[INVITED] State of the art of Brillouin fiber-optic distributed sensing

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1. General Introduction

Following the immense impact they had on telecommunications, optical fibers have finally established their advantageous value also in the field of sensing. Almost all physical quantities of interest, such as strain, temperature, magnetic field, electric field, acoustic fields, rotation, humidity and many more (to be called from now on: measurands), can be sensed by their direct or indirect effect on the propagation of light in the fiber [1,2]. For example: When a section of a fiber is strained, either by tension or compression, its physical length is obviously changed and, in addition, the averaged refractive index along the section is affected as well. These changes have a direct impact on the phase of the optical wave propagating in the fiber, which can then be measured in order to quantify the applied strain. Strain also affects the speed of sound in the fiber, which is another characteristic of the fiber that can be interrogated by the Brillouin effect, see below. Through the Faraday effect, a magnetic field parallel to the fiber longitudinal axis will rotate the State Of Polarization (SOP) of light propagating in the fiber by an angle, which is proportional to the strength of the field, paving the way to electrical current sensors (where the induced magnetic field in a closed loop of optical fiber around a conductor is a measure of the carried electrical current). Bonding a magnetostrictive material to an optical fiber provides an indirect measure of the magnetic field, since light propagating in the fiber is not directly affected by the magnetic field itself but rather by the strain induced by the expanding/contracting magnetostrictive intermediary.

Optical fibers are outstanding candidates to serve as sensors due to their unique properties: (i) they can both sense and transmit the sensed information by the same waveguide; (ii) they offer a low-loss link and thus can be used for long range sensing; (iii) they are dielectric and as such are not affected by electromagnetic interference nor generating one; and finally, (ix) they are very thin (~0.1 mm) and low weight, easily embeddable in graphite-fiber based composites, as well as in printed structures, or, alternatively, bonded to the surface of almost any material.

A variety of linear and non-linear optical transduction mechanisms have been studied in the last 30–40 years, dealing with the conversion of all kinds of measurands to local measurable optical effects in the fiber. Many optical-intensity-based point sensors have been developed, including simple optrodes, where special materials are attached to the fiber tip to sense temperature, partial pressure of various gases and other relevant measurands. Also developed and commercialized are highly sensitive interferometric hydrophones, highly accurate current sensors and fiber-optic gyroscopes [3]. Multiplexing many point sensors on the same strand of fiber has always been a laudable goal, culminating in the successful deployments of very large and quite complex arrays of individual interferometric hydrophones and...
accelerometers for sonar and seismic oil exploration and utilization [1,2].

By far the most successful and widely used strain/temperature fiber-optic point sensor today is the fiber Bragg grating (FBG). It is rather easily made by exposing a few millimeters of standard single mode fiber to a periodic pattern of UV illumination (at ~244 nm), which inscribes a permanent refractive index grating along the fiber core. This grating of period \( \Lambda \) selectively reflects light, having a peak reflectivity at a wavelength of \( \lambda_B = 2n\Lambda \), where \( n \) is the local effective refractive index of the fiber. Strain and/or temperature will shift \( \lambda_B \) by \( \sim [1 \text{ picometer (pm)} \text{ of wavelength}] [\text{ [1 microstrain (\( \mu \text{e} \))]} \text{ and 10 pm/1} ^\circ \text{C (at} \lambda_B - 1550\text{nm in standard silica-based single mode fibers}] \). The sensitivity to strain mainly originates from the induced change in \( \lambda \), while temperature predominantly affects \( n \), with some dependence also on the fiber coating (e.g., standard acrylic vs. high-temperature-tolerant polyimide). Wavelength division technologies (wavelength selective receivers, or, alternatively tunable lasers, which scan the available optical bandwidth looking for the FBGs’ reflection peaks) make it simple to multiplex a few tens of FBGs with different \( \lambda_B \) ‘s along a strand of fiber, using currently available and quite affordable commercial interrogators. FBGs are highly reliable sensors, capable of handling a huge dynamic range of strain and/or temperature under both static and highly dynamic scenarios.

But FBGs must be imprinted on the fiber, significantly increasing its cost. Also, as mentioned above, most commercially available interrogators can handle only a fairly small number of FBGs, setting a limit on the number of sensing points, as well as on their density along the fiber. Still quite expensive, draw tower gratings (DTGs), comprising thousands of densely written FBGs, all of same inscribed- \( \lambda_B \) ‘s, have recently become commercially available. However they require special interrogators.

Security applications from border fences to the protection of oil and gas pipes against leaks and theft, as well as the need to monitor the health of structures, such as airplanes, train tracks, dams, bridges, buildings etc., can tremendously benefit from distributed sensing using standard fibers, where, without any special preparations, the whole length of the fiber serves as a sensor, assuming it is also possible to selectively read the measurand of interest at an arbitrary point along the fiber with a sufficient spatial resolution and sensitivity [4].

Currently available, as well as under-development distributed fiber-optic sensors provide amazing capabilities, unmatched by any other sensing mechanism. Embedded optical fibers, distributedly interrogating the local strain all along their length, can serve as the material/structure nerve system, and as such can tell the end user how the material/structure “feels” strain-wise. A crack, early detected by such a distributed sensor in a supporting concrete beam of a bridge, or the identification of a developing delamination in a critical composite-made part of an airplane, while in-flight, can save many human lives. Such systems may eventually lower the cost of ownership by moving from scheduled-based to condition-based maintenance and may also help in guaranteeing the airworthiness of unmanned piloted vehicles (UAVs) for civil licensing and other purposes. Recent applications of distributed strain sensing include 3D shape sensing and distributed acoustic sensing (DAS) [5–8]. Distributed temperature sensing using the Raman effect [9], has definitely come of age with many applications and affordable interrogators.

The vast majority of distributed fiber-optic sensing technologies rely on one or more of the Rayleigh, Raman and Brillouin scattering effects, which are schematically described in Fig. 1 and its caption. The sensing information is extracted by using an appropriate interrogator, which transmits optical radiation into the fiber and then collects the backscattered radiation, originating from one (or more) of the three physical effects shown in the figure. Dedicated processing is then used to infer the relevant measurand at every resolution cell along the fiber. Localization is achieved, either by pulsing the probing light, like in a radar (OTDR – Optical Time Domain Reflectometry), or through scanning of the probing optical frequency (OFDR – Optical Frequency Domain Reflectometry), or through correlation techniques using codes of varying level of sophistication (OCRD – Optical Correlation Domain Reflectometry). Advanced configurations may also require feeding light to the remote edge of the fiber.

This paper reviews recent developments in the field of distributed fiber-optic sensing using the Brillouin effect. Its structure is described in the following section.

2. The Brillouin effect in optical fibers

2.1. Introduction

Brillouin-based fiber-optic distributed sensing [12–16] is a promising technology for the monitoring of many types of structural and environmental changes, already commercially implemented and widely used for the protection of pipelines against leaks, for the inspection of long electrical cables against local heating, for a variety of geotechnical applications and more [2,17]. Sensors based on this technology use the Brillouin nonlinear frequency shift (BFS) and represented by \( \nu_B \), which is a function of the local temperature and mechanical stress. For standard single-mode fibers using wavelengths around 1550 nm the near-room-temperature sensitivities of \( \nu_B \) are 1 MHz per degree \( ^\circ \text{C} \) and 50 MHz per 1000 \( \mu \text{e} \), i.e., 50 MHz per 0.1% elongation/contraction of the fiber. Thus, using appropriate interrogation techniques (and there are a few), the BFS can provide information on the surrounding temperature and strain distributions along the optical fiber. While intensively researched for more than two decades (see
In stimulated Brillouin scattering (SBS) two lightwaves, $A_{\text{pump}}(z, t) \exp[i(k_{\text{pump}}z - 2n_{\text{a}}v_{\text{pump}}t)]$ and $A_{\text{probe}}(z, t) \exp[i(-k_{\text{probe}}z - 2n_{\text{a}}v_{\text{probe}}t)]$, having a frequency difference of $\nu_{\text{d}} = \nu_{\text{pump}} - \nu_{\text{probe}} > 0$, counter-propagate in the fiber. Their interference, having an efficiency dictated by their relative SOPs [20–22], creates a moving optical intensity pattern of frequency $\nu_{\text{d}}$ and wavenumber, $q = k_{\text{pump}} + k_{\text{probe}}$. Fig. 2. Thanks to the phenomenon of electrostriction (the material tendency to become denser in areas where the electromagnetic intensity is higher [10]), the moving intensity wave induces a corresponding density wave, i.e., an acoustic wave, $Q(z, t) \exp[i(qz - 2n_{\text{a}}v_{\text{d}}t)]$, which moves in the same direction as the higher frequency ‘Pump’ wave. The generation of this density wave is not efficient unless the frequency, $\nu_{\text{d}}$, and wavenumber, $q$, of the density wave obey the dispersion relation of acoustic waves in the fiber, namely: $2n_{\text{a}}v_{\text{d}} = V_{\text{d}}$, where $V_{\text{d}}$ is the velocity of longitudinal acoustic waves in the fiber. This phase-matching condition ensures maximum growth of the acoustic wave, provided $\nu_{\text{d}}$ is equal to the aforementioned BFS, $\nu_{B}$, given by [17]:

$$\nu_{B} = \frac{2nV_{\text{pump}}}{c} = \frac{2nV_{\text{d}}}{\lambda_{\text{pump}}}$$

(1)

where $c$ is the light velocity in vacuum, $\nu_{\text{pump}}$ and $\lambda_{\text{pump}}$ are the frequency and (vacuum) wavelength of the incident wave and $n$ is the refractive index of the fiber. Due to the elasto-optic effect, the optically-induced density (acoustic) wave acts as a moving refractive index (Bragg) grating. Coupled with the Doppler effect, this moving Bragg grating is responsible to a one-way coherent power transfer from the high frequency pump to the lower frequency (Stokes) probe, resulting in net gain for the latter and net loss for the former. A schematic description of the SBS process is presented in Fig. 3.

Mathematically, the assumed co-polarized but counter-propagating pump and probe waves generate an acoustic field, which couples the two optical fields. The propagation of these three waves is governed by [10]:

$$\frac{\partial A_{\text{pump}}(z, t)}{\partial z} + \frac{1}{V_{\text{g}}} \frac{\partial A_{\text{pump}}(z, t)}{\partial t} = \frac{1}{2} g_{\text{g}} A_{\text{pump}}(z, t) Q(z, t) \exp \left(-\frac{1}{2} \alpha \frac{A_{\text{pump}}(z, t)}{A_{\text{probe}}(z, t)}\right)$$

(2.1)

$$\frac{\partial A_{\text{probe}}(z, t)}{\partial z} - \frac{1}{V_{\text{g}}} \frac{\partial A_{\text{probe}}(z, t)}{\partial t} = - \frac{1}{2} g_{\text{g}} A_{\text{pump}}(z, t) Q(z, t) \exp \left(-\frac{1}{2} \alpha \frac{A_{\text{pump}}(z, t)}{A_{\text{probe}}(z, t)}\right) + \frac{\alpha}{2} \frac{A_{\text{pump}}(z, t)}{A_{\text{probe}}(z, t)}$$

(2.2)

$$\frac{\partial Q(z, t)}{\partial t} + \Gamma_{\text{d}} Q(z, t) = (g_{\text{g}} A_{\text{pump}}(z, t) A_{\text{pump}}^{*}(z, t) + \Gamma_{\text{d}}/2 \nu_{\text{d}}) Q(z, t)$$

(2.3)

$g_{\text{g}}$ and $g_{\text{g}}^{*}$ represent, respectively, the electrostrictive and elasto-optic coupling effects. $\Gamma_{\text{d}} = 1/\tau_{\text{d}}$ is the acoustic damping constant and $\alpha$ is the logarithmic optical loss in the fiber (Unlike [10], we chose $A_{\text{pump}}(z, t)$ and $A_{\text{probe}}(z, t)$ to have units such that their intensities (in Watt/m²) equal the square of their magnitudes, e.g., $P_{\text{probe}}(z, t) = |A_{\text{probe}}|^{2}$).

When the initial probe amplitude and Brillouin amplification are both weak enough so that the amplified probe does not deplete the pump (Section 3.3.3), Eq. (2.1), the evolution of the amplitude, $A_{\text{pump}}(z, t)$, and power, $P_{\text{pump}}(z) [\text{Watt}]$, of a CW probe wave, propagating in the $-z$ direction over a segment of fiber of length $L$, are easily obtained from (2):

$$A_{\text{pump}}(z) = \left|A_{\text{pump}}(z = L)\right| \exp \left[\frac{g_{\text{g}} B_{\text{p}}}{2} \text{Re} \left(\frac{1}{\Gamma_{\text{d}}}\right) |L - z| + \frac{\alpha}{2} (L - z)\right]$$

$$\times \exp \left[\frac{g_{\text{g}} B_{\text{p}}}{2} \text{Im} \left(\frac{1}{\Gamma_{\text{d}}}\right) |L - z|\right]$$

(3)

and

$$P_{\text{pump}}(z) = P_{\text{pump}}(z = L) \exp \left[g_{\text{p}}(z) P_{\text{pump}}(L - z) |A_{\text{eff}} - \alpha (L - z)|\right]$$

(4)

$A_{\text{eff}}$ is the effective area of the fiber core. The logarithmic Brillouin gain, $g_{\text{g}}(z)$, given by:
\[
g(\nu = \nu_{pump} - \nu_{probe}) = g_1 g_2 \text{Re}\left[ \frac{1}{T_{BA}} \right] \Rightarrow \frac{g_0}{(\Delta \nu_B/2)^2} \frac{(\Delta \nu_B/2)^2}{(\nu - \nu_B)^2 + (\Delta \nu_B/2)^2}
\]

has a Lorentzian shape with peak gain of \( g_0 = 2g_1 g_2/\tau_B \) and a Full Width Half Maximum (FWHM) linewidth of \( \Delta \nu_B = 1/(2\pi\tau_B) \), Fig. 4. In standard single mode fibers at \( \nu_B = 11\text{GHz}, \Delta \nu_B = 30\text{MHz}, g_0 = 2 - 3 \times 10^{-11}\text{m/W}, \alpha = 4.6 \times 10^{-8}\text{Neper/m} \) \((-0.2 \text{ dB/km})\) and \( A_{eff} = (50 - 80) \times 10^{-12}\text{ m}^2 \). For a recent analysis of a depletion scenario see [24].

Eq. (3) was spelled out to emphasize that in stimulated Brillouin amplification not only the magnitude (i.e., power) of the probe wave is frequency dependent, but also its phase, which exhibits, Fig. 4, quite sharp characteristics, often used in slow light experiment [25].

In summary, while SBS requires access to both ends of the fiber, this extra degree of freedom has paved the way to a unique and versatile distributed sensing technology of strain/temperature and related measurands. Indeed, a variety of old and new spectral and spatial SBS-based interrogation techniques, to be described below, have made it possible to determine the BFS, and consequently the strain/temperature, of very short fiber segments (high spatial resolution) along hundreds of kilometers (range) of a single strand of fiber under both static and dynamic conditions.

### 2.3. Spontaneous Brillouin scattering

In the case of spontaneous Brillouin scattering, an incident light wave, launched from only one end of the fiber, now interacts with thermally initiated acoustic waves, i.e., acoustic phonons, which function as moving Bragg gratings. Energy and momentum conservation laws exclusively dictate backscattering of the incident light only by those acoustic waves whose frequency is in very close vicinity of \( \nu_B = 2\nu/\nu_{\text{incident}} \). In spontaneous Brillouin scattering the frequency of the backscattered light is both downshifted (by acoustic waves sharing the same propagation direction as that of the incident light), as well as upshifted (by acoustic waves propagating against the light direction) by the same \( \nu_B \), respectively creating Stokes and anti-Stokes backscattered waves, Fig. 1. Both Lorentzian-shaped spectral lines, (1), have the same linewidth as in SBS, i.e., \( \sim 30\text{ MHz} \) in standard single mode fibers under CW conditions (very strong CW pump waves have narrower spectra [26,27]).

Stimulated Brillouin scattering also plays a very important role in the spontaneous Brillouin scenario, i.e., where only the pump wave is launched into the fiber. For a strong enough pump, the spontaneously generated noisy Stokes wave assumes the role of the counter-propagating probe in SBS and thus experiences gain. Once the pump power exceeds a threshold given by \( 21 \cdot A_{eff}/(g_0 L) \), [28], most of the pump is back-scattered, resulting in severe pump depletion. This process limits the allowable launched power in distributed sensing interrogation techniques, which employ highly coherent sources (with a linewidth \( \sim \Delta \nu_B = 1/(2\pi\tau_B) \). If a launched probe is also present, as in SBS, its Brillouin amplified output will be heavily contaminated by this SBS amplification process of the noisy, thermally generated process [29].

We now move to the description of some of the leading interrogation techniques, emphasizing recent progress.

### 3. Brillouin Optical Time Domain Analysis (BOTDA)

#### 3.1. Introduction

BOTDA [17,12] is the most common Brillouin interrogation technique. Here, a coherent (linewidth \( < \Delta \nu_B \)) optical pump pulse of duration \( T \) and optical frequency \( \nu_{pump} \), is launched into the fiber under test (FUT) at \( z = 0 \) and propagates against a CW probe wave of frequency \( \nu_{probe} \), \( \nu_{pump} < \nu_{probe} \). Which enters the FUT from its opposite side at \( z = L \). Wherever the pump pulse meets the probe, SBS becomes effective in imparting gain to the probe, depending on the value of the local Brillouin gain, i.e., on how close \( \nu_{pump} - \nu_{probe} \) is to the local BFS, \( \nu_B(z) \). The results of this interaction are monitored at \( z = 0 \), where the optical intensity of the counter-propagating probe wave, arriving there at time \( t \) after the pump pulse was launched, provides information on the probe Brillouin gain at location \( z = 0.5V_p t \) along the FUT. In order to determine the BFS profile of the FUT, the full BGS is measured by sweeping the optical frequency of either the pump or probe waves across a range of frequencies, as wide as dictated by the variability of \( \nu_B(z) \) along the FUT, see Fig. 5. Note that it is possible to pulse the probe wave (with the lower frequency) and measure the Brillouin loss of a counter-propagating CW pump wave [30,31].

#### 3.2. The basic BOTDA experimental setup

While BOTDA can be experimentally implemented in different ways, the setup of Fig. 6 is representative in that it includes almost all necessary components to take care of most relevant issues.

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Fig. 4. The magnitude (left) and phase (right) of the Lorentzian shaped Brillouin Gain Spectrum (BGS) in a regular silica optical fiber. A FWHM of 30 MHz is assumed.

Fig. 5. A 3D frequency-distance Brillouin gain mapping of an 80 m sensing fiber, zooming in on the last 10 m of the fiber, showing that the BFSs of two stretched segments have a different BFS than the rest of the fiber.
Quite commonly used, it will serve us in reviewing recent developments. Here, a highly coherent laser is split into pump and probe channels. A microwave sine wave, which can be scanned over the required range of $k_{pump} - k_{probe}$ around the fiber average BFS ($\sim 11$ GHz), feeds the probe channel Mach–Zehnder modulator (EOM1), which is biased at its zero transmission point to generate two sidebands, the lower one for the probe wave and the upper one for the pump wave. The EOM1 output is then optionally amplified by an Erbium doped fiber amplifier (EDFA1), normally polarization scrambled by a polarization scrambler (Pol. S), and then launched into one side of the FUT. Modulator EOM2, preferably of the semiconductor optical amplifier (SOA) switching type, forms a pump pulse of the required duration, which is amplified by EDFA2 and launched into the other side of the FUT through a circulator (CIR1).

The Brillouin-amplified probe wave is finally routed by CIR1 and CIR2 to a fast photodiode (PD), whose bandwidth is inversely proportional to the pump pulse width. A narrow bandwidth fiber Bragg grating (FBG), or its equivalent, filters out pump backscattering, as well as the upper sideband generated by EOM1. The output of the photodiode, representing the probe power, is normally processed digitally, first to determine the gain by dividing it by the probe output power prior to the launching of the pump wave, and then, after the required range of the pump-probe frequency difference has been scanned, to reconstruct the normalized BGS, Fig. 4, and locate it maxima (i.e., the BFS at $\Delta \nu_B(2)$) along the fiber. Accurate estimation of the BFS from the measured BGS profile depends on system parameters presented in Fig. 7. The frequency step, $\delta\nu$, used in the frequency scanning, the Brillouin linewidth, $\Delta \nu_B$, and the unavoidable (normalized) noise $\sigma$, which equals the inverse of the signal to noise ratio (SNR), $\lim_{N \to \infty} \sigma = \frac{1}{\text{SNR(z)}}$. Assuming $\nu_B(z)$ is estimated from the BGS profile at $z$ by fitting a quadratic function (i.e., a parabola) to all experimental data points exceeding a fraction $\eta$ of the peak, the estimation error of $\nu_B$ has been recently found to be [32]:

$$
\sigma_{\nu_B} = \frac{1}{\text{SNR(z)}} \frac{3}{4} \frac{\delta \nu_B}{\eta^{1/2}}.
$$

As expected, denser frequency sampling and higher SNR values improve the obtained accuracy. Finally, the averaging of $N_W (> 1)$ probe traces, generated by sequentially launched $N_W$ pump pulses, can significantly boost the SNR, which is normally proportional to $\sqrt{N_W}$. The Brillouin signal is normally quite weak, and in long range sensing thousands of averages are required to get an accurate estimation of $\nu_B$.

3.3. Major issues with BOTDA

3.3.1. Laser coherence

For efficient interaction, the narrow linewidth of SBS ($\sim 30$ MHz) requires a much narrower laser linewidth. However, while a laser linewidth of < 1 MHz should be narrow enough to provide maximum available gain for commonly used pump pulse widths, the phase noise it carries may deteriorate the overall SNR [33].

3.3.2. Polarization fading and its elimination

Polarization fading [22] refers to the fact that the Brillouin interaction depends on the degree of parallelism of the States of Polarization (SOPs) of the pump and probe, a degree which is not maintained in standard single mode optical fibers. These fibers are weakly birefringent causing the pump/probe SOPs to hover around each other. This changing degree of parallelism results in highly non-uniform gain along the FUT, and almost always fiber segments are encountered with minimum Brillouin gain and, consequently, poor SNR, see Fig. 8.

Most often, this problem has been eliminated by scrambling the SOP of one of the interacting waves, Fig. 6, and averaging the sensor readings over multiple pump pulses, until a sufficiently

![Fig. 6. BOTDA setup: Sig. Gen.: Signal generator, Pulse Gen.: Pulse generator, EOM: electro-optic modulator, EDFA: Erbium-doped fiber amplifier, CIR: circulator, FBG: fiber Bragg grating, Pol. S: polarization scrambler, FUT: fiber under test, PD: photodiode Sig. proc.: Signal processing.](image1)

![Fig. 7. Typical local Brillouin spectral response after normalization, measured by a distributed time-domain sensor. The distribution maps a resonant Lorentzian profile and the peak gain frequency must be determined to get an estimated value for the measurand. Noise on the signal (s) induces uncertainty and the estimation of the peak gain frequency is subject to statistical errors, depending on the Brillouin FWHM ($\Delta \nu_B$) and the frequency step (s) used to measure the gain spectrum (after [32]).](image2)

![Fig. 8. A Brillouin gain-frequency-distance map of a standard, weakly birefringent single-mode fiber without addressing the polarization fading issue. Due to the random orientations of the SOPs of the interacting waves, the probegain is highly non-uniform along the fiber, resulting in locations with maximum interaction (19 m) and minimum interaction (30 m).](image3)
high SNR is recorded along the full length of the FUT. This process significantly slows down the BGS acquisition speed. An alternative solution to the polarization fading problem, which reduces the acquisition speed by only a factor of 2, involves the use of a fast polarization switch, where two orthogonal SOPs are sequentially launched into the fiber, and the resulting readings added. Recently, several new techniques have been introduced to eliminate the polarization fading using polarization diversity.

In the frequency scanning BOTDA implementation of [34], two probes interacted with a single pump so that one experienced gain while the other loss. The two probes, of different frequencies, were made orthogonal by separating them using a wavelength division demultiplexer, having a mirror on one output port and a Faraday mirror on its other port. The second technique [35], belonging to the slope-assisted BOTDA category, Section 3.4.1, does not use frequency scanning but rather a single frequency interrogation, a pair of probes, propagating against a pair of pumps, as in this case. Orthogonality of the different frequency pumps was obtained by passing them through a Differential Group Delay (DGD) module, which differentially transformed their (originally) same polarization into two orthogonal ones. The output intensities of the two amplified probes was summed to achieve a polarization independent Brillouin gain. This method has been successfully applied to a Fast-BOTDA setup, Section 3.4.2 to achieve ultimately fast sensing performance of a frequency scanning BOTDA configuration [36].

3.3.3. Pump depletion and related nonlocal effects

The Brillouin gain enjoyed by the probe is fueled by the pump: the higher the probe gain, the higher the pump loss. Consider a fiber segment at coordinate z0 down the fiber. Clearly, the Brillouin gain in that segment is proportional to the power of the arriving pump pulse, Ppump(z0). For proper evaluation of the gain one must assume, therefore, that the value of Ppump(z0) is independent of any Brillouin interaction that the pump pulse experienced throughout its journey from its launch point z = 0 to z = z0. However, this condition is not fulfilled if there is a strong Brillouin-mediated exchange of power at z = z′ < z0, where the probe depletes the pump, whose power arriving at z0 now depends on how close the pump-probe frequency difference to the BFS at z′. Clearly, this may result in an erroneous evaluation of \( \kappa_b(z_0) \) [37]. At the expense of a lower SNR, pump depletion can be avoided if the amplified probe power is kept much below that of the pump. Interestingly, this requirement is somewhat eased by the setup of Fig. 6, where the rejection of the redundant upper sideband of EOM1 is done only before detection. Thus, three waves propagate in the FUT and two Brillouin power exchanges are taking place: wherever the pump loses power to the lower frequency probe (the lower sideband of EOM1), it gains basically the same amount from the higher sideband, which now acts as a higher frequency pump for the pump pulse, having just the right frequency shift: \( \nu_{\text{higher-sideband}} = \nu_{\text{pump}} - \nu_{\text{BGS}} - \nu_{\text{probe}} \). Another utilization of the upper sideband has been demonstrated in [38], where both the SBS-amplified lower sideband probe and the SBS-attenuated upper sideband probe were spectrally separated and fed into the two inputs of a balanced detector, thereby improving the SNR, and simultaneously overcoming some of the source intensity noise. It has been recently noted [39], however, that these gain and loss processes are not spectrally identical, concluding that gain measurements, where the BGS information is retrieved from the lower sideband gain, are more robust to this non-local effect than the loss measurements, where BGS information is obtained from the upper sideband.

The BFS can be also determined from measurements of the optical phase, (3), of the amplified (or attenuated in case of loss measurements) probe. These phase measurements, which require additional modulation of the probe wave, [40], are in principle independent of the pump power and, therefore, less sensitive to non-local effects.

3.3.4. Pump pulse extinction ratio and non-local effects

Proper operation of a BOTDA implementation requires the Brillouin interaction between the pump and probe waves to be strictly confined to the duration of the pump pulse. This assumes an infinite extinction ratio for the pump pulse, an ideal condition that cannot be achieved by existing switching components, whose emitted pulse always rides on some non-zero pedestal. Assume a fiber of length L, which is interrogated with a spatial resolution of \( \Delta L \), using a pump pulse of extinction ratio \( ER = P_{\text{pump}-\text{peak}}/P_{\text{pedestal}} \). The higher the ratio \( L/\Delta L \) the more sensitive is the measurement of the Brillouin gain in the short section \( \Delta L \) to the disturbing Brillouin amplification of the pedestal pump light along the rest of the fiber. Indeed, it has been recently found out [41] that accurate measurements are obtained only if \( ER > L/\Delta L \). Thus, to achieve 10 cm spatial resolution over 10 km of fiber, \( ER \) must be larger than 50 dB. Mach–Zehnder modulators, often used in BOTDA setups, are characterized by lower \( ER \) values, although their performance can be improved using a nonlinear loop mirror (NOLM) [42]. Instead, semiconductor optical amplifiers, operating in their switching mode, may meet some of these high-end extinction ratio requirements.

3.3.5. Spatial resolution and pulse width

For any given value of the frequency difference \( \nu_{\text{pump}} - \nu_{\text{probe}} \), the spatial resolution is determined by the pulse width and is given by \( 0.5\nu_bT \). Decreasing T should, supposedly, improve the spatial resolution, although at the expense of lowering the SBS gain, due to the shorter interaction length and, consequently the available SNR. However, since the pump pulse SBS amplifies the probe only after their interaction had excited the acoustic field, and since it takes time \( \sim 30 \text{ ns} \) for the acoustic field to fully build up (similar to a charging of a capacitor with a time constant of \( \tau_b \)), pump pulses shorter than \( \sim 30 \text{ ns} \) broaden the BGS. Mathematically [17], the effective BGS can be expressed by:

\[
g^{\text{eff}}_B(\nu) = g_B(\nu) \otimes \frac{\text{Pump Power Spectral Density}(\nu)}{\text{Total Pump Power}},
\]

where the natural BGS, \( g_B(\nu) \), is given by (5). For pump pulses shorter than 20 ns, the BGS linewidth \( \Delta \nu_b(T) \) is approximately given by \( 1/T \) (e.g., \( \Delta \nu_b(T = 15\text{ ns}) = 70 \text{ MHz} \)). This inherent broadening of the BGS reduces the peak gain and makes the determination of the peak of the Brillouin gain spectrum more susceptible to noise. All in all, it lowers the strain/temperature sensitivity, thereby practically limiting the spatial resolution to \( \sim 1 \text{ m} \).

Recently, several somewhat similar techniques have been developed to significantly improve the spatial resolution in BOTDA. Their common basis is pre-excitation of the acoustic field.

3.3.5.1. Differential Pulse-width Pair BOTDA (DPP-BOTDA)

In this technique [43], [44] two consecutive measurements of the Brillouin gain are taken, using two long pulses of widths \( T \) and \( T + \Delta T \), where \( T > \tau_b \) (e.g., \( > 30 \text{ ns} \)) is long enough for the acoustic field to develop to its full strength, while \( \Delta T \) can be much shorter, down to 1 ns or less. While both pump pulses give rise to the same amplification of the probe wave during the common time interval \([0, T]\), only the longer one contributes amplification during \( T + \Delta T \) since there is no Brillouin interaction beyond the end of the shorter pump pulse. Thus, subtracting the measured Brillouin amplified probe signal of the short pulse from that of the longer one yields information on the gain in the time slot \( \Delta T \), without compromising the shape or strength of \( g_B(\nu) \). Note, however, that the shorter \( \Delta T \), the shorter the Brillouin interaction
length ($L$ in Eq. 4) and the lower the SNR. The need for two consecutive measurements and gain subtraction can be omitted by launching two pump pulses into the fiber, having different frequencies and slightly different durations, such that one (the longer pulse), of frequency higher than that of the probe, contributes gain to the probe signal while the second (the shorter pulse), of lower frequency, simultaneously, causes the probe to lose power, see Fig. 9. In this manner the subtraction will occur optically at the detector. This method was suggested in [45] for polarization maintaining fibers, later it was demonstrated in regular single mode fiber [46] and recently was slightly modified to be more suitable for long range sensing [47]. The use of the DPP method in a BOTDA measurement based on the Brillouin phase has been demonstrated as well [48].

DPP-BOTDA was employed for long range sensing and together with Raman amplification a 100 km fiber was probed with 0.5 m spatial resolution. A measurement based on DPP-BOTDA in combination with pre-excitation technique and pulse coding, to be described below, achieved 25 cm spatial resolution over 60 km of fiber.

The high achievable spatial resolution of the DPP-BOTDA method comes at the expense of halving the sampling rate. Also, subtraction of experimental, always somewhat noisy data, requires fairly high SNR values, normally obtained through massive averaging, which, again, takes time.

3.3.5.2. Pump pre-pulse BOTDA. Here [49], the pump pulse is shaped to comprise a low power long pedestal, which excites the acoustic field, immediately followed by a narrow (down to 1 ns) high power part that probes the fiber. The resulting BGS, Fig. 10, is characterized by a wide skirt, corresponding to the narrow part of the pulse, which lies, however, under a narrow cap, whose width is determined by the long part of the pulse. This narrow spectral cap allows the technique to achieve a strain resolution of 25 με at a spatial resolution of 10 cm ($T = 1$ ns).

![Fig. 10. The BGS of a fiber segment interrogated using the pump pre-pulse BOTDA technique with a complex amplitude pump pulse comprising a 100 ns long week pedestal, 50 dB weaker than the 0.1 ns narrow strong part of the pulse (simulation) [49]. Inset: An illustration of a pre-pump pulse with a 97 ns pedestal and a 2 ns strong pulse.](image)

3.3.5.3. Gain-Profile Tracing BOTDA (GPT-BOTDA) [50]. When a very long pump pulse, which completely fills the whole length of the fiber is suddenly terminated, the previously amplified probe wave progressively loses its SBS gain as the falling edge of the pump continues its journey through the fiber. Specifically, the (time or distance) derivative of the decreasing probe power at a given distance into the fiber is directly proportional to the local gain. The spatial resolution is given by $0.5\sqrt{t_{\text{fall}}}$, where $t_{\text{fall}}$ is the falling time of the pump pulse. 2 cm of spatial resolution were demonstrated over a few meters of fiber. While impressive, the method, being based on derivatives, is also sensitive to noise. Also, filling the whole length of the fiber with a pump wave of sufficient power may work well for short fibers but not for long ones due to strong spontaneous Brillouin backscattering.

3.3.5.4. Other pre-excitation BOTDA techniques. ‘Bright pulse’ [51], ‘Dark pulse’ [52] and ‘Brillouin echoes’ [53] fill the fiber with a pre-excitation CW pump and then, launch a short interrogation disturbance. High spatial resolution has been successfully demonstrated, but the fact that the CW pump maintains its presence after the interrogating ‘pulse’ leads to artificial echoes. A somewhat similar technique first proposed in [54] was recently improved using a Walsh coding to obtain higher SNR and 10 cm of spatial resolution [55]. The use of a four-section-bright pulse was suggested to compensate for the second echo of bright (and dark) pulses [56].

In [57], a commercial Brillouin interrogator, based on a pre-excitation technique (2 cm spatial resolution over 25 km), was used for railway traffic monitoring.

Spatial resolutions of 1 cm and less have been obtained with other interrogation techniques, see Sections 6.1 and 6.2 below.

3.3.6. Range

Classical BOTDA configurations, similar to Fig. 6, provide sensing distances to a few TENS of kilometers. many applications, however, could benefit from much longer ranges (e.g., monitoring the temperature of electrical cables transporting energy from distant off-shore wind turbines [58]). to avoid depletion in such long range scenarios, the Brillouin induced power addition to the probe at $z$, $\Delta P_{\text{probe}}(z) = P_{\text{probe}}(z) - P_{\text{probe}}(z + \Delta z)$ at each resolution cell, $\Delta z$, is given by, (4) and (17):

$$\Delta P_{\text{probe}}(z) \approx \frac{g(\nu) |P_{\text{pump}}(z)| P_{\text{probe}}(z)}{A_{\text{eff}}} \Delta z$$

(8)

Assuming for simplicity that the Brillouin gain is small enough so that the propagation of both pump and probe from their respective launch points to $z$ is governed by the fiber loss one find $\Delta P_{\text{probe}}(z)$ to be independent of $z$ [17]:

$$\Delta P_{\text{probe}}(z) \approx \frac{g(\nu) |P_{\text{pump}}(z)| P_{\text{probe}}(z)}{A_{\text{eff}}} \exp[-\alpha(L - z)] \Delta z$$

$$= \frac{g(\nu) |P_{\text{pump}}(z)| P_{\text{probe}}(z)}{A_{\text{eff}}} \exp[-\alpha L] \Delta z$$

(9)
But in order to be detected, $\Delta P_{\text{probe}}(z)$ must travel to the fiber entrance, $z = 0$, suffering additional loss:

$$
\Delta P_{\text{probe}}(z = 0) = \frac{\sum_l P_{\text{pump}}(z = l) P_{\text{probe}}(z = L) \exp[-\alpha(z + L)]}{A_{\text{eff}}} dz
$$

Thus, a long interrogation range involves very weak probe signal and extremely poor SNR values. Unfortunately, the input probe power, $P_{\text{probe}}(z = L)$, cannot be arbitrarily increased in fear of depletion. Also, the input pump power, $P_{\text{pump}}(z = 0)$, must be kept below the threshold of a variety of nonlinear processes, such as, Raman and modulation instability [59].

Several techniques have recently pushed the sensing range of BOTDA to beyond 100 km. These include: (i) discrete amplification of the pump and probe waves along the FUT (which necessitates the installation of active devices, as well as electrical power supply, along the sensing fiber), (ii) distributed Raman amplification over the (unmodified) sensing fiber, and finally: (iii) the use of coding to substantially increase the energy of the pump pulse without bringing its peak power to problematic levels.

3.3.6.1. Discrete amplification. Using multiple Erbium doped Fiber Amplifiers (EDFAs) in the form of discrete repeaters, spaced 65 km apart, a total sensing length of 325 km was achieved, corresponding to a 650 km loop, demonstrating a measurement repeatability of 2 °C (2σ) [58].

3.3.6.2. Pump coding. Coding, Appendix A, can be used in BOTDA to spread the pump energy over a relatively long time using a specifically chosen sequence of $N$ identical chips (some of them of zero intensity), each of duration $T_{\text{chip}}$. The received probe trace is then processed, using the known mathematical properties of the transmitted sequence, resulting in a probe trace with SNR, which has been improved by the code gain, and more importantly, without compromising the spatial resolution, which is still given by $0.5\sqrt{T_{\text{chip}}}$. With a higher SNR, less averages are required and faster scanning rates are possible (e.g., with cyclic pulse intensity coding a 10 km fiber was interrogated in 0.4 s with 1 m spatial resolution [60]). Also, a higher SNR can also extend the measurement range. In [61], a bipolar Golay pulse coding was implemented by letting the positive code chips modulate a gain-providing pump of higher frequency than that of the probe, while negative code chips modulated a loss-providing pump of lower frequency than that of the probe. The technique was experimentally implemented on a 100 km-long fiber with 2 m of spatial resolution, fully resolving a 2 m hot-spot at the end of the sensing fiber with no distortion introduced by the decoding algorithm. As expected, bipolar Golay codes provide a higher signal-to-noise ratio enhancement and stronger robustness to pump depletion in comparison to optimum unipolar pulse codes known for BOTDA sensing.

3.3.6.3. Raman amplification. Following its success in extending the range of fiber-optic links, [62], Raman distributed amplification has been applied also to Brillouin sensing. In the so-called first-order Raman amplification, a strong CW Raman pump is launched into the FUT, most often from both sides, at a wavelength which creates Raman gain for the Brillouin pump and/or probe waves. This Raman gain, being distributed over the whole length of the FUT, helps to distributedly compensate for the fiber loss of the relevant wave, significantly improving the SNR at the receiver. Using this technique with a Raman-amplified pump (Raman wavelength of 1455 nm provided gain at ~1550 nm), 2 m of spatial resolution and 1.2 °C uncertainty over a 100 km loop fiber were achieved in [63]. While providing gain, Raman amplification contaminates the amplified waves with Relative Intensity Noise (RIN). With judicious processing of this transferred RIN, [64], 0.5 m of spatial resolution and hot spot detection were demonstrated over 100 km of fiber. A slightly modified scheme comprising a dual-sideband modulated probe and balanced detection [65] was employed to mitigate the RIN of Raman amplification. In real applications of BOTDA, however, 100 km of FUT do not translate to a 100 km of sensing range: An additional 100 km link is required to bring the probe wave to the remote end of the sensing fiber. A true 120 km sensing range (240 km of fiber in total) was demonstrated in [66] with a spatial resolution of 5 mm, see Fig. 11 below. Here, the pump signal was processed by a more advanced ‘seeded’ second-order Raman amplification, where a low-power first-order Raman pump at 1455 nm acts as a seed, which is amplified by a high-power second-order Raman pump at 1365 nm. This higher order pumping scheme helps in shifting the maximum Brillouin pump power to a more distant location along the sensing fiber. The probe wave was also Raman amplified but only with a first-order Raman pump. An important ingredient in achieving this record range was the use of Simplex coding of the pump pulse. In another recent experiment, [67], a dual-sideband Brillouin optical time-domain analyzer (BOTDA) with bi-directional first-order Raman amplification and balanced detection has achieved 100 km of sensing range in a loop of 200 km with a spatial resolution of 8 m and 1.2 °C of temperature accuracy.

A few other techniques were used to simply extend the sensing range via SNR improvement without coding. For example, a multi-frequency pump pulse interacting with multi-frequency continuous-wave probe provided a ~5 dB SNR improvement, which was used to extend the measurement range to 50 km [68]. When the single frequency light source of Fig. 6 was replaced by a comb of three frequencies, equally spaced by twice the BFS, an interesting power transfer occurred among the three pumps and their induced Brillouin backscattering signals, resulting in better range performance, reaching 100 km with 20 m of spatial resolution [69] (see also Section 4.1 below). Alternatively, by using the phase of the complex B GS, (3), rather than its magnitude, [40], for the determination of the BFS, measurements become independent of the pump power, resulting in much less sensitivity to non-local effects, and consequently stronger probe and an extended dynamic range. A BOTDA setup that combines simultaneous Brillouin gain/loss

![Fig. 11. Left: The Brillouin gain profile (at 10.66 GHz) of the 200 km long loop fiber with 3 m spatial resolution. Center: The BFS along the first 100 km of the looped fiber, exhibiting a frequency uncertainty of 1.5 MHz at the end of the sensing fiber. Right: Detection of a 3 m hot spot at the end of the fiber. (After [66]).](image)
measurements with color coding allows the use of strong pump pulses, compared to other coding techniques, thus increasing the sensing range to 200 km with 3 m of spatial resolution [70]. SNR can be improved as well by modulating the laser in order to suppress the noise originated from coherent Rayleigh scattering [71], demonstrating sensing range of 25 km with 1 m spatial resolution.

Phase modulation and computing-based optimization techniques were suggested in Ref. [72] to achieve SNR improvement and suppressing of SBS effects on long range distributed Brillouin based sensing.

These long distances can be utilized, for instance, for offshore integrity monitoring of subsea wells [73].

3.4. Dynamic sensing with BOTDA-based techniques

The last few years have seen significant progress in making Brillouin distributed sensing truly dynamic, with sampling rates approaching tens of kHz. Classical implementations of BOTDA have traditionally eyed long range performance, which entails long averaging times, thereby limiting these implementations to the static or quasi-static domain. BOTDA techniques, Section 5, have demonstrated in the past 200 Hz distributed sensing (at 1 kHz sampling rate) at a single fiber location over 20 m measurement range with a 10 cm spatial resolution [74] and strain distribution along the entire length of a 100-m fiber with 80-cm spatial resolution and 20 Hz sampling rate [75]. Below we describe the latest much faster results, which open up new applications for Brillouin distributed sensing.

3.4.1. Slope-assisted techniques

Rather than scanning a wide range of frequencies in order to find the peak of the BGS, a single interrogating frequency, tuned to the center of the rising/falling slopes of the BGS, was used in [76]. Here, Fig. 12, frequency shifts induced by variations of the local strain (and/or temperature) are translated to gain variations, easily tracked by measuring the intensity of the Brillouin amplified probe wave.

In [76] the localization was defined by the meeting point of two counter-propagating pump and probe pulses, which could be controlled by the relative delay between the propagating pulses and a sampling rate of 200 Hz was demonstrated. Clearly, at each interrogated location the optical frequency of the probe must be adjusted to properly sit at (or near) the center of the (preferably) linear portion of the slope of the local BGS, whose peak, however, is likely to vary along the sensing fiber according to the local average strain/temperature and/or fiber properties. For interrogating pump pulses longer than ~30 ns, the width of the BGS is about 30 MHz so the extent of the linear portion of its slope is also of the order of 30 MHz, which translates to an available measurable dynamic range of ~600 με. Shortening the pulse width widens the BGS, resulting in a somewhat larger dynamic range at the expense of reduced sensitivity.

The slope assisted BOTDA (SA-BOTDA) technique of [78] also works on the slope of the BGS but can handle a fiber with an arbitrary BFS profile along its length. It is based on the classical BOTDA technique with the following modifications: instead of using a pump pulse and a CW probe wave, whose frequency difference sits on the slope of the BGS, it uses a variable optical frequency CW probe wave. The time evolution of the probe frequency is tailored in such a way that when the probe wave meets the counter-propagating pump pulse at any location along the fiber, the optical frequency difference between these two waves sits as close as possible to the middle of the slope of the BGS at that location (of course, a preliminary classical BOTDA scan of the fiber is required to determine the frequency of the mid-slope at each point along the fiber). Hardware-wise, the frequency synthesizer of EOM1 in Fig. 6, is replaced by an Arbitrary Waveform Generator (AWG), whose frequency can be changed in nanoseconds. The first demonstration of the technique successfully monitored a few hundred Hz of vibrations over an 85 m fiber, having two sections with widely different BFSs. The initial 1.5 m spatial resolution was later improved to 5 cm using the DPP method and its dynamic performance were verified by a comparison to a co-located FBG, monitored by a commercial interrogator [79]. The fastest slope-based BOTDA measurement, so far, demonstrated the monitoring of a strain wave travelling at a speed of 4 km/s [80].

Slope-based Brillouin distributed sensing techniques rely on an initial determination of the calibration factor controlling the conversion of the measured intensity variations to the actual measured-induced frequency shifts of the BGS. This calibration factor depends on both the shape of the BGS but, more significantly, also on the value of the pump power along the FUT. Unfortunately, the latter can drift either at the FUT input or, worse, along the lossy link due to fiber bending, deteriorating connectors etc. This issue of pump power dependency of the calibration factor has been practically eliminated by the Double SA-BOTDA method, [81,82], where use was made of the agility offered by the AWG to sequentially probe both rising and falling slopes of the BGS. Thus, pump-pulse-power-immune dynamic measurements of 110 Hz vibrations with 1 kHz sampling rate over a 50 m fiber were demonstrated Fig. 13.

An entirely different approach employs the pump-power-independent slope of the phase of the BGS, [3], Fig. 4, [83] and demonstrated a dynamic measurement of 3 Hz vibrations with a sampling rate of 1.66 kHz over a 160 m fiber with an extended dynamic range. An additional RF modulation of the probe was used for the BGS phase measurement, together with a self-heterodyne demodulation circuitry.

Recently, [84], it was found that the shape of the BGS itself is also pump power dependent. For strong enough pump pulses, usually employed (in dynamic sensing purposes over short distances) to minimize averaging, the BGS linewidth appears to grow with the Brillouin gain with a slope that is inversely proportional to the pulse width. Thus, for example, in a standard single-mode fiber, a 15 ns pump pulse, strong enough to generate a gain of 0.5 dB, broadens the logarithmic BGS by ~1.5 MHz, while a 45 ns pulse, providing the same gain, increases the linewidth by only ~0.5 MHz. A recent study [85] indicates that this phenomenon may introduce strain/temperature error of ~5–7% per dB of gain change.

![Fig. 12. Brillouin gain spectra of a fiber segment under time average (black), high (blue) and low (red) strain values. A frequency working point is chosen near the center of the left slope; see the black point on the black Lorentzian. Positive (negative) strains introduced to the fiber, shift the BGS to higher (lower) frequencies, thereby modulating the Brillouin gain experienced by the propagating probe wave (after [77]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
Slope-based techniques are also sensitive to polarization fading, see above Section 3.3.2. Remedies include speed slowing polarizations scrambling and switching. Recently, a pair of parallel monitoring of small and large structures, such as short [86], a long cantilevers [87], where the use of a tailored probe [86] was observed to the 120 Hz strain variations. Although the pump pulse power varied by more than 5 dB during the measurement, the amplitude of the deduced strain variations remained constant (after [82]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In summary, slope-based techniques, using only one or two interrogating frequencies, avoid the time consuming full frequency scan of the BGS, thereby allowing sampling rates limited only by the length of the FUT (time of flight) and the number of required averages. They suffer, though, from a limited (measurand) dynamic range and vulnerability of the gain-to-frequency conversion factor to possibly drifting system parameters.

3.4.2. Fast-BOTDA

Four main factors control the sensing speed of a frequency scanning BOTDA setup: (i) The round-trip time of flight through the fiber under test (FUT), which limits the pump pulse repetition rate; (ii) The granularity of the frequency sampling of the BGS, which affects the measurement resolution and accuracy; (iii) The tuning speed of the optical frequency scanning mechanism and (iv) Number of averages. Factors (i) and (ii) impose an ultimate bound on the speed by which a frequency scanning BOTDA acquires a single BGS. Tuning speed of the optical frequency, factor (iii), has been on the order of milliseconds in classical BOTDA setups, which commonly aim at long measurement range, requiring so many averaging that switching time was not a limiting factor. Recently, the Fast-BOTDA (F-BOTDA) technique was introduced, [89], where EOM1 of Fig. 6 is now fed by an AWG, which replaces the otherwise commonly used microwave synthesizer. Using the AWG, frequency switching speeds of the order of nanoseconds over hundreds of MHz’s are achieved. The first demonstration [89], using a 15 ns pump pulse, distributedly monitored a 100 m long vibrating fiber, at an effective pulse repetition rate of 833 Hz, probing the BGS at 100 frequency points and employing 10 averages to deal with polarization variations. Thus, an effective sensing speed of 833 [full-fiber-BGS] per second was achieved, see Fig. 14. The 1.5 m spatial resolution was then improved with the DPP method [90].

The fourth speed-limiting factor deals with averaging, which is normally required for two reasons: (a) To improve the signal to noise ratio (SNR), which, however, may not be of a problem for relatively short fibers (< 1 km), where strong pump pulses provide high gains without giving rise to detrimental nonlinear optical effects; and (b) To overcome the inevitable polarization fading. Using the two probes and two orthogonally polarized pumps layout of [35] an ultimately possible measurement speed of frequency scanning BOTDA, in terms of number of [full-fiber-BGS] per second, was demonstrated, limited only by the round trip time of flight through the FUT and the number of interrogating frequencies [36], see Fig. 15 below. Specifically, a no-averaging acquisition speed of 11,300 [full-fiber-BGS]/s was reported, which is indeed the ultimate speed for the 145 m sensing fiber and the 61 interrogating frequencies. With a spatial resolution of 1.5 m (pump pulse width of 15 ns) it represents an acquisition speed of \(10^6\)
resolution points per second. BFS uncertainty was measured to be \( \pm 10 \mu \text{e} \). In another experiment, which required 6 averages to accommodate the limited transfer speed of the electronic data acquisition system, a 4200 \( \mu \text{e} \) dynamic range with 105 scanning frequencies, achieving an acquisition speed of 430 [full-fiber-BGS]/s with a spatial resolution of 10 cm and with the same BFS uncertainty of \( \pm 10 \mu \text{e} \).

3.4.3. The sweep free BOTDA (SF-BOTDA)

Sensing speed is further accelerated by this sweep free method [91,92]. Here, multiple pump tones generate multiple BGSs, whose center frequencies are down shifted from the pump tones by the corresponding BFSs, Fig. 16. A similar number of probe tones are simultaneously launched into the fiber from its opposite side, downshifted by approximately the BFS, but with slightly different frequency spacings than those of the pump tones. These probe tones are arranged in such a way that each probe tone is located in a different region of the BGS of the corresponding pump tone.

Once the individual gains of the many probe tones are simultaneously recorded, the BGS can be reconstructed in a single measurement (excluding averaging), without the need for frequency sweeping. The number of pairs of pump-probe tones used and their frequency spacing between each pair eventually determine the frequency resolution of BGS reconstruction. Thus, the SF-BOTDA should perform faster than classical BOTDA (for the same number of interrogating frequency) by a factor, which can be as high as the number of simultaneous tones used. To avoid interferences between neighboring pump-probe pairs the pump tones spacing must be significantly larger than the width of the BGS. For pump pulses longer than \( \sim 30 \) ns, 100 MHz spacing proved sufficient. With relatively little time penalty (the number of tones multiplied by the pump pulse width), equally-frequency-spaced multiple pump pulsed tones were sequentially launched in [91] in order to avoid nonlinear interactions among them, as well as overloading of the optical amplifiers. Fast (a few kHz) measurements were demonstrated in [92]. Clearly, however, strain or temperature changes, which move the BFS by an amount larger than the frequency spacing between adjacent pump tones will introduce ambiguity, thereby, severely limiting the strain (temperature) dynamic range. This limitation has been recently removed by sequential interrogation of the FUT with up to three sets of multiple tones, each having a different frequency spacing. This improved SF-BOTDA method still provides a major speed advantage over the classical BOTDA in spite of the use of three sets of tones [93].

The main drawback of the technique is its complexity in terms of tones generation and information recovery.

Dynamic sensing can be also accomplished using the ROCDA technique, to be described below, where the most recent achievement is 5000 resolutions points per second. While slower than the maximum performance of some of the aforementioned BOTDA techniques, it has the advantage of being able to randomly access multiple arbitrary points along the FUT.

Dynamic Brillouin sensing, with sampling rates of hundreds of Hz/s and spatial resolution of a few centimeters, could be quite beneficial in many application scenarios, including: structural health monitoring of airplanes in general and Unmanned Aerial Vehicles (UAVs) in particular, security and surveillance, geotechnical events and more. We note, however, that a major challenge for the wide spread use of dynamic Brillouin distributed sensing is the ability of current electronic data processing systems to handle all the incoming data in real time and to display it in a useful way for the benefit of the users, preferably after mining out important user information.

Brillouin based distributed sensor has been recently utilized for real life applications such as distributed Hydrogen sensing [94], bridge monitoring [95], high temperature measurements [96] and temperature monitoring of energy piles [97].

3.5. Discrimination between strain and temperature

The Brillouin frequency shift is sensitive to both strain and temperature. Thus, a single measurement cannot differentiate between these two measurands. The simplest, though not the cheapest solution is to have two spatially close by sensing fibers with one exposed to both temperature and strain and the other to temperature only, by mechanically isolating it from the strain. Most attempts to add an independent measurement in the same fiber have been based on the use of fibers which support more than one acoustic mode, thereby demonstrating more than one Brillouin peaks. The measurement process now involves the determination of the Brillouin frequency shifts of two peaks (at least): BFS\(_1\) and BFS\(_2\). Then the dependence of these two shifts on the strain and temperature is characterized, producing the matrix relationship:

\[
\begin{bmatrix}
\Delta \text{BFS}_1 \\
\Delta \text{BFS}_2
\end{bmatrix} = C
\begin{bmatrix}
\Delta \varepsilon \\
\Delta T
\end{bmatrix}
\]  

(11)

Provided \( C \) can be accurately inverted, the separate but simultaneous distributed determination of both strain and temperature becomes possible.

Initially, specially designed fibers were used such as in [98], using a Photonic Crystal Fiber (PCF), in [99,100] using a high-delta fiber with F-doped depressed inner cladding, and in [101] using a dispersion shifted. More recently, [101,102], the more common and commercially available non-zero dispersion LEAF fiber made it possible to simultaneously measure strain and temperature with measurable resolution of 5 °C and 60 με, respectively.

Yet another approach takes advantage of the fact that two fibers are involved in BOTDA configurations: one is the sensing fiber and the other one is used to bring the Probe signal to the distant end of the sensing fiber. By choosing two fibers of different properties and exchanging their roles two Brillouin frequency shifts can be recorded and processed.

In spite of their elegance the relevant \( C \) matrices may not be always reliable invertible.

Simultaneous strain/temperature measurements can also be achieved by using a combination of Raman (sensitive only to temperature) and Brillouin (sensitive to both) distributed sensing [103a] or even a combination of Rayleigh and Brillouin sensing, taking advantage of the temperature dependence of the ratio of the intensities of Rayleigh and Brillouin backscattered light (Landau Placzek ratio) [103b].

Quite a few time-domain Brillouin interrogation techniques have been reviewed above, having a common denominator: They need access to both ends of the fiber. This extra degree of freedom
provides much better SNR and more design flexibility. However, in many practical applications access is available only to one end of the fiber. Sometimes, one of the two originally designed access points becomes unreachable. In either case, Brillouin Optical Time Domain Reflectometry (BOTDR) offers a one end interrogation technique, to be described next.

4. Brillouin Optical Time Domain Reflectometry (BOTDR)

4.1. Introduction

In Brillouin Optical Time Domain Reflectometry (BOTDR), Fig. 17, a strong coherent optical pulse of optical frequency \( \nu_{\text{pulse}} \) and duration \( T \) is launched into the fiber, say at \( z = 0 \), where \( z \) is a length coordinate along the fiber under test. The Brillouin backscattered light arriving at \( z = 0 \) at time \( t \) after the launching of the pulse, originate from Stokes and anti-Stokes contributions from a fiber segment of length \( \Delta z = 0.5V_z T \), located at distance \( z = 0.5V_z t \) into the fiber. The optical spectra of these Stokes and anti-Stokes contributions are equally shifted from \( \nu_{\text{pulse}} \) by the BFS at \( z = 0.5V_z t \), namely by: \( \pm \nu_z (z = 0.5V_z t) \), whose value is dictated by the strain and temperature at \( z \). Deducing \( \nu_z (z) \) from the arriving spectra provides information about the value of the measurands of interest at \( z \).

Measurement of the Brillouin signal around \( \nu_{\text{pulse}} \pm \nu_z \) is accompanied by parasitic light, originating from Rayleigh backscattering and Fresnel reflections from connectors, both at frequency \( \nu_{\text{pulse}} \), as well as from Raman backscattering at \( \sim 13 \) THz away from \( \nu_{\text{pulse}} \). Thus, to avoid detector saturation and elevated levels of shot noise, these parasitic signals should be filtered out and, most commonly, the Stokes backscattered signal is selected. Two main techniques are used to deduce \( \nu_z (z) \) from the received Stokes signal:

(a) In the heterodyne setup of Fig. 17 (left), the preferably filtered Stokes signal is made to interfere on the photodetector with the output of the laser that produced the launched pulse [104]. The spectrum of the generated electrical signal, \( s(t) \), is now \( \sim 11 \) GHz (for standard single-mode fibers at 1550 nm) with a bandwidth of \( \Delta \nu_z (\sim 30 \) MHz when \( T > 30 \) ns) plus the variation of \( \nu_z (z) \) along the FUT. Traditionally, \( s(t) \) has been electronically mixed with a local microwave oscillator whose frequency was carefully scanned against that of \( s(t) \), followed by narrow band filtering. This process generates the constant-frequency, distance-dependent line of Fig. 17 (right), thereby reconstructing the frequency-distance map of the backscattered light (Fig. 17 (right)), having a frequency resolution determined by the narrow band filter. The resulting distance-dependent spectral data are best fit to a known function, mostly to a Lorentzian, (5), and the frequency of the peak, which is the line trailing the maxima of the different distance-dependent spectra gives the sought-after BFS, i.e., \( \nu_z (z) \), and consequently the strain and/or temperature at \( z \). More recently, following the huge progress made in fast analog to digital converters (ADC) and digital signal processing, a fixed local microwave oscillator down shifts \( s(t) \) to the few-hundred MHz regime, where it is converted to a digital stream with a sampling rate commensurate with the required spatial resolution, as determined by \( 0.5V_z T \). The digital stream is then divided into time segments, corresponding to spatial segments along the FUT, followed by a Fourier analysis of each time segment (also known as Short Time Fourier Transform - STFT) to obtain the local BGS and deduce \( \nu_z (z) \) from a best-fit search for the frequency location of its peak value.

(b) Optical frequency discrimination: Here an optical filter, such as the Mach–Zehnder Interferometer (MZI) [106], or similar architectures, is used to process the backscattered optical signal. The MZI has a periodic transfer function proportional to \( (1 + \cos(2\pi \nu \tau)) \), where \( \tau \) is the delay between the MZI arms. If \( \tau \) is chosen such that \( \cos(2\pi \nu \tau) = -1 \) then this transfer function serves as a rejection filter to “kill” all unwanted radiation (Rayleigh backscattering and Fresnel reflection at the pump frequency, \( \nu_{\text{pulse}} \)). Alternatively, it can be used to convert measurand-induced frequency changes to easily detected intensity variations. Thus, if the device is set to have the average center frequency of the Stokes signal, \( \nu_{\text{fs}} \), sitting near or at its quadrature point, \( \nu_{\text{fs}} T/2 = 3/2 + \nu_z \), its output power is now given by:

\[
P_{\text{MZI-out}}(\nu_z(z)) \propto 1 + \cos(2\pi \nu_{\text{fs}}(z) \tau) = 1 + \cos(2\pi (\nu_{\text{fs}}(z) - \nu_{\text{fs}}) \tau + 2\pi \nu_{\text{fs}}) = 1 + \sin(2\pi (\nu_{\text{fs}}(z) - \nu_{\text{fs}}) \tau)
\]

Thus, following calibration, the MZI output power is directly proportional to \( \nu_z (z) - \nu_{\text{fs}} \). Variations of the technique include double path MZI and a combination of two MZI’s: one for rejection of signals at \( \nu_{\text{break}} \) and one for measuring the frequency of the Brillouin spontaneous backscattering [106].

BOTDR has one major advantage: it requires access only to one end of the fiber, which often is a compelling practical necessity. On the other hand, the spontaneous Brillouin backscattering is \( \sim 100 \) times weaker than the Rayleigh signal, resulting in a fairly poor SNR. This SNR can be increased by: (i) Increasing the duration of the interrogating pulse at the expense of reducing the spatial resolution; (ii) Increasing the pulse power up to a limit set by the onset of stimulated spontaneous Brillouin scattering, or other fiber nonlinearities; (iii) Employing \( N \)-times averaging (\( N > 10^4 \)) for covering a range of 30 km with 2 m of spatial resolution [17]; (iv) Employing amplification of the weak backscattered light using distributed Raman amplification and/or discrete Erbium doped fiber amplifiers (EDFAs), and finally using codes, see Appendix A.

Other issues that challenge classical implementations of BOTDR are similar to those described above for BOTDA: (i) Trying to improve the spatial resolution by shortening Tto below \( 1/\Delta \nu_{\text{fs}} \), broadens the Brillouin spectrum, with a consequential reduction

Fig. 17. A typical BOTDR setup (after [17]), where the local Brillouin frequency shift is recovered either by a heterodyne technique or through the use of a frequency discriminator, see text. Right: Frequency distance BOTDR map (after [105]).
of the sensor sensitivity to measurand variations, see Section 3.3.5; (ii) Spontaneous Brillouin scattering is not fully polarized [21], resulting in a decreased efficiency of both the heterodyne and frequency discrimination detection processes. Polarization scrambling, as well as polarization-diversity techniques have been commonly used to prevent FUT locations with polarization-penalized SNR; Finally, (iii) Insufficient extinction ratio (on/off ratio) of the pulse forming circuit gives rise to spatial crosstalk, see Section 3.3.4.

Quite a few papers have been published since 2012, aiming at improving the performance of BOTDR, either at the optical level, using more sophisticated configurations, or in the electronic processing of the Brillouin backscattering signal.

4.2. Advanced BOTDR optical setups

Delaying the onset (i.e., the threshold) of stimulated Brillouin spontaneous backscattering makes it possible to get the pump deeper into the fiber, thereby extending the measurement range. When the single frequency pump of Fig. 17 was replaced by a comb of three frequencies, equally spaced by twice the BFS, an interesting power transfer occurred among the three pumps and their induced Brillouin backscattering signals, Fig. 18. (69,107).

For the same total input pump power the threshold for stimulated Brillouin spontaneous backscattering was increased by 4 dB and for a 20 km FUT the transmitted power of the low frequency pump was enhanced by 1 dB, compared to the single frequency pump. These results indicate that the use of such a comb allows the transmission of high power pump pulse to longer distance, potentially elongating the measurement range in BOTDR. It appears that FUTs whose BFS significantly varies along their length, can also be handled by this technique, since the 2xBFS spacing requirement is not too strict [69].

Increasing the received SNR is key to improving the overall performance of a BOTDR in terms of range and sensitivity. As mentioned earlier, Section 3.3.2, the birefringence of standard single-mode fibers gives rise to polarization related ‘noisy’ trace of the BOTDR signal with reduced signal at many points along the FUT. Injecting two closely spaced, orthogonally polarized pump pulses has been shown [108] to significantly mitigate the polarization fading effect beyond that achievable with polarization scrambling, but at the expense of a twice longer spatial resolution. SNR improvement, resulting from the use of a high-extinction ratio modulator implemented by using and MZI followed by and optical switch [109], enabled measurements at the end of a 48.5 km fiber with an improved temperature accuracy of 0.8 °C and 25 m of spatial resolution.

A high-precision temperature-controlled narrowband fiber Bragg grating (FBG) filter was used in [110] to separate the Brillouin backscattering from the Rayleigh contaminating signal. Additional stability was obtained by monitoring the power of the laser source and then compensating for its variations in the post-processing stage. The experiment results demonstrated a temperature precision of ± 1 °C and temperature stability of ± 0.7 °C over a range of 8 km.

In the MZI-based, frequency discrimination BOTDR scheme, yet another way to improve performance is by increasing the discriminator sensitivity, which is defined by how much the output power changes for a given frequency change. However, a large path imbalance between the two arms of the MZI seriously impairs the stability of the interferometer, making it too sensitive to the surrounding environment. In [111] the BOTDR sensitivity was improved by almost 20 times, in comparison to the sensitivity of a double pass MZI, by invoking the phenomenon of structural slow light [25] in a non-uniform Fiber Bragg grating, serving as one of the MZI branches. Measurand-induced frequency changes are translated to corresponding changes of the optical phase shift, Δφ/Lbranch/Vg, in the FBG branch, which is proportional to the reciprocal of the group velocity. An appropriately designed FBG can demonstrate “structural slow light” performance by having a designed-in ‘sweet’ frequency operating-point, where the local group velocity is significantly reduced. Working at this point provides higher frequency discrimination sensitivity without the penalty of a long path imbalance. Incidentally, the FBG also served as an optical filter to reject backscattering at the pump frequency.

4.3. Coding in BOTDR

Golay complementary sequences coding, with good auto-correlation properties, was shown to improve the measurement SNR, without compromising the spatial resolution in [112]. A theoretical analysis and design of general coding methods in BOTDR (and all time domain distributed methods) systems with APD detectors was conducted in [113]. A dedicated hardware system for the implementation of Simplex coding in OTDR demonstrated measurement SNR improvement [114], it uses FPGAs for data decoding instead of software based data processing to speed the process and to optimize the size of the system.

4.4. Improvements via post-detection signal processing

In the Short Time Fourier Transform (STFT) technique, mentioned above, the BFS is determined from a Fourier transformation of a data segment, which corresponds to Brillouin backscattering originating from a finite fiber segment. Clearly, due to the basic properties of Fourier analysis, the longer the segment the better the frequency resolution and the better is the obtained estimate for νB. However, a longer segment means a more coarse spatial resolution (this basic problem is also shared by the frequency scanning method of Section 4.1). A more precise determination of frequency requires a narrower spectral filtration which may smooth fast varying values of strain/temperature along the fiber). In [115] the Fourier kernel was replaced by a more computationally complex one belonging to the so-called Cohen’s class, thereby improving the frequency accuracy by a factor of 3 without worsening the spatial resolution.

In practical BOTDR systems the spatial resolution is often longer than 0.5νB/T due to a finite electronic bandwidth or limited sampling rate of the ADC. Under normal processing a point event will show a width commensurate with the effective spatial resolution. An iterative subdivision algorithm, [116], based on energy density distribution in combination with a cross correlation algorithm method, can deconvolve the data, resulting in a significantly narrower signature of the point event. The paper claims 1.5 m of spatial resolution in 50 km of sensing fiber when probed by a 100 ns pulse, which normally exhibits no better than 10 m of spatial resolution. Similarly, 0.1 m of spatial resolution was obtained in 1 km of sensing fiber when probed by a 10 ns pulse, which normally exhibits no better than 1 m of spatial resolution. It
remains to be seen how efficient the method is for extended events.

A common signal processing method in sweep-frequency heterodyne BOTDR employs envelope detection of the amplitude-modulated intermediate frequency signal from the heterodyne receiver. In [117] a fast Digital Envelope Detection (DED) method, based on generalized harmonic wavelet transform is employed. The trade-off between BFS accuracy, spatial resolution and measurement speed, induced by common DED methods, is reported to be significantly improved.

In [118] STFT was employed, in a direct detection BOTDR setup, to demonstrate dynamic measurement of 17 Hz vibrations at the end of a 270 m fiber with 4 m spatial resolution.

Some examples for BOTDR based applications are: landslide thrust on anti-sliding pile monitoring [119], submerging test of precast piles [120], monitoring anti-sliding pile internal force [121], roof fall and collapse in coal mines [122], steel structures damage detection [123], crack detection [124], strain and temperature measurement of Optical Fiber Composite Overhead Ground Wire (OPGW) [125], corrosion monitoring of a concrete column with central rebar [105], bridge monitoring [126], submarine cable monitoring [127] and for the detection of sinkhole formation [128].

Distributed birefringence measurement, using BOTDR, was accomplished in BOTDA by measuring the power changes of the Brillouin beat spectrum of a large effective area fiber (LEAF) [129].

Brillouin interrogators are known for their relatively high cost. A potentially low cost BOTDR readout chip was realized in [130], using the basic heterodyne-type architecture. The InP photonic integrated circuit included a tunable laser, an MZI pulse former and a coherent receiver with photodiodes. No sensing results were reported.

In summary, in spite of the relative weakness of the spontaneous Brillouin backscattered signal, BOTDR has found many applications, especially where access is available to only one end of the fiber.

5. Brillouin Optical Frequency Domain Analysis (BOFDA)

The time domain probing at a given optical frequency using a temporal pulse can be replaced by interrogating the fiber with an RF modulated CW wave of the same optical frequency, while scanning the RF modulation frequency over a range commensurate with the RF spectral contents of the temporal pulse. Using a network analyzer, a complex transfer function is obtained, from which, Fourier analysis can produce the same trace as obtained by the temporal pulse. While the CW nature of the measurement offers advantages such as a much higher SNR and the use of relatively slow inexpensive electronic sampling circuitry, the additional need to sweep the RF frequency significantly prolongs the measurement process, as compared with BOTDA [131–133]. High spatial resolution (~3 cm) was demonstrated with BOFDA [134]. An iterative correction algorithm was used to minimize artifacts associated with acoustic wave relaxation when the interrogated fiber has a non-uniform Brillouin profile. Some recently presented variants of the traditional BOFDA method include a single ended variant [135], where Fresnel reflection is utilized to reflect the probe wave from the far end of the fiber, and a hybrid BOFDA/FBG sensor system offering simultaneous distributed and quasi-distributed sensing abilities [136]. A BOFDA based measurement was recently realized in Polymer Optical Fiber (POF) [137] showing the potential of POFs based SBS.

6. Brillouin Optical Correlation Domain Analysis (BOCDA) and Reflectometry (BOCDR)

Localization in SBS-based distributed sensing is achieved by spatially selective excitation of the acoustic field, a mission accomplished in BOTDA by the finite extent of the propagating pulsed pump. Too short pump pulses, however, successfully define the resolution cell but fail to allow the acoustic field to develop to its full strength and narrow (~30 MHz) spectral characteristics, resulting in a weaker and spectrally wider SBS interaction. It turns out that localization of the Brillouin interaction can also be achieved by judicious tailoring of the pump and probe waves to provide extremely high spatial resolution (down to millimeters) without compromising the width of the BGS.

6.1. BOCDA with sinusoidally modulated pump and probe frequencies

6.1.1. Classical BOCDA

The original paper, [139] proposed to (sinusoidally) frequency modulate the pump and probe waves in a correlated manner so that the acoustic field enjoys a stable buildup only at predetermined locations. Following [17] we assume the pump and probe waves to be of the form:

\[
E_{\text{pump}} = A_{\text{pump}} \exp \left\{ i \left( k_{\text{pump}} - k_{\text{probe}} + \Delta f \cos(2\omega_{m}(t - z/V_s)) \right) \right\}
\]

\[
E_{\text{probe}} = A_{\text{probe}} \exp \left\{ i \left( k_{\text{pump}} - k_{\text{probe}} + \Delta f \cos(2\omega_{m}(t - (L - z)/V_s)) \right) \right\}
\]

where \(\Delta f\) is the amplitude of the frequency modulation and \(f_m\) its frequency.

Thus, at those locations obeying:

\[
z_k = 0.5 \left( L - k \frac{V_s}{f_m} \right), \quad k = \ldots -2, -1, 0, +1, +2, \ldots
\]

the \(\Delta f\) term in (14) is zero and \(\nu(z_k, t)\) has a time-independent value of \(\nu = \nu_{\text{pump}} - \nu_{\text{probe}}\), as if the fiber were interrogated by CW waves, Fig. 19:

Thus, the BFS at any of these \(z_k\) can be simply obtained by scanning \(\nu = \nu_{\text{pump}} - \nu_{\text{probe}}\) over the appropriate frequency range and then looking for the location of the peak of the measured BGS. Note that when \(\nu\) assumes the value of the local BFS, \(V_s(z_k)\), a complete and stable buildup of the acoustic field is guaranteed. Also, the width of the measured BGS should ideally be as narrow as obtained from a CW interrogation. However, as \(z\) departs from
the correlation peaks of (15), the \( \Delta f \) term in (14) is no longer zero, and the efficiency of the acoustic field buildup quickly deteriorates since \( \nu(z, t) \) differs from the local BFS, \( \nu_g(z) \), even when \( \nu_{\text{pump}} - \nu_{\text{probe}} = \nu_g(z) \). The spatial resolution of this method, \( \Delta z \), is expected to be related to the BFS linewidth, \( \Delta \nu_B \), since there is no appreciable buildup of the acoustic field once the pump-probe frequency difference exceeds \( \Delta \nu_B \). Indeed, it has been shown [139] that:

\[
\Delta z \approx \frac{v_g \Delta \nu_B}{2 \pi \Delta f_{\text{fm}}}
\]  

(16)

In the BOCDA method [139–141] the fiber is spatially scanned point by point by changing \( f_z \) in (15). To avoid the simultaneous probing of more than one location along the fiber, the FUT length, \( L \), must be maintained shorter than the distance between neighboring \( \{z_k\} \) in (15), \( L \leq V_f /(2f_{\text{fm}}) \). There is, therefore, a trade-off between the length of the FUT and the desired spatial resolution: \( \Delta z \) can be made smaller by increasing \( \Delta f \) and \( f_{\text{fm}} \), but \( \Delta f \) cannot come too close to \( \nu_g \) (otherwise the distinction between the unwanted backscattered pump light and probe frequencies will not be possible) and increasing \( f_{\text{fm}} \) shortens \( L \) and consequently the FUT length, \( L \). It has been pointed out [17] that in its basic configuration BOCDA can handle up to no more than \( l_p / \Delta z \approx 600 \) resolution points, as opposed to much higher values in BOTDA. On the other hand, quite early in its development the BOCDA has demonstrated spatial resolutions down from \( \sim 1 \) cm [139] to \( \sim 1 \) mm [142].

The original BOCDA configuration has gone through many improvements aiming to address a few limiting issues (see recent reviews [138] and [141]):

6.1.2. Range extension

Using additional time domain gating, it has become possible [143] to remove the ambiguity among the multiple co-existing correlation peaks \( L > L_f \), thereby demonstrating a 1 km sensing range with 7 cm spatial resolution;

6.1.3. Measurement speed

The point-by-point spatial scanning, on top of the required frequency sweep of \( \nu_{\text{pump}} - \nu_{\text{probe}} \) is quite time consuming. Modulating the optical frequencies of the pump and the probe waves at slightly different frequencies, the temporal position of the measurement was continuously and repeatedly swept along the fiber under test, achieving a repetition rate of 20 Hz over 100 m with a spatial resolution of \( \sim 80 \) cm [75]. Recently, using a voltage-controlled oscillator for faster sweeping of the probe wave frequency and higher-speed receiver electronics a dynamic strain measurement speed of 5,000 points/s was demonstrated with a spatial resolution of 3 cm, emphasizing the unique advantage of BOCDA over the otherwise faster BOTDA, in its ability to randomly access arbitrary multiple points along a fiber [144]:

6.1.4. Disturbance from points away from the correlation peaks

The oscillating acoustic fields at the many more off-correlation locations along the fiber causes the narrow (\( \sim 30 \) MHz) Brillouin spectrum to ride on a much wider skirt. Originally recognized in [139], it had been claimed there to be dealt with using post-processing. A recent improvement has appeared in [145]. Using an additional phase modulation of the pump to reconstruct just the disturbing skirt of the spectrum, and then subtracting the result from a normal BOCDA measurement, a fivefold enhancement of the result of (16) was demonstrated. The same differential approach was also successfully applied to a linearly configured BOCDA, where both pump and probe enters the fiber from only one side and an end mirror is used to make the two waves counter propagate [146].

6.2. Phase modulated BOCDA

An important extension of the original BOCDA techniques has been proposed and demonstrated by A. Zadok’s group. Fast randomly changing phase, rather than sinusoidal frequency is now used for the localization of the induced acoustic field. Initially, [147], a single pseudo-random sequence of 0/\( \pi \) bits, each of duration \( T_{\text{bit}} \), was used to modulate the CW pump and probe waves, Fig. 20. Assume now that the launching times of this sequence into the two sides of the fiber is set such that a pre-chosen arbitrary point, \( z’ \), in the fiber is at equal time delays from the source of the random sequence.

Clearly, regardless of their particular values, the phases of the bits arriving at \( z’ \) from the two directions, are always the same, either both are zeros, or both are \( \pi \). Thus, as long as these two counter-propagating equal phases overlap (\( \sim T_{\text{bit}} \)), the product term \( A_{\text{pump}}(z’, t)A_{\text{probe}}^*(z’, t) \), which drives the acoustic field in (2.3), is always positive during \( \sim T_{\text{bit}} \), constantly contributing to the creation of a stable acoustic field at \( z’ \). Provided \( T_{\text{bit}} \) is much shorter than the acoustic life time, \( \tau_A \), and provided the random sequence is long enough, \( A_{\text{pump}}(z’, t)A_{\text{probe}}^*(z’, t) \) averages to zero at all points other than \( z’ \). Thus, Brillouin amplification occurs only along a segment of the order of \( V_f T_{\text{bit}} \), centered around \( z’ \), and scanning the frequency of the pump against that of the probe will provide the BFS at \( z’ \) with a spatial resolution of \( V_f T_{\text{bit}} \). The sensed location can be moved along the fiber by controlling the delay between the instances the random sequences are launched into the pump/probe ends of the fiber. For \( T_{\text{bit}} = 100 \) ps, a spatial resolution of 1.7 cm was demonstrated.

While seemingly offering unlimited number of resolution points, a few issues with the basic method of [147] have been taken care of in subsequent publications. First, it has been noted that the spatial region of sustained Brillouin amplification is governed by the spatial extent of the autocorrelation function of the sequence [147]. As a result, non-zero sidelobes of the auto-correlation function contaminate the probe with unwanted gain contributions from regions other than the resolution cell of interest. Consequently, the pseudo-random phase sequence, having a relatively widely spread autocorrelation function, was replaced by perfect Golomb codes, having a periodic correlation with theoretically zero sidelobes [149,150]. Second, scanning a long fiber with this now-available high resolution may take impractically long time. Thus, a hybrid BOTDA/BOCDA technique has been proposed [151,152]. This time only a short phase sequence is used, giving rise to multiple correlation peaks along the FUT. If the pump is additionally pulsed, as in BOTDA, this travelling pulse will sequentially interrogate the different correlation peaks. With a
pump pulse duration shorter than the distance between the correlation peak and long enough to allow the high-rate phase sequence to fully excite the acoustic field, this hybrid BOTDA/BOCDA technique significantly accelerates the measurement speed, as the information about the individual correlation peaks can now be extracted during post-processing of the Brillouin amplified probe signal. While speeding up the measurement process, the Brillouin amplification of a short spatial resolution cell is quite weak, requiring substantial averaging for an acceptable SNR. Boosting the amplification by a stronger pump power is bounded by unwanted nonlinear effects. This hurdle is overcome by replacing the pump pulse by a coded amplitude sequence, which spreads the pump energy, while preserving the spatial extent using correlation processing of the received amplified probe. These combined techniques have culminated by measuring 110,000 resolution points with only 499 scans of the correlation peaks, achieving a spatial resolution of 2 cm along a 2.2 km long fiber [154]. With a similar concept, a measurement system based on phase correlation combined with temporal pump gating, ~1,000,000 sensing points were resolved when a 14 mm spatial resolution was demonstrated over a fiber length of 17.5 km, marking the highest number of resolved points ever demonstrated [155].

Finally, replacing the phase modulated sequence by the noisy output of an amplified spontaneous emission optical source (filtered to a bandwidth of 25 GHz), [156] achieved a spatial resolution of 4 mm over a 5 cm fiber.

6.3. BOCDR

A one end access variant of BOCDA is Brillouin Optical Correlation Domain Reflectometry (BOCDR) [157]. Here, the spontaneously backscattered light excited by a frequency modulated CW pump is heterodyned with a frequency modulated portion of the pump source. As in BOCDA, correlation peaks are defined and methods have been developed to isolate just one peak and remove background noise from non-correlation locations. Recently using double frequency modulation and phase modulation 5 cm spatial resolution was demonstrated over a 1250 m fiber [158].

Brillouin based distributed sensing has been recently utilized for real life applications such as distributed Hydrogen sensing [94], bridge monitoring [95], high temperature measurements [96] and temperature monitoring of energy piles [97].

7. Brillouin Dynamic Grating Distributed Sensing

7.1. Introduction

Brillouin Dynamic Gratings (BDG) in Polarization Maintaining (PM) fibers, [159], have recently gained considerable attention due to their highly controlled generation mechanism and wide range of possible applications, including: high spatial resolution distributed sensing of strain and temperature [130,143–144], reliable separation of these two measurands [130,143–144], distributed birefringence measurements [162] optical delay lines [163,164], all-optical calculus [165,166], and microwave photonic filters [167].

In BDG, Fig. 22, two pumps, \( P_{\text{PumpH}} \) and \( P_{\text{PumpL}} \), counter-propagate in a polarization maintaining (PM) fiber, with their polarizations parallel to the slow axis of the fiber. As in previously described SBS interactions, these co-polarized pumps interfere to generate (via electrostriction) a density disturbance in the fiber with a temporal frequency of \( v_{\text{PumpH}} - v_{\text{PumpL}} \) and a spatial frequency of \( 2\pi n_{\text{slow}} (v_{\text{PumpH}} + v_{\text{PumpL}})/c \).

For a long enough interaction duration of the two pumps (CW pumps or pulsed pumps of duration much longer than \( \tau_{\text{c}} \)), the dependence of the strength of this density wave on \( v_{\text{PumpH}} - v_{\text{PumpL}} \) follows the BGS Lorentzian shape of (5), attaining its maximum value at the local BFS of the slow axis,

\[
\nu_{\text{BFS-Slow}} = (2\pi n_{\text{slow}} V_A / P_{\text{PumpH}} / c),
\]

with a narrow linewidth of \( \sim 30 \text{ MHz} \) for standard PM fibers at \( \sim 1550 \text{ nm} \). This Brillouin-induced longitudinal acoustic wave, acting as a refractive index moving Bragg grating, is used to interact with a third, linearly polarized optical wave (Probe), which is polarized parallel to the fast axis of the fiber, having a refractive index of \( n_{\text{fast}} \). For a Stokes BDG scenario, Fig. 22, a Probe of frequency \( v_{\text{Probe}} \) is injected into the fiber from the same side as the strong writing pump \( P_{\text{PumpH}} \) and propagates in the direction of the moving Bragg grating. The receding periodic grating can efficiently reflect the Probe into a backward-propagating fourth wave, \( \text{ProbeR} \).

Fig. 22. Generation of a BDG by two counter-propagation vertically polarized pumps: \( P_{\text{PumpH}} \) and \( P_{\text{PumpL}} \), with \( v_{\text{PumpH}} > v_{\text{PumpL}} \). The resulting longitudinal acoustic wave acts as a refractive index grating for the horizontally polarized probe, reflecting it into a horizontally polarized \( \text{ProbeR} \).
also polarized parallel to the fast axis, provided the frequencies and wavelengths of Probe and ProbeR phase-match those of the induced grating. Strict phase matching, and consequently maximum Probe reflectivity is obtained when [29]:

\[
\nu_{\text{Probe-Max}} = \nu_{\text{PumpH}} + \nu_{\text{PumpL}}(\nu_{\text{slow}} - \nu_{\text{fast}})/\nu_{\text{fast}} \quad \text{and} \\
\nu_{\text{ProbeR}} = \nu_{\text{Probe}} - 2\nu_{\text{fast}} \nu_{\text{Probe}}/c,
\]

(18)

In commercially available PM fibers \(\nu_{\text{Probe}}\) must be set higher than \(\nu_{\text{PumpH}}\) and \(\nu_{\text{PumpL}}\) by a few tens of GHz. Thus, the back-reflected ProbeR can be clearly measured: not only are both PumpH and PumpL orthogonal to ProbeR, so high quality polarization beam-splitters can effectively attenuate them, but spectral filtering can also be used to efficiently isolate ProbeR, which lies tens of GHz away from both pumps. Moreover, contrary to all previously described methods, here we have complete separation between the generation of the acoustic field and its interrogation, offering, in principle, unlimited spatial resolution, subject, of course, to SNR considerations.

Assume a y-polarized Probe pulse of duration \(T\), propagating through a fiber, where a BDG was established by two PumpH and PumpL waves. The reflectivity of the Probe at position \(z\) along the induced grating \(R(z)\), depends on the strength of the grating, as determined by \(\Delta \nu_{\text{BGS}} \equiv \nu_{\text{ProbeH}} + \nu_{\text{ProbeL}}(\nu_{\text{slow}} - \nu_{\text{fast}})/(2\nu_{\text{fast}}\nu_{\text{Probe}})\) (\(\Delta \nu_{\text{BGS}} = 0\) corresponds to maximum grating strength), as well as by the deviation of the Probe frequency from the optimum condition of (18): \(\Delta \nu_{\text{BDG}} \equiv \nu_{\text{Probe}} - \nu_{\text{ProbeH}} - \nu_{\text{ProbeL}}(\nu_{\text{slow}} - \nu_{\text{fast}})/(2\nu_{\text{fast}}\nu_{\text{Probe}})\). Modelling the BDG as a weak grating of length \(L_{\text{Grating}} = 0.5\nu_{\text{y}}Ti\), this reflectivity can be approximately expressed by [168] (in (19))

\[
R(\Delta \nu_{\text{BGS}}(z), \Delta \nu_{\text{BDG}}(z)) \\
\propto \left[\frac{\Delta \gamma_{\text{B}}}{\Delta \nu_{\text{BGS}}(z)}\right]^2 + \left[\frac{\Delta \gamma_{\text{BDG}}}{\Delta \nu_{\text{BDG}}(z)}\right]^2 \times \text{sinc}^2\left[\frac{\Delta \nu_{\text{BDG}}(z)\nu_{\text{c}}}{L_{\text{Grating}}}\right],
\]

(19)

which is a product of a narrow (\(\Delta \nu \sim 30\) MHz) Lorentzian-shaped Brillouin spectrum and the reflection spectrum of a weak grating whose width is inversely proportional to the duration of the Probe pulse [169].

Distributed BDG sensing is accomplished by scanning the frequency of PumpL against that of PumpH, and for each value of their frequency difference, \(\nu_{\text{PumpH}} - \nu_{\text{PumpL}}\), the reflectivity of the Probe pulse is measured. This process characterizes the narrow BGS of the interacting pumps, resulting in the accurate determination of the measurand-dependent value of the BFS of the slow axis along the fiber (since normally the reflection spectrum of the induced grating is much wider than \(\Delta \nu_{B}\), there is no need to adjust the Probe frequency for each different value of \(\nu_{\text{PumpH}} - \nu_{\text{PumpL}}\)). Again, in BDG sensing there is no linkage between the measurand sensitivity, benefitting from the narrow SBS spectrum of the fast axis, and spatial resolution solely determined by the width of the Probe pulse. Arbitrarily high resolution can be obtained at the expense of a decreasing SNR. A sub-centimetric spatial resolution was demonstrated in [161] using a 55 ps Probe pulse. Intensity modulation can be used to apodize and suppress the side lobes such that the locality of the BDG, and as a consequence the measurement spatial resolution, will be significantly improved [170].

7.2. Distributed dynamic sensing using Brillouin dynamic gratings

The slope-assisted BOTDA technique of Section 3.4.1 can be also applied to the slope of \(R(\Delta \nu_{\text{BGS}}(z), \Delta \nu_{\text{BGS}}(z))\), (18). Adjusting the pair of operating frequencies, \(\{\Delta \nu_{\text{BGS}}(z), \Delta \nu_{\text{BDG}}(z)\}\) to their values which maximize the response of the probe reflectivity \(R(\cdot)\) to changes of the measurand, 400 Hz of strain vibrations were sampled at an effective rate of 16 kHz (following 500 averages), with a spatial resolution of 4.2 cm [168]. As mentioned above, short Probe pulses suffer result in low SNR per a single interrogation, requiring averaging that limits the effective sampling rate. In order to extend the measurement capabilities of the technique to the ultrasonic regime, while further shortening the pulse width, coding was employed. The slope-assisted, direct detection BDG setup of [168] was augmented with a 256 long Golay unipolar coding of the Probe [172] to achieve record sensitivity of 50 nε/√Hz, while measuring 10 kHz of strain vibrations with a spatial resolution of 2 cm. The use of direct detection, which necessitates a unipolar code, limits the choice of \(\Delta \nu_{\text{BDG}}(z)\) to values very close to zero, compromising performance. This restriction was alleviated in [171], where bipolar coding and coherent detection in BDG-SA-BOTDA were demonstrated, see Fig. 23.

7.3. Discrimination between temperature and strain

The values of the optical frequencies providing maximum strength of the Brillouin dynamic grating, \(\nu_{\text{BGS-Slow}}\), (17), and maximum Probe reflectivity, \(\nu_{\text{Probe-Max}}\), (18), depend on the local strain and temperature. \(\nu_{\text{BGS-Slow}}\) mainly depends on these two measurands through their effects on the acoustic velocity, \(V_{\text{A}}\), \(\nu_{\text{Probe-Max}}\), however, depends on the fiber local birefringence, \((\nu_{\text{slow}} - \nu_{\text{fast}})/(\nu_{\text{fast}})\), which is also a function of the two measurands, albeit characterized by an independent functional dependence. Thus, distributed sensing of strain and temperature should now be performed by scanning not only \(\nu_{\text{PumpH}} - \nu_{\text{PumpL}}\) but also \(\nu_{\text{Probe-Max}}\) so that both \(\nu_{\text{BGS-Slow}}\) and \(\nu_{\text{Probe-Max}}\) can be measured. Their deviations,

---

**Fig. 23.** (a) Two normalized time records of the vibrating segment of the fiber. The red (noisier) belonging to the case where a single pulse was launched into the FUT, and the blue (quieter) to the case where a 64 bit code was used. (b) Dynamic strain measured as a function of time and fiber location, when 20 cm section of the FUT vibrates at 750 Hz. (after [171]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
\[ \Delta \text{BFS}_{\text{Slow}} \text{ and } \Delta \text{Probe}_{\text{Max}}, \text{ from an arbitrary initial state, are then related to changes of } \Delta \varepsilon \text{ and } \Delta T \text{ through a } 2 \times 2 \text{ matrix } C \text{.} \] 

\[
\begin{bmatrix}
\Delta \text{BFS}_{\text{Slow}} \\
\Delta \text{Probe}_{\text{Max}}
\end{bmatrix} = C
\begin{bmatrix}
\Delta \varepsilon \\
\Delta T
\end{bmatrix}
\]

\[
\begin{bmatrix}
0.03938 \text{ MHz/}\mu\text{e} \\
0.8995 \text{ MHz/}\mu\text{e}
\end{bmatrix} + 1.0580 \text{ MHz/}^0\text{C} \begin{bmatrix}
\Delta \varepsilon \\
\Delta T
\end{bmatrix}
\]

(20)

which is very reliably invertible to obtain accurate estimates of \( \Delta \varepsilon \) and \( \Delta T \)[138].

8. Specialty fibers and miscellaneous topics

It is of importance to mention that up to now Brillouin scattering has been investigated not only in silica-based optical fibers. Researchers have been constantly looking for fibers with higher Brillouin efficiencies. Some of these specialty fibers include: Tellurite glass fibers [176, 177], As2Se3 Chalcogenide fibers [178, 179], and Bismuthoxide fibers [180, 181]. The Brillouin effect and its application to sensing have also been investigated in Photonic Crystal fibers [PCF] e.g. [182, 183] and in Plastic Optical Fibers (POF) e.g. [137, 184], (all citations in this section are only representative).

The sensitivity of the BFS to temperature and strain can be substantially increased by placing the fiber under test in a cavity to produce a frequency comb of high order Stokes lines [192]. Since each Stokes order (2\(^{nd}\) and higher) is driven by its lower order counterpart, it is only to be expected that the sensitivity of its BFS to temperature and strain will be proportional to its order number. Indeed, by using the sixth-order Stokes line the temperature sensitivity of the BFS in a standard silica-based fiber was demonstrated to increase six-fold to ~7 MHz/°C, with a similar potential increase of the strain sensitivity to ~0.30 MHz/\mu e [192].

It should also be noted that while strain and temperature were the ‘star’ measurands in this review, Brillouin-based distributed sensing of other measurands, such as humidity [193], and also [194] and pressure [195] has also been demonstrated.

9. Summary

In this paper we have attempted to review the state of the art in Brillouin-based fiber-optic distributed sensing. The various interroga-
tion techniques have been described and recent achieve-
ments have been discussed (and, regrettably not all recent work could be referenced). Besides many small improvements, the major progress of the last few years has been in extending the measurement range, in improving the spatial resolution, in making Brillouin distributed sensing a dynamic technique, and last but not least in better understanding of the physics behind the various interrogation methods. These achievements should open new markets, e.g., in structural health monitoring of dynamic structures, which require distributed sensing (the locations of emerging problems is not known in advance), high spatial resolution (damages of critical concern are small) and dynamic performance (airplanes and many other structures are constantly vibrating). However, pushing these advances into the commercial arena may critically depend on proper dissemination of the technology among potential users, and most importantly, by providing standards and guidelines [173, 174]. Clear performance specifications are necessary to allow products comparison (see [32] for a recently proposed figure of merit), to insure proper use, and proper installations and maintenance of both interrogators and sensing fibers. Sensor systems should be also seriously validated according to a generally agreed or well-developed standard, otherwise they would not be accepted for intelligent structures design and construction, especially for safety-relevant functions. A standard on strain distributed measurements based on Brillouin scattering effect is currently under consideration. More standards were recently presented in [175]. Another disturbing issue is the high cost of current systems.

Brillouin distributed sensing has been a fascinating research field. Since the original publication of Horiguchi and Tateda [13], tremendous progress has been made. Hurdles, considered unsurmountable, have been leapt over, and every time it was felt limits have been reached, new surprising ideas have pushed the technology even further. We thus hope that this trend will continue and Brillouin distributed sensing will further develop into an extremely useful sensing technology widely employed by many industries, filling monitoring needs no other technology can provide.

Note added in proof

The proofs of this review arrived at the end of the 24th International Conference on Optical Fibre Sensors [191], where many papers were devoted to Brillouin-based fiber-based distributed sensing. Many performance characteristics of current implementations have been improved (e.g., the simultaneous achievement of both high spatial resolution and long sensing range; the removal of non-local effects and more), novel and/or simpler setups have been demonstrated for the measurement of both the magnitude and phase of the BGS along with new applications, and image processing of the Brillouin frequency distance map has been shown to significantly improve the achievable SNR, and consequently the measurement accuracy. The interested reader is encouraged to consult the conference proceedings [191].

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Appendix A

Many fiber-optic sensing systems rely on the transmission of a short and intense pulse down the fiber, followed by the measurement of the reflected/backscattered light. In most cases, the received SNR and the accuracy of the measurement depend on the energy of the pulse, which is determined by its peak power and duration. In practical systems, the available pulse peak power may be limited, and more than often it cannot be increased indefinitely due to the onset of optical nonlinear effects. Hence, there exists a fundamental trade-off between the sensor spatial resolution, being proportional to the pulse width, and the signal-to-noise ratio. Coding techniques offer the possibility of providing measurements with improved SNR without sacrificing spatial resolution. The relevant coding techniques that are mostly used in fiber-optic distributed sensing can be roughly divided into two types: correlation techniques (pulse compression), and simplex coding.

Pulse compression is a well-established signal processing technique, widely used in radio-frequency (RF) and microwave radar systems [185]. Let \( p(t) \) represent the transmitted, possibly quite long coded field waveform, comprising a pre-chosen sequence of short pulses of width \( T_{\text{chip}} \). The backscattered/reflected electromagnetic field, \( y(t) \), is then given by the convolution of the input waveform with the fiber response, \( h(t) \), \( y(t) = p(t) \otimes h(t) \). Unwrapping of the coding action is done by correlating \( y(t) \) with \( p(t) \):

\[
p(t) \ast y(t) = p(t) \ast [p(t) \otimes h(t)] = \{p(t) \ast p(t)\} \otimes h(t). \tag{A.1}
\]
where correlation of two generally complex (possibly including phase) sequences, is defined here as (the superscript * inside the summation denotes complex conjugation):

$$\{x_k\}^* \{y_k\} = \left\{ \sum_{m=0}^{N-1} x_m^* y_{m+k}, \quad k = 0 \ldots (N-1) \right\} \quad (A.2)$$

Ideally, we would like the pulse compression code correlation function to be an amplified Dirac delta function with zero sidelobes, $p(t)^*p(t) \approx N\delta(t)$, yielding:

$$p(t)^*y(t) \approx N\delta(t) \otimes h(t) = N\ h(t) \quad (A.3)$$

In practice, the width of the correlation peak is of the order of the width of the code building blocks, $T_{\text{chip}}$, and non-zero sidelobes may exist. Also, the summation operations involved in the correlation procedure increase the standard deviation of the noise by a factor of $\sqrt{N}$. Thus, the overall coding gain is of the order of $\sqrt{N}/N$. Finding optimal codes for different radar applications has kept engineers busy from the early days of radar [186]. For example: in fiber-optic sensing scenario dominated by distributed scattering the total power from the sidelobes, also known as the integrated sidelobe level (ISL), is of prime importance. On the other hand, if the application requires detection of discrete events, then the peak sidelobe level (PSL) must be minimized.

$$p(t)^*y(t) \text{ of (A.1)} \quad \text{the \ 'matched-filtering' \ choice for the correlation kernel, maximizing the SNR in the presence of additive white noise and assuming the bandwidth of the fiber response is much wider than the bandwidth of the transmitted waveform. If, however, the desired ISL or PSL performance cannot be achieved using } p(t) \text{, then a mismatched filter [187], may be employed to achieve the desired sidelobe levels although at the expense of some SNR reduction. Most fiber-optic distributed sensors employ direct detection where the phase of the backscattered/reflected wave is totally lost in the receiver, almost always precluding the use of bi-polar or phase codes. Coherent detection, while more complex and expensive to implement, can, in principle, handle any type of code.

So what is the real gain of codes? After all, they require the transmission of many pulses. Had we sent the same number of pulses and averaged the resulting multiple traces we would have achieved the same spatial resolution and SNR improvement of the code! It turns out that the use of codes may save substantial measurement time. Imagine a sensing length, with a round-trip time of flight $T_{\text{fiber}}$, which is the minimum duration between consecutive isolated pulses (e.g., 500 $\mu$s for a 50 km fiber length).

Sending and receiving $N$ isolated pulses of width $T_{\text{chip}}\sim 10$ ns would take $NT_{\text{fiber}}$ [µs], while using an $N$-long compression code takes only $T_{\text{chip}} + NT_{\text{chip}}$ (ignoring processing time). Since normally $T_{\text{fiber}} >> T_{\text{chip}}$ ($500 \mu$s vs. 10 ns) the time saving is quite significant!

A pulse compression code often used in fiber-optic distributed sensing is the Golay complementary-correlation aperiodic code. When properly transmitted and processed it is an ‘ideal’ code, having zero sidelobes. Basically bipolar, a pair of $N$-long sequences $(A_k)$ and $(B_k)$ is said to be complementary if the sum of the autocorrelations of the two sequences is zero for all non-zero shifts: $(A_k)^* (A_k) + (B_k)^* (B_k) = 2N\delta_k$. If the transmitter and receiver are capable of generating and detecting complex waveforms, then the sequences $(A_k)$ and $(B_k)$ are separately transmitted to probe the system under test. The received sampled responses, $(y_m^a)$ and $(y_m^b)$, being the convolutions of the code with the sampled system impulse response, $(h_n)$, are then cross-correlated with $(A_k)$ and $(B_k)$, and the results are summed to give:

$$\{A_k\}^* \{y_m^a\} + \{B_k\}^* \{y_m^b\}$$

$$= \{A_k\}^* \{(A_k) \otimes [h_n]\} + \{B_k\}^* \{(B_k) \otimes [h_n]\}$$

$$= \{[(A_k)^* (A_k)] \otimes [h_n]\} + \{[(B_k)^* (B_k)] \otimes [h_n]\}$$

$$= (2N\delta_k) \otimes [h_n] = 2N\delta_k \otimes [h_n]$$

$$\text{SNR} \approx 2N$$

The coding gain is $\sqrt{N}$, rather than $\sqrt{2N}$ since the performance of the two transmitted sequences has to compete with the transmission of two isolated pulses, whose averaged returns provides an SNR which is also $\sqrt{2}$ larger than that resulting from the return from a single pulse.

If the system is incoherent or either the transmitter or the receiver is incapable of generating or detecting complex waveforms, the use of Golay bipolar code is precluded. A modified Golay unipolar code is obtained from the bipolar one by transmitting the bipolar code on a bias, thereby generating four sequences [188]:

$$A_1 = \frac{1}{2} \{[A_k] + \{B_k]\}$$

$$A_2 = \frac{1}{2} \{[B_k] - \{A_k]\}$$

$$B_1 = \frac{1}{2} \{[B_k] + \{A_k]\}$$

$$B_2 = \frac{1}{2} \{[B_k] - \{B_k]\}$$

By subtracting the measured backscattering signals in pairs:

$$\{y_m^a\}^1 - \{y_m^a\}^2, \quad \{y_m^b\}^1 - \{y_m^b\}^2$$

the signal components generated by the bias are cancelled, whereas the components generated by the codes are reinforced. By correlating these differences with their respective codes and summing the results, an estimate of the fiber response is obtained:

$$\{A_k\}^* \{y_m^a\} + \{B_k\}^* \{y_m^b\}$$

$$= \{A_k\}^* \{(A_k) \otimes [h_n]\} + \{B_k\}^* \{(B_k) \otimes [h_n]\}$$

$$= \{[(A_k)^* (A_k)] \otimes [h_n]\} + \{[(B_k)^* (B_k)] \otimes [h_n]\}$$

$$= \{[(A_k)^* (A_k) + (B_k)^* (B_k)] \otimes [h_n]\}$$

$$= 2N\delta_k \otimes [h_n] = 2N\delta_k \otimes [h_n]$$

Again, considering the fact that we are sending 4 sequences the coding gain is only $\sqrt{N}/2$.

Simplex coding is of an entirely different nature [189]. The codes, which are all positive, are defined by the rows of an $NN^2$ binary, so-called $S$-matrix, which is derived from Hadamard matrix of order $N + 1$. All rows are sequentially transmitted and separately received. For each row, the received signal is a weighted sum (as defined by the code in the corresponding row) of delayed versions of the system basic response. The column vector comprising the received signals for each launched code is then multiplied by the inverse of the $S$-matrix, and the result is a column vector of delayed and amplified estimates of the system response. Since it turns out that these $N$ estimates are delayed versions of one another, additional improvement is obtained by taking their average, following the necessary time shifts. The final trace has a coding gain of $(N + 1)/(2\sqrt{N})$ over the average of traces obtained from $N$ isolated pulses. When compared to the result from a single isolated pulse, simplex codes improve the measurement SNR by a factor of $(N + 1)/2$.

Simplex codes are unipolar, and, thus, perfectly suit most of the fiber-optic distributed sensing techniques, where the measured quantity is the (positive) optical intensity. Also, simplex codes can accommodate (known) variability in the heights of the transmitted chips, a variability that results in measurement artifacts (sidelobes) for pulse compression codes. On the other hand, if the length of sensing fiber significantly exceeds that of the code, and measurement time is at premium, correlation codes are preferred: simplex codes require $N^2T_{\text{chip}} + N^2T_{\text{fiber}}$ seconds, while a unipolar Golay compression code needs only $4T_{\text{fiber}} + 4N^2T_{\text{chip}}$ seconds.

A default implementation of Simplex coding for BOTDA is based on on/off intensity modulation of pump pulses, all pulses having the same optical frequency. The distributed BGS is attained by
sending and processing Simplex code for each frequency difference between pump and probe waves, step by step. An interesting variant of the above technique, termed Color Simplex coding [190], suggest to assign each column of the S-matrix with a specific pump frequency, while keeping the probe frequency constant. The code length is equal to the number of discrete frequencies scanning the BGS. Following reconstruction using inverse S-matrix, each reconstructed sequence corresponds to the distributed fiber response to a specific pump-probe frequency pair, as assigned during code transmission, but with the bonus of a coding gain of $(N + 1)/2\sqrt{N}$.

In addition to their role in breaking the fundamental trade-off between response resolution and SNR in fiber optic sensing systems, codes have also been used in correlation-based Brillouin sensors to confine the stimulated Brillouin scattering to narrow correlation peak of phase modulated counter propagating optical waves [147]. The strength of the interaction outside the correlation peak (known as “coding noise”), significantly impairing the optical SNR, was appreciably inhibited owing to the perfect Golomb code with ideal periodic correlation [151]. Lately [153], the use of additional layer of slower amplitude coding (a Manchester coded (originally) bipolar Barker code) on top of the rapid phase modulation was proposed, efficiently temporally separating the Brillouin amplification from adjacent correlation peaks, thus effectively combining the codes advantages both in correlation domain and in pulse compression techniques (explained in details above).

References


