a repetition rate of ~300 kHz respectively with the same measurement time.

Figure 4.23:
Back-reflected 100-traces of single-pulse and 63-bit cyclic decoded at room temperature. (a) Single pulse time-domain traces of SP1 and (b) Single pulse time-domain traces of SP-2 (c) Decoded traces of SP1 and (d) Decoded traces of SP2.

The horizontal axis corresponds to the distance between the interrogation unit and FBG locations in the fiber. Because TDM FBG based sensors can only measure time, it translates the time scale to fiber distance by using a conversion factor which approximately equals 10 nsec / m. It is evident from Figure 4.23 that the distance between L-FBG and R-FBG in SP2 is ~3 m (corresponds to ~30 nsec) located at ~20.1 km and the obtained spatial location of back-reflected FBGs traces using single-pulse and 63-bit cyclic code (decoded trace) are similar. The experimentally achieved effective reduction of noise around ~6 dB in the decoded point sensor measurements is clearly evident from the comparison of acquired traces. Note that back-reflected coded pulse stream from SP2 is not influencing detrimental effects on the coding gain from SP1 and vice versa.

Similarly after decoding of the distributed-coded traces, the single-pulse response of the fiber for the anti-Stokes and Stokes components are recovered with an extended dynamic range as well as an improved SNR compared to the standard single-pulse technique and with the same measurement time. Figure 4.24 shows a comparison of the normalized anti-Stokes traces obtained with the conventional scheme and with the distributed coding (after decoding), both measured by averaging 100k traces,
corresponding to the same ~30 s measurement time. By calculating the root-mean-square (rms) of both normalized traces, the experimentally achieved coding gain (equivalent to the SNR enhancement) was found to be ~5.8 dB, which is in good agreement with the expected theoretical value of 6 dB.

**Figure 4.24:**
Comparison of RDTS anti-Stokes single-pulse and 63-bit decoded traces.

It is worth mentioning here that the FBGs peaks in the distributed decoded traces do not affect the RDTS measurements and they can be successfully removed during FPGA-based processing. Figure 4.25 compares the experimentally achieved coding gain for both distributed as well as discrete measurements with its theoretical value as a function of the codeword length; good agreement can be noticed with a maximum measured coding gain of ~6 dB with a 63-bit codeword. Note that our proposed coding technique is providing simultaneously effective enhancement in the performance of both distributed and point-based sensing approach in terms of coding gain.

**Figure 4.25:**
Coding gain of interrogation function and RDTS against code length.
Figure 4.26:
FBG time-domain reflected pulses at different temperatures from SP2 (a) with single pulse (b) with 63-bit-Decoded trace. (c) Characterization of interrogation function against temperature.

To confirm the linear behavior of the used interrogation function we have first characterized the FBGs response around SP1 and SP2 in static condition by varying the temperature inside the TCC from 5 °C to 45 °C with 10°C incremental step; Figure 4.26(a) and 4.26(b) show the back reflected traces obtained from SP2 by using conventional single-pulse and 63-bit codeword. We can clearly see the significant reduction of noise by implementing coding as well as counteracting temperature effect on both FBGs. Since the reflectivity profile of L-FBG and R-FBG in each sensing point is symmetrically shifted w.r.t. central wavelength of laser, any temperature changes impact differently on the reflected power from L-FBG and R-FBG (i.e. reflectivity of L-FBG increases with temperature while decreases in R-FBG and vice versa). Figure 4.26(c) shows the measured interrogation function, confirming a highly linear behavior and significant noise reduction up to 6 dB with the same measurement time by using cyclic pulse coding.

The RDTS calibration procedure has been carried out to take into account all possible effects impacting on acquired anti-stokes and stokes coded traces, such as receiver gain, fiber Raman cross section, and wavelength-dependent local losses (at the unit
input/output or near fusion splices). In order to study the influence of the FBG-based sensing points on the decoded distributed temperature measurements, Raman-based temperature measurements were carried out by setting the TCC temperature at three different values: 5 °C, 25 °C, and 45 °C, respectively. Using the decoded Raman backscattered intensity trace, the distributed temperature profile has been obtained along ~21 km SMF.

**Figure 4.27:**
Experimentally measured RDTS temperature profile along 21.4 km SMF fiber.

Figure 4.27 reports the distributed temperature profile along the sensing fiber with ~40 m of SMF placed inside a TCC and heated up together with the FBG sensors. Note that the good accuracy of the temperature values obtained by the RDTS measurement confirms the effectiveness of the presented highly-integrated hybrid measurement technique, proving that FBGs are not impacting any detrimental effects on the RDTS measurement performance and vice versa. Temperature traces at different TCC values are clearly showing the temperature variations and the increased noise near the far fiber end. To fully demonstrate the robustness of our hybrid sensor system, excluding possible spurious effects of the FBGs on the RDTS performance, distributed temperature measurements at 25°C have been repeated under the same conditions using the same optical fiber spools without splicing the FBG-point sensors, fully demonstrating that FBG sensing points have no impact on the Raman temperature measurements.

The distributed temperature resolution, calculated as rms values of the normalized anti-Stokes to Stokes ratio, is reported in Figure 4.28 for both single pulse and coded RDTS. Note that the temperature resolution at ~21 km distance is improved from ~15.5 °C down to ~4.3 °C by using cycling pulse coding. Actually the performance of standard RDTS with SMF is affected by a very low achievable SNR, an issue that strongly impact on the final temperature resolution of the sensor as reported in Fig 4.28. We can clearly see that the coding provides a sensing distance enhancement of
~12 km, which is consistency with 6 dB coding gain (using 63 bits cyclic codes) and the loss of sensing fiber at 1450 nm.

![Graph showing comparison of RDTS temperature resolution along the SMF fiber.](image)

**Figure 4.28:**
Comparison of RDTS temperature resolution along the SMF fiber.

The spatial resolution along the sensing fiber can be computed, by observing the measured temperature profile versus distance corresponding to a near step-like temperature variation, such as at the output of the TCC. To evaluate the spatial resolution achieved in our experiment, the temperature of the ~40 meters of fiber (near 10 km distance) has been set to 5 °C and 45 °C respectively, while the rest of the fiber is kept at room temperature (25 °C). Figure 4.29 shows the measured temperature profile, where a spatial resolution of ~1 m can be observed (10% – 90% response distance to a temperature step).

![Graph showing temperature profile as a function of distance.](image)

**Figure 4.29:**
Temperature profile as a function of the distance, near the SP1, when TCC is set to 5 °C and 45 °C.

It is worth mentioning that the use of distributed coding in SMF allows for temperature resolutions similar to what is typically achieved over MMFs (using conventional RDTS); however, the attainable spatial resolution using SMFs is significantly better than over MMFs. Moreover, the proposed technique can enable
the use of already-installed SMFs (e.g., for telecommunication purposes) for high-spatial-resolution sensing over long ranges, without the need of installing new MMF cables. Note that the absence of intermodal dispersion in SMFs also potentially allows for long-range sensing with sub-meter spatial resolution, which is in practice impossible to achieve with conventional RDTS systems over MMFs.

![Figure 4.30](image)

**Figure 4.30:**
Dynamic strain measurements at 0.25 kHz. (a) Sinusoidal reconstruction with single-pulse. (b) Sinusoidal reconstruction with 63-bit code. (c) Normalized FFT of single pulse. (d) Normalized FFT with 63-bit code.

Regarding simultaneous dynamic strain measurements, we have finally investigated the benefit of cyclic pulse coding on the dynamic strain resolution improvement by applying a 250 Hz sinusoidal strain waveform (506 με peak-to-peak) to the PZT. It is worth noticing that the coding/decoding process, consisting in a simplex matrix to vector multiplication, can be performed in real time with negligible overhead-time, by exploiting for example a multi-core architecture. Figures 4.30(a) and 4.30(b) show the acquired sinusoidal time-domain dynamic strain reconstruction based on the described integration function by Eq. 4.4.1. We can clearly observe that single-pulse method provides a poor sinusoidal waveform reconstruction as compared to the cyclic pulse coding technique. Final reconstructed decoded dynamic strain traces show very good agreement with the known strain waveform applied to the PZT. The normalized fast Fourier transforms (FFT) of the measured traces are shown in Figure 4.30(c) and 4.30(d), pointing out that the fundamental component can only be clearly identified when using cyclic pulse coding. While the single-pulse measurement provides a poor dynamic strain resolution of ~292 ne/√Hz at ~20.2 km, the use of distributed cyclic coding improves the attainable resolution down to 77 ne/√Hz which is very consistent with the expected theoretical coding gain value.
Chapter 5

Novel Hybrid Brillouin/FBG Optical Fiber Sensors for Simultaneous Distributed and Discrete Measurements

Significant research has been devoted to develop a truly distributed optical fiber sensors based on spontaneous Brillouin scattering (SpBS). Literally these sensors have the potential to realize hundreds of thousands of measuring points on a single optical fiber cable providing distributed measurements of strain and temperature along every position. However due to the low intensity of the SpBS, optical fiber sensors based on Brillouin optical time-domain reflectometry (BOTDR) usually impose severe limitations to the ultimate performance of the sensing system. Consequently long range BOTDR sensors provide poor spatial resolution in the order of tens of meters, limiting the application requirements where meter- or centimetre-scale spatial resolution is needed.

During the last years, distributed optical fiber sensing based on stimulated Brillouin scattering (SBS) [79]-[90] has become an interesting alternative for high-performance temperature and strain sensing over tens of km providing meter-scale spatial resolution in many industrial applications. In particular, distributed sensing with meter and sub-meter scales spatial resolution along several tens of km has been demonstrated using the so-called Brillouin optical time-domain analysis (BOTDA) technique [91]-[92]. Such scheme based on SBS generally provides higher SNR values at the receiver and are consequently characterized by a higher attainable accuracy exploiting the amplification/depletion process of the Stokes/anti-Stokes signals [93]. This feature provides the possibilities to reach long range sensing distances achieving high spatial resolution with respect to BOTDR based system. However BOTDA system configuration requires the access to both fiber ends that involves more complex implementation for an accurate parameter estimation while SpBS-based scheme although characterized by lower sensing performance, require access to only one fiber end leading to a simpler implementation [94].

In this chapter the basics of BOTDA technique and integrated hybrid BOTDA/FBG sensing scheme are explained. First we present the fundamental dependence of Brillouin frequency shift on temperature and strain changes then the detailed BOTDA system working principle and performance parameters are discussed. In the last
section, the latest research and developments in integrated hybrid distributed/discrete sensors based on time-domain is presented. Finally, the use of advanced optical pulse coding technique for hybrid BOTDA/FBG sensing system is proposed for future work to obtain significant improvements in sensing performance in terms of long-range distributed sensing with sub-meter scale spatial resolution, enhanced dynamic strain resolution and improved FBGs multiplexing capability.

5.1 BOTDA Sensing Principle

5.1.1 Brillouin Scattering Fundamentals

Brillouin scattering originates from an interaction between the propagating optical pump signal and thermally excited acoustic waves in the gigahertz range present in the silica fiber, leading to frequency-shifted components [95]. The optical wave is scattered by a propagating periodic variation of the density of the medium, giving rise to the frequency shifted Stokes and anti-Stokes components. The scattered beam optical frequency experiences a Doppler shift known as Brillouin Frequency Shift (BFS) $v_B$ associated to the acoustic waves velocity in the fiber and is given by:

$$v_B = \frac{2nV_a}{\lambda}$$  \hspace{1cm} (5.1.1)

where $n$ is the refractive index of the fiber, $V_a$ is the acoustic wave velocity within the fiber and $\lambda$ is the pump signal wavelength of the incident lightwave.

This process can become SBS in the presence of an externally applied counter propagating probe wave with an optical frequency shifted from that of the optical pump signal by the BFS. In this case, the two counter propagation waves interfere generating an optical beat signal with minimal and maximal intensity of light. By electrostriction the density in regions of high and low optical intensity will change and leads to a moving density grating resulting also in a moving refractive index grating. The incident pump wave is now scattered by the refractive index grating, generating a scattered Stokes/anti-Stokes waves downshifted/ upshifted by the BFS, reinforcing also the imposed counter propagating probe and the acoustic wave.

In terms of spectral response this interaction is characterized by the Brillouin gain coefficient, which has a Lorentzian dependence profile [96] given by:

$$g_B(v) = g_0 \frac{\left(\frac{\Delta v_B}{2}\right)^2}{(\Delta v)^2 + \left(\frac{\Delta v_B}{2}\right)^2}$$  \hspace{1cm} (5.1.2)
where $\Delta v_B$ is the full-width at half maximum (FWHM), $g_B$ is the peak gain coefficient, $g_0$ is the linear gain coefficient and $\Delta v$ is the detuning from the center of the Brillouin resonance and $\Delta v_B$ the Brillouin linewidth.

An optical pump signal injected in an optical fiber generates a Lorentzian shaped Brillouin gain/loss spectrum for counter propagating optical wave (probe wave). The BGS is centred at an optical frequency downshifted from that of the optical pump signal by the BFS. Simultaneously the Brillouin loss spectrum (BLS) is upshifted in optical frequency also by the BFS.

![Figure 5.1: Schematic diagram of energy transfer between the optical pump and the two modulation sidebands.](image)

The BGS is measured by sweeping the modulation frequency $v_m$ in the vicinity of the Brillouin frequency shift $v_B$ and by detecting the total intensity using a low frequency detection scheme. When the modulation frequency falls within the BGS, an interaction takes place between waves propagating in opposite directions. The lightwave at frequency $v_0 - v_m$, the first lower sideband, is amplified by the line at $v_0$ and is found to grow exponentially, provided that the intensity at $v_0$ is much larger and pump depletion can thus be neglected. On the contrary, the lightwave at frequency $v_0 + v_m$, the first upper sideband, amplifies the line at $v_0$. The sideband intensity being very low, the actual gain is very small and the intensity increase at $v_0$ can be fully neglected. This is called Brillouin loss and is schematically represented in Figure 5.1.

Since SBS originates from the interaction of pump and counter propagating probe wave, the efficiency of the effect is polarization dependent. This particular aspect of SBS in fibers has been observed by several authors and a polarization averaging technique has been proposed in order to reduce contrast fluctuations due to polarization change in distributed Brillouin gain based sensors [95].
5.1.2 Brillouin Frequency Shift with Strain and Temperature

![Image of Brillouin Frequency Shift with Strain and Temperature](image)

**Figure 5.2:**
Typical BGS of a SMF fiber showing temperature effects on the central frequency, the linewidth and the peak gain.

The BGS contains important information, such as Brillouin frequency shift (BFS), the Brillouin linewidth, and the linear gain coefficient $g_0$, that all depends on environmental quantities. In this thesis we report the BGS parameters dependence on temperature and strain.

![Image of BFS as a function of temperature](image)

**Figure 5.3:**
BFS as a function of temperature.

Any temperature or mechanical stress would change the density of medium, and in consequence, both $n$ and $v_0$. The effect of temperature on the BGS is shown in Figure 5.2, where we can see a linear dependence of the BFS on the temperature. The temperature variation relates to the Brillouin frequency is expressed by[92]:

$$v_B(T) = v_B(T_r)[1 + C_T(T - T_r)]$$  \hspace{1cm} (5.1.3)
where $T$ is the temperature and $T_r$ is the reference temperature. A typical value for the temperature coefficient $C_T$ is $1.05$ MHz/°C [92]. Another interesting feature can be noted by Figure 5.3 is the decrease of the Brillouin linewidth with temperature and as a consequence the maximum gain increases with temperature. When temperature remains constant, the BFS $v_B(\varepsilon)$ relates to applied strain as [92]:

$$v_B(\varepsilon) = v_B(0)[1 + C_\varepsilon \varepsilon]$$  \hspace{1cm} (5.1.4)

where $v_B(0)$ is the unstrained Brillouin frequency shift and $C_\varepsilon$ is the strain proportionality coefficient. A typical value for $C_\varepsilon$ is $0.0550$ MHz/με.

**Figure 5.4:**
Typical BGS of a SMF fiber showing the effects of applied strain on the central frequency, the linewidth and the peak gain.

**Figure 5.5:**
BFS as a function of applied strain.

As expressed in Eq. 5.1.1, the acoustic velocity $V_a$ in silica fiber is strain dependent, therefore the BGS central frequency is expected to vary when strain is applied. Figure 5.4 shows the effects of applied strain on the BGS, the linewidth and the peak gain. It
has been experimentally demonstrated that that the BFS changes close to 600 MHz per percent elongation at 1.32 μm, which is reported in Figure 5.5 [92]. Figure 5.4 reports that the linewidth remains unchanged with strain, while the gain $g_0$ decreases for elongation.

### 5.1.3 BOTDA Measurement Sensor Configuration

The basic configuration of BOTDA system is shown in Fig 5.6. It requires two single frequency lasers; one emitting a pulsed pump light and the other emitting a continuous wave (CW) probe light. The fundamental idea is to mimic OTDR systems by using a pump pulse counter propagating with CW probe wave. The pulsed light is launched at $z = 0$ and propagates in $+z$ direction, while CW light is launched at the opposite fiber end at $z = L$ and propagates in the $-z$ direction. There are two schemes to realize a BOTDA, including Brillouin gain [93] and Brillouin loss [93]. The optical pulse propagates along the fiber and at each location imparts Brillouin gain/loss to the probe. This position-dependent gain/loss is measured by a classical time-of-flight method detecting the received probe signal in the time domain. If the probe wave is at the Stokes frequency, then energy flows from the pump to the Stokes wave providing Brillouin gain to this CW wave. If the probe wave instead takes the anti-Stokes frequency, it then gives energy to the pump wave and the detected CW signal experiences a Brillouin loss.

![Figure 5.6: Typical sensing configuration of BOTDA using two lasers.](image)

In Brillouin gain scheme, the pump pulse generates backward Brillouin gain in a single-mode fiber. The center frequency in the Brillouin gain bandwidth is downshifted from the pump frequency to the Stokes frequency. When the CW light frequency is equal to the Stokes frequency, the CW light is amplified through Brillouin interaction with the pump pulse. The amplified CW light is passed through an optical circulator and an optical frequency filter, and is detected by time-resolved measurement. Since the Brillouin frequency depends on the temperature and strain, variations at specific location in the fiber of these parameters lead to change in the Brillouin amplification of the probe at that position. The Brillouin gain spectrum can
be obtained by sweeping the frequency of the probe wave and measuring the intensity variation at the receiver end.

In Brillouin loss configuration the CW probe light acts as a pump of the SBS process and requires a frequency higher than the one of the pulsed light. So that the power transfer occurs from the continuous wave to the pulsed signal, resulting in a Brillouin loss process.

The disadvantage of BOTDA is that it requires lasers to be placed at both ends of the fiber being tested and that these lasers should have a fixed frequency relationship to each other. Any jitter in the frequency separation of the lasers will result in a variation in the gain experienced by the signal and will degrade SNR property. However BOTDA sensor system provides superior range performance with improved accuracy..... An efficient way to stabilize the frequency difference in BOTDA was proposed [92] using a microwave generator and a $LiNbO_3$ Electro-Optic Modulator (EOM) to generate pump and probe signals from a single light source. The EOM modulates the laser light at a frequency near the Brillouin frequency shift to generate a probe wave. The same EOM also produces a pump pulse by applying an electrical pulse on the EOM electrodes. They formed both pump and probe signals into pulse shape. This technique actually offers significant advantages with respect to the use of two independent lasers, since in this case there is no dependence on the laser frequency drift and no need of a tuneable laser source [92].

5.1.4 BOTDA Sensing System Performance Definition

1. Brillouin frequency resolution

The Brillouin frequency resolution is defined as the smallest Brillouin frequency that can be resolved at a given location along the fiber. It is directly related to the noise of the measurement. Once the fiber sensor is calibrated, it is always possible to display the measurement resolution in terms of strain or temperature [96]. A relation that accounts for the measurement dependence to noise and Brillouin spectrum characteristics is given by:

$$
\delta \nu_B = \frac{\Delta \nu_B}{\sqrt{2SNR}} \quad (5.1.5)
$$

As it is clearly appears in Eq. 5.1.5, Brillouin frequency resolution not only depends on the signal level but also on the BGS width $\Delta \nu_B$. Common distributed Brillouin sensors are then limited in frequency resolution when the pulse spectrum is larger or equal to $\Delta \nu_B$ which is in the case when pulse width is shortened to achieve better spatial resolution. As a result, BOTDA sensors configuration keeps a clearly trade-off between spatial and frequency resolution [96].
2. Spatial resolution

The spatial resolution is the ability of the BOTDA sensor to resolve two adjacent sections of distinct Brillouin frequencies, induced by either strain or temperature. This parameter is defined by the length over which the interaction between pump and probe waves occurs. In other words the spatial resolution is determined by the fiber length covered by the pulse width and it is defined as \( \nu_g \Delta \tau \) where \( \nu_g \) is the pulse group velocity in the optical fiber sensor and \( \Delta \tau \) is the pulse width. The spatial resolution is then expressed as:

\[
w = \frac{\nu_g \Delta \tau}{2}
\]

The factor \( \frac{1}{2} \) comes from the backscattered nature of the detected signal. It accounts for the round trip of the signal in the fiber [96]. Since in silica fiber the group velocity is \( \nu_g = 2 \times 10^8 \) m/s the rule of thumb that 10 ns corresponds to 1 m spatial resolution. Based on this definition, a given temperature/strain that spreads uniformly over a distance greater than the spatial resolution is measured with the lowest measurement uncertainty. If the local temperature/strain change occurs in a distance scale smaller than the preset spatial resolution, it might still be detected but the change will not be measured with the lowest uncertainty.

3. Dynamic range

The dynamic range (DR) expressed in dB is defined as the difference between the maximum input power to the photo-detector and the smallest optical power level that can be detected. The dynamic range is then a function of the power launched into the fiber, the Brillouin interaction, the loss of the components and the receiver characteristics [96], it can be expressed as:

\[
DR = \frac{1}{2} \left( P_{\text{max}} - |G_p| - \alpha_{\text{comp}} - \frac{1}{2} SNR_{\text{req}} + \frac{1}{2} SNR_{\text{imp}} \right)
\]

where \( P_{\text{max}} \) is the maximum fiber input power, \( G_p \) is the Brillouin loss, \( \alpha_{\text{comp}} \) is the loss of any component located along the fiber, \( SNR_{\text{req}} \) is the signal-to-noise ratio required to achieve a target frequency resolution (Eq. 5.1.5), and \( SNR_{\text{imp}} \) is the signal-to-noise ratio improvement obtained by electrical signal processing (averaging, electrical amplifiers).

Various causes limits the maximum fiber input power i) \( P_{\text{max}} \) must be lower than the threshold value of nonlinear effects which is governed by the modulation instability [96]; ii) \( P_{\text{max}} \) has to be lower than the maximum power that the receiver can handle; iii) \( P_{\text{max}} \) is determined by the available power at the laser output. The factor \( \frac{1}{2} \) in front of the bracket is introduced to account for the fact that the signal suffers twice the loss as it propagates in both
directions before being measured [96]. The others $\frac{1}{2}$ factors account for the fact that these SNRs are expressed in electrical decibels.

### 5.1.5 BOTDA System Operation and Theoretical Model

In order to reconstruct the Brillouin gain/loss spectrum along the fiber, variations on the CW signal intensity, resulting from the Brillouin interaction with the pulsed beam, measured at the fiber input ($z = 0$) as the function of both time and frequency offset $\Delta \nu$ [82], [95], if we consider optical pulses longer than the phonon lifetime (~ 10 ns), the steady-state coupled intensity SBS equations can be used to describe the SBS pump-probe interaction along the optical fiber [82], [95]:

\[
\frac{d}{dz} I_p(z) = -g_B(z, \Delta \nu)I_p(z)I_{CW}(z) - \alpha I_p(z) \tag{5.1.8}
\]

\[
\frac{d}{dz} I_{CW}(z) = -g_B(z, \Delta \nu)I_p(z)I_{CW}(z) + \alpha I_{CP}(z) \tag{5.1.9}
\]

Where $I_p(z)$ and $I_{CW}(z)$ are the pump and CW light intensities, $\alpha$ is the fiber attenuation, and $g_B(z, \Delta \nu)$ is the Brillouin gain spectrum. When the gain factor $g_B(z, \Delta \nu)$ is considered positive, energy transfer from the pulse to the CW signal takes place at every fiber location, according to the local BGS, referring to Brillouin gain configuration. Conversely, if the factor $g_B(z, \Delta \nu)$ is taken as a negative quantity, energy is transferred from the CW beam to the pulsed signal, resulting in depletion of the CW signal, i.e. Brillouin loss configuration. In order to obtain the variations of the CW signal as a result of SBS interaction in BOTDA sensors, a perturbation method can be used to solved the system of equations (5.1.8)-(5.1.9) [82], [95]. If we first suppose that the CW signal is only affected by the fiber attenuation, we can neglect the first right-side term of Eq. (5.1.9) leading to the following solution:

\[
I_{CW}(z) = I_{CW}(L) \exp[-\alpha (L - z)] \tag{5.1.10}
\]

where $I_{CW}(z)$ is the input power of the CW light and $L$ is the fiber length. Then the pulse intensity can be calculated substituting Eq. (5.1.10) to Eq. (5.1.8) resulting in [82]:

\[
I_p(z) = I_p(0) \exp(-\alpha z)G(z, \Delta \nu) \tag{5.1.11}
\]

where the factor $G(z, \Delta \nu)$ represents the depletion/amplification experienced by the pulsed beam due to Brillouin interaction with the CW light, which is given by:

\[
G(z, \Delta \nu) = \exp \left[ - \int_0^z g_B(\xi, \Delta \nu)I_{CW}(L) \exp[-\alpha(L - \xi)] \, d\xi \right] \tag{5.1.12}
\]

The Brillouin gain coefficient $g_B(z, \Delta \nu)$ depends at each fiber location $z$ on both the local Brillouin frequency shift $\nu_B(z)$ and the pump-probe frequency offset $\Delta \nu$, and has typical Lorentzian shape. However it is worth pointing out that the local Brillouin gain also depends on the status of the polarization of the two beams at each fiber.
position \( z \) [82], [95], so that the Brillouin gain may vary along the fiber even in the condition of a uniform BFS profile, according to [82]:

\[
g_B(z, \Delta \nu) = g_{B0} \frac{\gamma(z)(\Delta \nu_B/2)^2}{(v - v_B)^2 + (\Delta \nu_B/2)^2}
\]  
(5.1.13)

where \( \Delta \nu_B \) is the full-width at half maximum (FWHM) BGS linewidth, \( g_{B0} \) is the peak gain, and \( \gamma(z) \) is the polarization factor, which takes into account the dependence of the Brillouin gain on the polarization of the two optical beams [82].

Substituting Eqs. (5.1.11)-(5.1.12) into Eq. (5.1.9), we can then integrate over the distance \( \Delta z \), which represents the length of fiber over which both pulse and CW signal interact. The distance actually corresponds to the spatial resolution of the sensor and is given by half of the pulse length on the fiber. Consequently, we obtain [97]-[98]:

\[
\int_{I_{CW}(z)}^{I_{CW}(z+\Delta z)} \frac{dI_{CW}(\xi, \Delta \nu)}{I_{CW}(\xi, \Delta \nu)} = \int_{z}^{z+\Delta z} \left[-g_B(\xi, \Delta \nu)I_p(\xi, \Delta \nu) + \alpha\right] d\xi
\]  
(5.1.14)

So that,

\[
\frac{I_{CW}(z+\Delta z, \Delta \nu)}{I_{CW}(z, \Delta \nu)} = \exp \left(\int_{z}^{z+\Delta z} \left[-g_B(\xi, \Delta \nu)I_p(\xi, \Delta \nu)\right] d\xi\right) \exp(\alpha \Delta z)
\]  
(5.1.15)

Thus, the use of Eqs. (5.1.11) - (5.1.15) allows one to estimate the CW light intensity (affected by SBS interaction) received at \( z = 0, \Delta I_{CW} (z = 0, t, \Delta \nu) \). In order to obtain the information of the distributed BGS along the fiber, such a signal has to be compared with the CW light intensity in the absence of Brillouin interaction, according to:

\[
\Delta I_{CW}(t, \Delta \nu) = |I_{CW}(z = 0, t, \Delta \nu) - I_{CW}(L) \exp(-\alpha L)|
\]  
(5.1.16)

Hence, the intensity contrast of the CW signal received at \( z = 0, \Delta I_{CW} (t, \Delta \nu) \), as a function of both the time \( t \) and the pump-probe frequency offset \( \Delta \nu \), can be expressed as:

\[
\Delta I_{CW}(t, \Delta \nu) = I_{CW}(L) \exp(-\alpha L)
\times \left\{ \exp \left[ -\int_{z}^{z+\Delta z} \frac{I_p(\xi, \Delta \nu)g_B(\xi, \Delta \nu) d\xi}{\frac{\nu_B}{2} + \Delta \nu} \right] - 1 \right\}
\]  
(5.1.17)

where \( 0 < t < 2 (L - \Delta z) / v_g \) [82].

It is important to point out that when the gain factor \( G(z, \Delta \nu) \), defined by Eq. (5.1.12), is nearly equal to 1 for any pump-probe frequency offset \( \Delta \nu \) and any position \( z \), the amplification/depletion induced by the CW beam on the pulse intensity is negligible, so that the changes in the pulse intensity are mainly due to the fiber attenuation. In
such a case (i.e. when $G = 1$) the energy transfer is indeed small, so that Eq. (5.1.16) can be linearized, leading to:

$$
\Delta I_{CW}(t, \Delta \nu) \propto \int_{\frac{t v_g}{2}}^{\frac{t v_g + \Delta z}{2}} g_B(\xi, \Delta \nu) I_P(\xi, \Delta \nu) d\xi
$$

(5.1.18)

Under this condition, the intensity of the pulsed signal depends only on the fiber position $z = t v_g / 2$. Therefore the Brillouin gain spectrum can be reconstructed directly from measurements of the CW intensity contrast $\Delta I_{CW}(2z/v_g, \Delta \nu)$, which actually exhibits the same spectral shape than the Brillouin gain coefficient $g_B(z, \Delta \nu)$ at the respective fiber location, i.e. a Lorentzian shape with its center located at the local BFS $v_B(z)$ [82]. This feature allows for the reconstruction of the BGS as a function of the distance measuring a set of BOTDA traces (i.e. the intensity contrast of the CW signal) at different frequency offset $\Delta \nu$.

### 5.2 First Demonstration of Hybrid BOTDA/FBG Sensor

BOTDA permits distributed temperature and strain measurement over long distances of single mode fiber (SMF). This feature is due to the high SNR of BOTDA technique, so that BOTDA based sensors look more attractive when large structures are to be monitored. However, temperature/strain measurement over longer distances require much more care, as the simple assumption of linear relationship between the local Brillouin gain coefficient and the local Brillouin signal is not valid anymore. In fact, the distributed nature of the interaction between the pump and the probe signal leads to a non local effects that distorts the Brillouin gain spectra measured at the farthest section of the fiber (the distance is intended with respect to the pulse launching section). As a main consequence the Brillouin frequency shift measurements may be affected by systematic errors which increase along the sensing length.

Even though the sensing capabilities provided by BOTDA systems are very attractive in many applications, the relatively long measurement time (of the order of a few minutes) makes this technology mainly suitable for static measurements, limiting its potential range of applications. Unfortunately, in normal conditions the level of Brillouin amplification is very low, and many traces have to be time-averaged to reduce the impact of Gaussian, zero-mean noise. This leads to a slow measurement process, which is typically of the order of a few minutes, limiting the system capabilities to static sensing only. For many fields, such as for industrial plant monitoring, the distributed information provided by BOTDA sensing is crucial for static strain and temperature monitoring, however, dynamic strain measurements at specific critical points would be also required for simultaneous structural health monitoring. Thus, a system with combined sensing capabilities could be of great interest in such a case.
In this section, we implement, for the first time to the best of our knowledge the use of a highly-integrated hybrid sensing system that effectively combines the advantages of both standard BOTDA and in-line time-division-multiplexed (TDM) FBG-based sensing, allowing for simultaneous dynamic punctual strain measurements and distributed (static) strain/temperature sensing using a single optical fiber, a common pulsed narrowband optical source and a shared receiver unit. The impact of FBG reflections on the measured BGS is also analyzed.

Besides methods based on FBG spectral analysis (using tunable lasers or broadband sources), a common intensity-based method for FBG interrogation uses a narrowband laser centered in the slope of the FBG reflection spectrum (see section 4.3.3), offering high integration with BOTDA. Typically a couple of FBGs is required to account for spurious losses and laser power variations (two FBGs could allow for strain-temperature discrimination). In our proof-of-principle experiment, we employed one FBG only, since the integration capabilities and/or interference effects with BOTDA are essentially unchanged with one or more FBGs, as discussed below.

5.2.1 Experimental Setup

Figure 5.7 shows the proposed integrated hybrid BOTDA/FBG sensor. The light from an external cavity laser (ECL, 0 dBm output power at 1550 nm) is split into two branches using a 3 dB splitter. One of the branches is employed to generate a pulsed signal which is used as Brillouin pump as well as to interrogate in time-domain the sensing FBG (S-FBG) placed in-line along the sensing fiber. A polarization controller (PC) and a Mach-Zehnder modulator (MZM1), driven by a pulse generator, are used to intensity-modulate the CW light with 10 ns pulses (to attain 1 m spatial resolution) at a repetition rate of 5 kHz. An Erbium-doped fiber amplifier (EDFA1) is used to obtain 20 dBm peak pulse power at the fiber input.

![Figure 5.7: Experimental configuration of hybrid BOTDA/FBG sensor using single lasers.](image-url)
In the other side, the CW light from the laser is amplified by EDFA2 and then modulated by a microwave signal using another modulator (MZM2, preceded by a PC) in order to generate a two-sideband probe signal. A polarization scrambler (PS) is used to depolarize the probe signal and to avoid polarization-induced fluctuations in the Brillouin gain. A narrow optical band-pass filter (OBPF, <100 pm band) is then used to select only the low-frequency probe sideband (Stokes frequency), thus filtering out ASE noise, the residual suppressed carrier and the high-frequency probe sideband (anti-Stokes component).

Pulses are sent into a 20 km standard SMF through an optical circulator which is also used to extract the probe signal (used in BOTDA sensing) and the pump Rayleigh back-reflected component (for FBG interrogation), which are then sent into two parallel receivers.

A Gaussian apodized S-FBG (2.5 nm bandwidth and 1% peak reflectivity) has been spliced at ~9.9 km distance along the sensing fiber, and glued to a piezoelectric (PZT) actuation stage for dynamic strain sensing assessment. The S-FBG, including the PZT-stage, and ~12 m of fiber have been placed inside a temperature-controlled chamber (TCC) in order to induce temperature changes to both the S-FBG and a few meters of fiber thus assessing both discrete and distributed sensing capabilities. Note that 3 m of fiber, connecting the S-FBG and the fiber spool inside the TCC, have been placed outside the chamber in order to evaluate the distributed sensing accuracy of our hybrid scheme in proximity of an S-FBG reflection.

At the receiver stage, an optical circulator and a narrowband FBG (6 GHz reflection band, centered at the Stokes frequency component) are used to couple the probe signal into a 125 MHz PIN photo-receiver (PIN1) for BGS measurements. At the transmittance port of the FBG another 125 MHz PIN photo-receiver (PIN2) has been used to simultaneously measure the S-FBG reflected light.

It is worth mentioning that the use of OBPF at the transmitter stage avoids CW light components (such as ASE noise and anti-Stokes light) to reach the photo-receiver PIN2, this being a key requirement to ensure a high dynamic range of S-FBG measurements and to reduce optical noise at the receiver stage.

### 5.2.2 Validation of Simultaneous Distributed-Static and Discrete-Dynamic Measurements

The S-FBG response has been first characterized as a function of the temperature, setting the TCC at different values and measuring the time-domain traces of the back-reflected light form S-FBG, as shown in Figure 5.8(a). For a proper S-FBG characterization, 1000 traces have been averaged at each TCC temperature, and then the back-reflected pulse has been integrated in time-domain to further reduce the noise impact. Figure 5.8(b) shows the measured pulse energy from S-FBG back-reflections (squares) versus temperature; a highly linear S-FBG behavior can be
observed (the solid line in the figure is the linear fitting). Note that, since the wavelength of the ECL has been centered in the positive slope of the S-FBG Gaussian spectrum, any increase in the FBG temperature (shifting its spectrum towards longer wavelengths) reduce the reflected light at the laser wavelength, leading to the negative slope reported in Figure 5.8(b).

**Figure 5.8:**
S-FBG back-reflected pulses at different temperatures. (a) Time-domain traces at around S-FBG location. (b) Measured S-FBG back-reflected pulses energy versus temperature (squares) and linear fitting (solid line).

The temperature of both the S-FBG and the 12 m fiber spool has then been measured using simultaneous time-domain FBG interrogation and BOTDA schemes, for several temperature values by setting the TCC at 5°C, 25°C, and 45°C. Figure 5.9 shows the measured BGS versus distance along the sensing fiber when the TCC is set at room temperature (25°C). It is worth mentioning that the S-FBG placed at ~9.9 km distance not only reflects the pulsed signal (which is used for FBG interrogation), but also reflects the probe signal into the forward direction (see Figure 5.7 scheme) possibly interfering with the measurements.
Figure 5.9:
Measured BGS vs distance along 20 km-long SMF.

However, we verified that the low S-FBG reflectivity (< 1%) and the phase mismatching conditions for SBS (consider that the reflected components co-propagate with the incoming signals) lead to negligible distortions in the BGS. This is actually confirmed by the BGS measurements shown in Figure 5.10, reporting the BGS acquisitions (and the respective Lorentzian fitted curve) immediately before and after the S-FBG location at two different FBG temperatures.

Figure 5.10:
Measured BGS (squares) and Lorentzian fitting (solid line) at different fiber locations and FBG conditions. (a) BGS at 9.8 km, FBG at 5°C. (b) BGS at 10.0 km, FBG at 5°C. (c) BGS at 9.8 km, FBG at 45°C. (d) BGS at 10.0 km, FBG at 45°C.

In particular, Figure 5.10(a)-(b) show the normalized BGS at 9.8 km and 10.0 km distance when the S-FBG (placed at ~9.9 km) is at 5°C, while Figure 5.10(c)-(d) show the normalized BGS at the same locations but with the S-FBG at 45°C. We can appreciate that the measured BGS and the respective fitted curve are similar in all four cases, indicating that the S-FBG back-reflected light (which varies considerably with temperature) has a negligible impact on the measured BGS. The use of a larger
number of S-FBGs is also expected to have a negligible impact, due to even lower amplitude of possible multiple reflections with low-reflectivity FBGs.

![Figure 5.11](image)

**Figure 5.11:**
Distributed temperature profile at around 9.9 km distance, under different TCC temperature settings.

![Figure 5.12](image)

**Figure 5.12:**
Dynamic strain measurements at 0.2 kHz. (a) Time-domain trace. (b) Normalized fast Fourier transform.

The distributed BFS has then been estimated along the sensing fiber, for the three different temperatures applied to the TCC, while keeping the rest of the fiber at room temperature; the corresponding temperature profiles are shown in Figure 5.11 for a fiber region in proximity of 9.9 km distance, i.e. near the S-FBG. As it can be seen from Figure 5.11, no extended distortion in distributed temperature measurements is induced by the presence of the in-band S-FBG in our hybrid sensing scheme. The BFS resolution has been estimated to be 2 MHz at 20 km distance (far fiber end), corresponding to a temperature and strain resolution of 2°C and 40με respectively.

It is important to point out that BOTDA-based temperature measurements in proximity of the S-FBG location can be effectively used to provide S-FBG calibration and to finally attain temperature-independent dynamic strain estimation with single S-FBG (overcoming the well-known temperature strain cross-sensitivity). Moreover, the effects of spurious losses on the S-FBG interrogation can be effectively eliminated introducing a reference FBG with a small frequency-shift from the S-FBG and
implementing a balanced interrogation function. In Figure 5.11 we can then notice the ability of the proposed scheme to properly measure the \(~3\) m of fiber (at room temperature) placed between the S-FBG and the fiber inside the TCC.

Finally, dynamic strain measurements have been carried out by applying a sinusoidal strain waveform (120 με peak-to-peak) to the PZT. The waveform frequency and the TCC temperature have been changed to evaluate the dynamic sensing capabilities of the system under different conditions. Figure 5.12 shows a dynamic strain acquisition at 25°C and 0.2 kHz. In particular, Figure 5.12(a) illustrates the acquired time-domain dynamic strain trace, which is in good agreement with the (known) applied strain waveform. The normalized fast Fourier transform (FFT) of the measured trace is shown in Figure 5.12(b); as we can see, the fundamental component is easily identified among other spurious spectral components with much lower power. Similar traces were obtained at different TCC temperatures and frequencies. The dynamic strain resolution was estimated to be \(7.8 \, \text{nε}/(\text{Hz})^{1/2}\) at 0.2 kHz.

We have successfully implemented a hybrid BOTDA/FBG sensor system using a highly integrated interrogation unit (sharing the narrowband source, the sensing fiber and the receiver stage). Experimental results show a distributed temperature (strain) resolution of 2°C (40 με) throughout 20 km fiber length, and a discrete FBG dynamic strain resolution of \(7.8 \, \text{nε}/(\text{Hz})^{1/2}\) at 0.2 kHz, enabling the use of this technique in many applications where distributed static and discrete dynamic measurements are simultaneously required.

### 5.3 Highly Integrated BOTDA/FBG Sensor System

In this section, we demonstrate a highly integrated optical fiber sensor, for simultaneous discrete dynamic strain and distributed strain/temperature static measurements, by combining BOTDA and time-division-multiplexed FBG interrogation. High integration is achieved by using a single laser source, one shared receiver block and broadband, low reflectivity FBGs.

The typical measurement time of the BOTDA technique, in the order of few minutes, makes this technology mainly suitable for static measurements, limiting its potential range of applications. Although the distributed information provided by BOTDA sensing is essential for static strain and temperature monitoring, there are several applications, such as for example in industrial Oil and Gas production plants monitoring, which also require dynamic strain measurements at specific critical points, adding in this way crucial information on the structure integrity (e.g. vibrations). For this aim, several techniques have been recently proposed to attempt distributed dynamic strain measurement exploiting Brillouin scattering. However, the achieved performances are not fully satisfactory. While in reference dynamic sensing at a randomly addressed position is achieved, losing the capability of any distributed measurement, in distributed dynamic measurement is achieved with limited bandwidth and sensing range. In several applications a dynamic strain measurement is
only really needed at some critical points, opening the way to hybrid sensors in which distributed static and point dynamic measurements are simultaneously performed. For example, distributed sensing based on either SpBS or SBS has been recently combined with point based Fiber Bragg Grating (FBG) sensors. In particular, BOTDA technique has been combined with wavelength-division-multiplexed FBG point sensors, using different demodulation techniques for distributed and discrete sensing, as well as distributed Raman amplification, increasing cost and complexity of the whole sensor system [99]-[100]. We propose a highly integrated hybrid optical fiber sensor for simultaneous dynamic FBG interrogation and distributed static strain/temperature measurements. The technique effectively combines standard Brillouin optical time-domain analysis with a robust and reliable time-division multiplexed FBG interrogation scheme, which employs a couple of broadband low reflectivity fiber Bragg gratings in each sensing point.

In BOTDA systems, a pulsed pump and a counter-propagating continuous-wave (CW) probe light interact with acoustic phonons generated into the sensing fiber by SBS. The maximum energy transfer from the pump to the probe (i.e. Brillouin amplification) takes place at every fiber location whenever the frequency separation among the optical waves equals the local acoustic frequency in the fiber, the so-called Brillouin frequency shift (BFS), which is a temperature- and strain-dependent parameter. By sweeping the pump-probe frequency difference, the Brillouin Gain Spectrum (BGS) can be reconstructed and the BFS can be estimated, providing information about the temperature and strain variations along the whole sensing fiber. Unfortunately, the BGS reconstruction technique requires typical acquisition times of the order of a few minutes, limiting then the application of the standard BOTDA technique to static temperature/strain sensing only. When dynamic strain measurements in specific critical points are required in addition to the distributed static temperature/strain measurement along the whole sensing fiber, more complex techniques are required. A typical example consists in fire detection and vibrations measurement in large civil and industrial structures.

The basic operating principle of the FBG interrogation technique exploited in this work, for a dynamic strain estimation and compatible with simultaneous BOTDA measurements is illustrated in Figure4.5 (see section 4.3.3); the technique employs a single pulsed narrowband pump laser and a pair of Gaussian apodized FBGs with low reflectivity and broadband spectrum at each sensing point.

5.3.1 Experimental Configuration and Validation of Results

The schematic setup of the proposed hybrid BOTDA-FBG sensor is shown in Figure 5.13. In this scheme, the light provided by an external cavity laser (ECL, 0 dBm output power at 1549.8 nm) is split into two branches using a 3dB splitter. One of the branches is employed to generate a pulsed signal which is used as Brillouin pump as well as to interrogate the FBGs-based discrete sensing points placed in cascade along the sensing fiber.
Figure 5.13:
Hybrid BOTDA/FBG experimental setup using two discrete sensing points.

A polarization controller (PC) and a Mach-Zehnder modulator (MZM₁), driven by a pulse generator, are used to modulate the intensity of CW light with 10 ns pulses (providing ~1 m spatial resolution) at a repetition rate of 5 kHz. An Erbium-Doped fiber amplifier (EDFA₁) is used to obtain a peak pulse power of 20 dBm at the fiber input. In the other branch, the CW light from the ECL is amplified by EDFA₂ and then modulated through a second Mach-Zehnder modulator (MZM₂) with a microwave signal in order to generate a two-sideband probe signal (suppressed carrier). A polarization scrambler (PS) is used to depolarize the probe signal and to avoid polarization-induced fluctuations in the Brillouin gain. A narrow optical band-pass filter (OBPF, bandwidth < 100 pm) is used to select the low-frequency probe sideband only (Stokes frequency), thus filtering out ASE noise, the residual suppressed carrier and the high-frequency probe sideband (anti-Stokes component). Light pulses are coupled into a ~20 km standard SMF through an optical circulator which is also used to extract both the probe signal (used in BOTDA sensing) and the back-reflected component at the pump frequency (used for FBGs interrogation). Both light components are impacting onto a shared receiver stage, composed of an optical circulator and a narrowband FBG which (6 GHz bandwidth), which couples the probe and the back-reflected pump light components onto different ports of a single multi-channel photoreceiver (employing PIN photodiodes, 125 MHz analog bandwidth).
Figure 5.14:  
(a) Reflected pulse intensity from both FBGs at different strain and TCC temperatures, and (b) characterization of the interrogation function against applied strain and temperature.

A pair of in-line FBG-based sensing points have been placed at ~10 km and ~19 km distances along the sensing fiber, both pairs within a temperature controlled chamber (TCC); each sensing point consist of a pair of spatially close Gaussian-apodized FBGs (~2 m separation, 2.5 nm bandwidth, 1% peak reflectivity), which are centered at two different wavelengths (L-FBG at 1548.65 nm and R-FBG at 1550.85 nm). The FBG pair at 19 km sensing point has been glued to a piezoelectric actuation stage for dynamic strain sensing assessment; the FBG-response of this sensing point, located near fiber end, has been first statically characterized as a function of strain and temperature, setting the PZT actuation stage and TCC at different values and measuring the time-domain traces of the back-reflected lights from both FBGs; these are shown in Figure 5.14(a). For a proper FBG characterization, 1000 traces have been averaged at each TCC temperature and strain value, and the interrogation function has then been calculated. Figure 5.14(b) shows the observed behavior (highly linear as expected by theory) of the interrogation function versus temperature and strain comparing linear fitting (solid line) with experimental data (dotted line). The same behavior was observed in the FBG pair at 10 km.
Figure 5.15:
BGS as function of the distance.

Figure 5.16:
Temperature profile as a function of distance at the fiber end, measured with 5°C and 45°C temperature changes of the TCC.

In order to investigate the compatibility of simultaneous time-domain FBGs interrogation and BOTDA technique, the BGS along the fiber length (whole fiber placed at room temperature, 25 °C) has been reconstructed and is shown in Figure 5.15. We have verified that the BGS follows a uniform Lorentzian profile and that no distortion is present along the 20 km fiber length. Furthermore, we verified that the two sensing points placed at ~10 and ~19 km distances are not affecting the Brillouin measurement, thanks to the low FBGs reflectivities leading to negligible distortions in the BGS. In particular Figure 5.16 shows the measured temperature after the second FBG sensing point with 12 m of fiber at two different TCC temperatures 5°C and 45°C, clearly demonstrating the negligible impact of the FBGs back-reflected light (which strongly depends on temperature) on the measurement. Due to the very low reflectivity values, we expect that our BOTDA measurement technique will be compatible with a large number of discrete sensing points. The resolution in terms of BFS has been estimated by calculating the standard deviation of the measured BFS distribution along the fiber length, resulting to be 2.4 MHz near the fiber end (~20 km) and corresponding to a temperature and strain resolution of 2.4 °C and 48 με respectively.
Finally, dynamic strain measurements have been assessed by applying a sinusoidal strain waveform (350 µε peak-to-peak) through the PZT. It is worth mentioning that, although strain and temperature variations are mapped to the same interrogation function values, dynamic strain variations can be extracted using frequency-domain high-pass filtering thus removing the static component of the signal. Figure 5.17 shows an example of dynamic strain acquisition at 25 °C and 0.25 kHz. In particular, Figure 5.17(a) illustrates the measured dynamic strain trace, which is in good agreement with the (known) applied strain waveform; Figure 5.17(b) shows the normalized fast Fourier transform (FFT) of the measured trace from which we can see that the fundamental component is easily identified among other (smaller) spurious spectral components. The dynamic strain resolution was estimated to be 24.2 nε/(Hz)\(^{1/2}\) at 0.25 kHz.

Figure 5.17:
Dynamic strain measurements at 0.25 kHz. (a) Time-domain trace and (b) relative fast Fourier transform.
Conclusion

This thesis is intended to focus on the development of advanced dynamic interrogation techniques for In-fiber Bragg gratings integrated with Raman- and Brillouin-based distributed optical fiber sensors. Three distinct optical fiber sensors development have been carried out in this thesis work; the most successful sensor of the first category is the In-fiber Bragg gratings based on advanced cyclic codes for dynamic strain measurements, the rest category is optical fiber distributed sensors based on Raman and Brillouin scattering. Excellent progress has been achieved towards the understanding and implementation of highly integrated hybrid distributed-discrete optical fiber sensors. Moreover it has been expected that proposed novel techniques will advance further toward commercialization, providing considerable promise for optical fiber sensor development and application in the distinct future.

The thesis begins with an introduction and fundamental principles of the optical fiber sensors. Chapter 1 provided state-of-the-art overview of the emergence of the fiber optic technology and how it has evolved; also introduced the types of optical fiber sensors and the physical phenomenon associated with optical fiber used for sensing. Chapter 2 is devoted to explain the theory and mathematical ground of In-fiber Bragg gratings; also providing the detail of linear and non-linear scattering phenomenon in optical fiber. Special attention has been paid to temperature and strain sensors based on Raman and/or Brillouin scattering, for which several innovative techniques have been successfully applied to improve their performance.

In chapter 3, first the principles of several FBG interrogation techniques have be explained and then the use of advanced cyclic pulse coding technique in TDM-FBG-based sensors has been thoroughly discussed. Certainly, the complete FBG dynamic sensing interrogation technique remains inexpensive so long as it is based on high speed TDM; offers significant improved performance in terms of multiplexing capacity, immunity to fiber losses, temperature-dynamic strain discrimination using unique interrogation function and considerable enhancement in SNR. One of the unique features of the proposed interrogation technique for in-fiber gratings arrays is their quasi-distributed sensing capability, which means that multiple points can be sensed simultaneously by a single pulse shot, without scarifying sensor interrogation speed. This capability not only reduces the cost but also makes the sensor very compact. The mechanism of noise reduction by quasi-periodic cyclic coding is quantitatively demonstrated, pointing out significant improvement in dynamic strain resolution with respect to single pulse TDM-FBG-based interrogation. Experimental results point out significant improvements; while a single-pulse based measurement provides a poor dynamic strain resolution of ~1.40 με/√Hz at ~12.5 km, the use of distributed cyclic coding improves the attainable resolution down to 380 nε/√Hz,
without scarifying the FBG interrogation measurement speed. Furthermore experimental results well demonstrate that by employing longer codeword with our proposed technique it is possible to practically obtain the coding gain predicted by theoretical estimation.

In Chapter 4 we investigated novel techniques for hybrid Raman-FBG sensing approach. In particular section 4.3 successfully demonstrate a highly-integrated hybrid sensing system that effectively combines the advantages of both Raman-based distributed temperature sensor (RDTS) and TDM-FBG-based dynamic sensing, by fully exploiting their respective specific functionalities. The first proposed solution is based on two separate sensing fibers; one is a single mode fiber (SMF) for FBG-TDM-based sensing array whilst the second is multi mode graded-index fiber (MMF) for distributed temperature sensing. Experimental results show a temperature resolution better than 1 °C with 2.7 m spatial resolution at a 20 km distance as well as a dynamic strain resolution of 7.8 ne/(Hz)^1/2 at 0.2 kHz repetition rate (the Nyquist limit for a 20 km-long fiber is 2.5 kHz). Moreover in section 4.4 we have proposed for the first time, a novel hybrid fiber optic sensing technique that effectively combines RDTS and in-line FBG dynamic interrogation using a single common SMF sensing fiber for both point-wise and distributed measurements; the proposed solution is highly integrated and cost-effective. This new and novel highly integrated hybrid sensor employs broadband apodized low reflectivity FBGs with a single narrow band optical source (the same used for RDTS measurement) and a shared receiver block, allowing for simultaneous measurement of distributed static temperature and point-wise dynamic strain detection. The experiment results prove simultaneous distributed sensing capability with temperature resolution of 2 °C at 10.9 km and dynamic sensing with discrete FBG dynamic strain resolution of ~60 ne/(Hz)^1/2 at 250 Hz, enabling the use of such an efficient and effective hybrid technique. Finally section 4.5 experimentally demonstrate state-of-the-art very efficient hybrid sensing approach by using cyclic pulse coding to effectively improve the performance of hybrid RDTS/FBG-based fiber optic sensors, for simultaneous measurement of distributed static temperature and discrete dynamic strain over the same SMF sensing fiber. Effective noise reduction is achieved in both RDTS and dynamic interrogation TDM-FBG sensors, enhancing the sensing range-resolution and providing real-time point dynamic strain measurement capabilities. This very efficient integrated sensor scheme employs broadband apodized low reflectivity FBGs, a single narrowband optical source and a shared receiver block. We experimentally evaluate the receiver SNR improvement provided by pulse coding, verifying its capabilities to significantly enhance the sensing range, measurement time, FBG multiplexing capacity, as well as the distributed-static temperature/strain and dynamic strain resolution with respect to conventional RDTS/TDM-FBG-based sensors operating with single pulse at the same peak power level. Experimental results prove substantial achievement of 4.7 °C temperature resolution at ~21 km distance with a 1 m spatial resolution (instead 18 °C by using conventional RDTS), and a dynamic strain resolution of 77 ne/√Hz (instead of 308 ne/√Hz by using conventional TDM-FBG sensor) at the far fiber end.
Chapter 5 has explained the most important hybrid distributed/discrete optical fiber sensing methods we have investigated related to Brillouin time-domain analysis (BOTDA) and FBG. For the first time experimental demonstration of a novel hybrid BOTDA/FBG optical fiber sensor has been reported and demonstrated, pointing out its accurate and efficient performance. In particular, a highly integrated optical fiber sensor for simultaneous discrete-dynamic strain and distributed-static strain/temperature measurements is experimentally demonstrated by combining BOTDA and TDM-FBG sensor. High integration is achieved by using a single laser source, one shared receiver block and broadband, low reflectivity fiber Bragg gratings. Experimental results have shown a distributed temperature (strain) resolution of $2^\circ C$ (40 $\mu e$) throughout 20 km fiber length, and a discrete FBG dynamic strain resolution of $7.8$ $ne/(Hz)^{1/2}$ at 0.2 kHz, enabling the use of this technique in many applications where distributed static and discrete dynamic measurements are simultaneously required. Finally in the last section we have been experimentally demonstrated the combined use of serially multiplexed FBG arrays and BOTDA sensor over the same SMF fiber, using a highly-integrated interrogation unit. Experimental results have proved concurrent distributed sensing, with temperature (strain) resolution of $2.4$ $^\circ C$ (48 $\mu e$) throughout ~20 km fiber length, and dynamic sensing with discrete FBG dynamic strain resolution of $24.2$ $ne/\sqrt{Hz}$ at 0.25 kHz, enabling the use of such an effective hybrid technique in many applications where distributed static and discrete dynamic measurements are simultaneously required.
Bibliography


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