High-Resolution Long-Reach Brillouin Distributed Fiber Sensing with Reduced Acquisition Time

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This work was carried out under the supervision of
Prof. Avi Zadok, Faculty of Engineering, Bar-Ilan University
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1st of Sivan, 5775

May 18th, 2015
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<td>Arbitrary Waveform Generator</td>
</tr>
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<td>CW</td>
<td>Continuous Wave</td>
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<td>DFB</td>
<td>Distributed-Feedback</td>
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<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifier</td>
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<td>FBG</td>
<td>Fiber Bragg Grating</td>
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<td>FUT</td>
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<tr>
<td>NEP</td>
<td>Noise Equivalent Power</td>
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<td>O/E</td>
<td>Optical-to-Electrical</td>
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<td>Polarization Controller</td>
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<td>PRBS</td>
<td>Pseudo-Random Bit Sequence</td>
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<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
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<td>SOP</td>
<td>State-of-Polarization</td>
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**Notation**

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<thead>
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<tbody>
<tr>
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<td>Speed of light in vacuum</td>
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<tr>
<td>$\lambda$</td>
<td>Optical Wavelength</td>
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<tr>
<td>$n$</td>
<td>Refractive index</td>
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<tr>
<td>$\omega$, $\Omega$</td>
<td>Angular frequency</td>
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<tr>
<td>$v$</td>
<td>Speed</td>
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<tr>
<td>$\nu$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$\gamma_e$</td>
<td>Electro-strictive constant</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain, dielectric constant</td>
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<td>$\Gamma'$</td>
<td>Acoustic damping parameter</td>
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<td>$\Gamma_B$</td>
<td>Brillouin linewidth</td>
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<td>$\rho$</td>
<td>Pressure wave amplitude, material density</td>
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<td>$C_T$</td>
<td>Brillouin shift temperature Coefficient</td>
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<td>$C_z$</td>
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<td>Group velocity</td>
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<td>$t$</td>
<td>Time</td>
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<tr>
<td>$\tau$</td>
<td>Lifetime</td>
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<tr>
<td>$E$</td>
<td>Electro-magnetic wave</td>
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<tr>
<td>$k$</td>
<td>Wavenumber</td>
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<tr>
<td>$q$</td>
<td>Acoustic wavenumber</td>
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<tr>
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<td>Material susceptibility</td>
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<td>$c_n$</td>
<td>Phase code symbol</td>
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<tr>
<td>$N$</td>
<td>Total number of symbols in Golomb series</td>
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<tr>
<td>$T$</td>
<td>Phase symbol duration, temperature</td>
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<tr>
<td>$\theta$</td>
<td>Duration of pump pulse</td>
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<td>Optical power</td>
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<tr>
<td>$\phi_{NL}$</td>
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<tr>
<td>$R_a$</td>
<td>Detector responsivity</td>
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<td>$\beta_2$</td>
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Abstract

*Stimulated Brillouin Scattering* (SBS) is a non-linear effect which can couple between two optical waves, an intense pump and a weaker, counter-propagating signal, along standard optical fibers. Coupling is mediated by a stimulated acoustic wave. Effective coupling occurs when the difference between the two optical frequencies matches a particular, fiber-dependent value known as the *Brillouin frequency shift*. The Brillouin shift equals approximately 11 GHz in standard single mode fibers at 1550 nm wavelength. The coupling leads to the amplification of the signal at the expense of the pump.

The value of the Brillouin frequency shift varies with both temperature and mechanical strain. Based on this dependence, the mapping of the local Brillouin frequency shift along standard fibers is used in distributed sensing of both quantities for 25 years. The most widely employed configuration for these measurements is Brillouin optical time domain analysis (B-OTDA), in which pump pulses are used to amplify a continuous-wave signal and the output signal power is monitored as a function of time. A typical commercial B-OTDA interrogator can provide a measurement sensitivity of 1 °C or 20 με, over a range of 50 km and with a spatial resolution of 2-3 m, with an acquisition time of ten minutes. Over the last 15 years, continuous monitoring systems based on the B-OTDA technique had been commercialized and deployed in variety of applications: pipeline integrity monitoring, subsea monitoring of umbilical cords in rigs, electrical power line cable monitoring and more.

Resolution in the fundamental B-OTDA scheme is governed by the duration of pulses, which are restricted in turn to the acoustic lifetime, signifying a spatial
resolution limitation on the order of 1 m. Starting in the late 90's, a new sensing scheme had been proposed to modulate the two waves so that their envelopes are correlated at discrete points of interest only, referred to as correlation peaks. The technique came to be known as Brillouin optical correlation domain analysis (B-OCDA), and it effectively confines the SBS interaction to the correlation peaks, where it is stationary. In previous works of our group and coworkers, the B-OCDA principle was extended to the joint phase modulation of the pump and signal waves by a common, high-rate bit sequence. The technique effectively decoupled between range and resolution in B-OCDA, and supported distributed measurements over 40 m of fiber with 1 cm resolution.

Phase-coded B-OCDA does suffer, however, from two primary drawbacks: (i) although the off-peak acoustic waves vanish on average, their instantaneous values are nevertheless nonzero and fluctuating. Residual off-peak interactions accumulate over the entire length of the fiber and severely degrade the signal-to-noise ratio (SNR) of the measurements; and (ii) Brillouin gain spectra must be mapped one spatial point at a time, scanning the entire length of the fiber in due course. The undertaking of tens of thousands of individual scans using laboratory equipment often proves impractical.

In this work, I propose, analyze and experimentally demonstrate a new scheme for distributed Brillouin sensing. The technique combines between time-domain and correlation-domain analyses principles. It addresses both the coding noise limitations and the long acquisition times of phase-coded B-OCDA. As in phase-coded B-OCDA, both Brillouin pump and signal waves are repeatedly co-modulated by a high-rate phase sequence, which introduces Brillouin interactions in discrete correlation peaks. However, two significant advances are introduced. First, a short, perfect
Golomb code is used in the phase modulation of the pump and signal waves instead of a long pseudo-random bit sequence. The special correlation properties of this sequence help reduce the coding noise considerably. Second, due to the short length of the phase code, a large number of periodic correlation peaks are generated during the propagation of the pump wave. However, the pump wave is also modulated by an amplitude pulse, which introduces a temporal separation between the generations of different peaks. With careful choice of the pump pulse duration with respect to the Golomb code period and the Brillouin lifetime, the SBS amplification which takes place at the different peaks can be temporally resolved in measurements of the output signal power, much like in a B-OTDA.

The technique provides the high spatial resolution and the long range of unambiguous measurement offered by phase-coded B-OCDA, with an improved SNR due to the use of Golomb code and with reduced acquisition times due to the simultaneous interrogation of a large number of resolution points in a single trace. Using this method, the number of scans per choice of frequency shift that is necessary for mapping the Brillouin gain spectra over the entire fiber equals the length of the Golomb code, which was only 127 bits-long in our case. This number of scans does not increase with the number of resolution points.

The principle of the method is supported by extensive numerical simulations of the stimulated acoustic field as a function of time and position along the fiber, and of the output signal power as a function of time. Performance limitations are analyzed both qualitatively and quantitatively. It is proposed that self-phase modulation (SPM)-induced distortion of the Golomb phase-code imposes a limitation on the pump power and therefore on the SBS signal gain. This limits the SNR of the measurement, which,
in turn, affects the Brillouin frequency shift measurement accuracy. Yet, the analysis suggests that distributed measurements of the Brillouin shift with 1 MHz precision should be possible, over km of fiber and with cm-scale resolution, and without averaging over many repetitions.

Using the proposed scheme, the Brillouin gain spectra was experimentally mapped along a 1700 m-long fiber under test with a spatial resolution of 2 cm, representing over 80,000 resolution points, with only 127 scans per choice of frequency offset between pump and signal. Compared with corresponding phase-coded B-OCDA with equal range and resolution, the acquisition time was reduced by a factor of over 600. A 2 cm-long hot spot, located towards the output end of the pump wave, was properly identified in the measurements. This result is at the state of the art of Brillouin scattering-based distributed fiber sensing. The method represents a significant advance towards practical high-resolution and long range Brillouin sensing systems. The combined B-OTDA/B-OCDA technique is already being used by our group in high-resolution sensing within composite-material beams.
1 Introduction

1.1 Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin Scattering (SBS) is a non-linear effect which can couple between two optical waves along standard optical fibers [1]. It is named after the French physicist Léon Brillouin (1889-1969), who was among the pioneers of quantum mechanics and solid state physics and was the first to describe the interaction of monochromatic light waves with thermally excited acoustic waves, leading to the scattering phenomena which became known as Brillouin scattering [2].

In SBS, a relatively intense pump wave interacts with a counter-propagating, typically weaker signal wave, which is detuned in frequency [1]. The combination of the two waves generates a slowly-traveling intensity pattern whose frequency equals the difference between the frequencies of the pump and signal, and its wavenumber is the sum of their wavenumbers. Through electrostriction, the slowly-traveling intensity wave introduces moving density variations, namely an acoustic wave, which in turn leads to a traveling grating of refractive index variations due to the photo-elastic effect.

The traveling grating can couple optical power between the counter-propagating pump and signal waves, much like to static Bragg grating. Effective coupling, however, requires that the difference between the two optical frequencies should closely match a particular, fiber-dependent value known as the Brillouin frequency shift: \( \nu_B \sim 11 \text{GHz} \) for standard single mode fibers at \( \sim 1550 \) nm wavelength. The power of a signal wave, whose optical frequency is \( \nu_S \) below that of the pump, is amplified by SBS. The amplification bandwidth achieved with continuous-wave (CW) pumping is rather narrow: on the order of 30 MHz, as dictated
by the relatively long lifetime of acoustic phonons [1, 3]. A schematic illustration of the non-linear mechanism of the SBS is shown in

Figure 1. SBS has the lowest threshold power among the nonlinear effects in standard silica fibers, therefore it provides an attractive platform for optical signal processing and optical sensing applications.

![Schematic illustration of the non-linear mechanism of the SBS](image)

The Brillouin frequency shift depends on temperature and strain through:

\[
\nu_B = \nu_B^0 + C_T (T - T_0) + C_s \varepsilon
\]

Here \( \nu_B^0 \) is the value of the Brillouin frequency shift at some reference temperature \( T_0 \) and without strain, \( T \) denotes temperature, and \( \varepsilon \) represents strain (or relative elongation). The thermal and strain coefficients of the Brillouin frequency shift in standard telecom single-mode fiber and at room temperature are \( C_T \approx 1 \text{ MHz}/^\circ\text{C} \) and \( C_s \approx 0.05 \text{ MHz/\mu e} \). That temperature and strain dependence of the
Brillouin frequency shift is the basis for Brillouin distributed fiber sensing technologies that will be described later in this work: A local measurement of the Brillouin frequency shift along the fiber gives an indication of the local values of temperature and strain.

A detailed mathematical analysis of Brillouin scattering can be found in [1]. The derivation of equations directly relevant for this work is given in the following subsection.

### 1.2 SBS coupled wave equations

Let us consider the electrical fields of counter-propagating optical waves: a typically strong pump wave \( E_p(z,t) \) and typically weaker, counter-propagating signal wave \( E_s(z,t) \), where \( z \) denotes position along a fiber under test and \( t \) stand for time:

\[
\text{Eq. 1.2 } E_p(z,t) = A_p(z,t) \exp\left[j(k_p z - \omega_p t)\right] + c.c.
\]

\[
\text{Eq. 1.3 } E_s(z,t) = A_s(z,t) \exp\left[j(-k_s z - \omega_s t)\right] + c.c.
\]

The complex envelopes of the pump and signal waves are \( A_{p,s}(t,z) \), their optical angular frequencies are \( \omega_{p,s} \) and their wavenumbers are \( k_{p,s} = 2\pi n / \lambda_{p,s} \). The overall optical field \( E(z,t) = E_p(z,t) + E_s(z,t) \) is associated with a slowly-traveling intensity wave that, through electrostriction, introduces a traveling disturbance in material density (acoustic wave). The acoustic wave is propagating in the same direction as the pump wave, and is expressed by:

\[
\text{Eq. 1.4 } \rho(z,t) = \rho_0 + \rho(z,t) \exp\left[j(qz - \Omega t)\right] + c.c.
\]

Here \( \rho_0 \) is the average medium density and \( \rho \) is the amplitude of the density (acoustic) wave. \( q \) is the wavenumber of the acoustic wave and \( \Omega \) is its angular
frequency. Since the acoustic wave in our arrangement is propagating in the same direction of the pump, and in the opposite direction to that of the signal, we have:

\[ \text{Eq. 1.5 } \Omega = \omega_p - \omega_s \]

and

\[ \text{Eq. 1.6 } q = k_p + k_s \approx 2k_p. \]

The wavenumber of the acoustic field must also obey the acoustic dispersion relation \( q = \frac{\Omega}{v} \), where \( v \) is the speed of sound in the fiber. This requirement is best fulfilled when the difference between the optical angular frequencies \( \Omega = 2\pi \nu \) matches the following specific value, which is defined as the angular Brillouin frequency shift \( \Omega_B = 2\pi \nu_B \):

\[ \text{Eq. 1.7 } \Omega_B = qv \approx 2k_p v = 2n\nu_p \frac{v}{c}. \]

The interpretation of Eq. 1.7 is that the frequency and wavenumber matching are best achieved between the pump, signal and acoustical waves when \( \Omega \), which is the frequency difference between the pump and the signal, is equal to \( \Omega_B \).

The acoustic wave obeys the following equation [1]:

\[ \text{Eq. 1.8 } \frac{\partial^2 \tilde{\rho}}{\partial t^2} - \Gamma' \nabla^2 \left( \frac{\partial \tilde{\rho}}{\partial t} \right) - \nu^2 \nabla^2 \tilde{\rho} = -\nabla \cdot f. \]

Here \( \Gamma' \) is an acoustic damping parameter (a property of the material), and \( f \) is the acoustical driving force, in units of \( N/m^3 \). It stems from the electrostriction associated with the sum of the electrical fields of the pump and signal waves. That force is the gradient of the pressure difference:
Eq. 1.9 \( f = \nabla p_{\pi} \)

While [1]:

\[
\nabla p_{\pi} = \frac{i}{2} \varepsilon_0 \gamma_e \left\{ (E_p + E_s)^2 \right\}.
\]

In Eq. 1.10, \( \gamma_e \) is the electro-strictive constant. The pressure difference is expressed by the average value of the total field squared, taken over multiple optical periods, since the response of the medium to pressure changes is much slower than the optical period. Applying Eq. 1.2 and Eq. 1.3 into Eq. 1.10, the acoustical source term can be expressed as the beating between the two optical fields:

\[
\nabla \cdot f = \varepsilon_0 \gamma_e q^2 A_j A^*_p \exp[j(qz - \Omega t)] + c.c. .
\]

Assuming that the magnitude of the density fluctuations is slowly varying (that is, the second derivative in Eq. 1.8 is negligible), the acoustic wave equation (Eq. 1.8) can be rewritten:

\[
-2i\Omega \frac{\partial \tilde{p}}{\partial t} + \left( \Omega_B^2 - \Omega^2 - j\Omega \Gamma_B \right) \rho - 2j \rho \nu^2 \frac{\partial \tilde{p}}{\partial z} = \varepsilon_0 \gamma_e q^2 A_j A^*_p
\]

Here \( \Gamma_B \equiv \rho^2 \Gamma \) is the Brillouin linewidth, which also defines the acoustic lifetime (or phonon lifetime): \( \tau \equiv 1/\Gamma_B \). Its value in silica fibers is approximately \( 2\pi \cdot 30 \text{ MHz} \). Several assumptions can be taken in order to further simplify Eq. 1.12: (i) we consider first the steady-state condition where the temporal derivative vanishes; and (ii) the acoustic wave is strongly damped and decays within a short length scale, on the order of few tens of microns. Therefore we can omit the last term in the left hand of Eq. 1.12. Consequently, the acoustic wave magnitude is regarded as a strictly local phenomenon, affected only by the optical fields at a given position, while the contribution from neighboring locations is neglected. We therefore obtain:
\[ \text{Eq. 1.13} \left( \Omega_B^2 - \Omega^2 - j\Omega \Gamma_B \right) \rho = \varepsilon_0 \gamma, q^2 A_p A_p^* \]

With the solution for the acoustic wave magnitude:

\[ \text{Eq. 1.14} \quad \rho(t, \Omega) = \varepsilon_0 \gamma, q^2 \frac{A_p A_p^*}{\left( \Omega_B^2 - \Omega^2 - j\Omega \Gamma_B \right)} \]

Eq. 1.14 shows that the magnitude of the acoustic wave is proportional to the inner product between the amplitudes of the pump and signal waves. Hereunder we substitute that relation into the nonlinear polarization term in the optical wave equation, and eventually show how that acoustic wave is affecting the optical waves themselves, through the elasto-optic effect.

\[ \text{Eq. 1.15} \quad \Delta \chi = \Delta \varepsilon = \frac{\partial \varepsilon}{\partial \rho} \rho = \frac{\gamma_e}{\rho_0} \rho \]

\[ \text{Eq. 1.16} \quad \tilde{P}(z, t) = \varepsilon_0 \Delta \chi \tilde{E}(z, t) = \frac{\varepsilon_0 \gamma_e}{\rho_0} \rho \tilde{A}_p(z, t) \tilde{E}(z, t). \]

In the above equations \( \tilde{P}(z, t) \) denotes the nonlinear polarization terms, \( \Delta \chi \) is the change in material susceptibility that is induced by density variations, and \( \Delta \varepsilon \) is the corresponding change in the dielectric constant. The nonlinear polarization term \( \tilde{P}(z, t) \) includes components that match the frequencies and wavenumbers of the pump and signal waves:

\[ \text{Eq. 1.17} \quad \tilde{P}_p(z, t) = p_p \exp\left( jk_p z - \omega_p t \right) = \frac{\varepsilon_0 \gamma_e}{\rho_0} \rho \tilde{A}_p(z, t) \exp\left( jk_p z - \omega_p t \right). \]

\[ \text{Eq. 1.18} \quad \tilde{P}_s(z, t) = p_s \exp\left( jk_s z - \omega_s t \right) = \frac{\varepsilon_0 \gamma_e}{\rho_0} \rho \tilde{A}_p(z, t) \exp\left( -jk_s z - \omega_s t \right). \]

In Eq. 1.17 - Eq. 1.18, \( p_{p,s} \) are the magnitudes of the nonlinear polarization terms which correspond to the frequency and wavenumber of the pump and signal, respectively. The nonlinear wave equations for the pump and signal waves are:
In applying the polarization terms of Eq. 1.17 - Eq. 1.18 into the nonlinear wave equations (Eq. 1.19), while invoking the slowly varying amplitude approximation and at steady-state condition, we obtain two coupled wave equations for the pump and the probe waves:

\[
\frac{\partial A_p}{\partial z} = j \frac{\omega \gamma_e}{2nc\rho_0} \rho A_s = j \frac{\varepsilon_0 \omega q^2 \gamma_e^2}{2nc\rho_0} \frac{|A_s|^2 A_p}{\Omega_b^2 - \Omega^2 - j\Omega\Gamma_b},
\]

\[
\frac{\partial A_s}{\partial z} = j \frac{\omega \gamma_e}{2nc\rho_0} \rho^* A_p = -j \frac{\varepsilon_0 \omega q^2 \gamma_e^2}{2nc\rho_0} \frac{|A_p|^2 A_s}{\Omega_b^2 - \Omega^2 - j\Omega\Gamma_b},
\]

where we approximate \( \omega_s \approx \omega_p = \omega \).

The two coupled wave equations Eq. 1.20 - Eq. 1.21 can be modified to describe the evolution of intensities \( I_{p,s} = 2n\varepsilon_0 c |A_{p,s}|^2 \):

\[
\frac{\partial I_p}{\partial z} = -g(\Omega) I_s I_p,
\]

\[
\frac{\partial I_s}{\partial z} = -g(\Omega) I_p I_s.
\]

The coefficient \( g(\Omega) \) is known as SBS gain coefficient. It is well approximated by a Lorentzian shape:

\[
g = g_0 \frac{(\Gamma_b/2)^2}{(\Omega_b - \Omega)^2 + (\Gamma_b/2)^2},
\]

\[
g_0 = \frac{\gamma^2 \omega^2}{nc^3 \rho_o \Gamma_b}
\]

\( g_0 \) is referred to as the line center gain factor.
In cases when the pump wave is much stronger than the signal wave, we can often assume that the pump magnitude changes due to transfer of power between the two waves are negligible *(undepleted pump condition)*, therefore the intensity of the pump \( I_p \) is taken as a constant parameter. Subject to the undepleted pump approximation, the solution to Eq. 1.23 is simple:

\[
\text{Eq. 1.26} \quad I_s(z) = I_s(L) \exp\left(gI_p(L - z)\right)
\]

Eq. 1.26 signifies that the signal wave intensity is exponentially amplified as it propagates from its input at \( z = L \).

The study of Eq. 1.12, subject to various boundary conditions of carefully modulated pump and signal waves, is central to this research thesis. In fact, much of this work is dedicated to the study and employment of the dynamics of the stimulated acoustic field, as governed by Eq. 1.12, subject to modulated pump and signal waves that are practically both undepleted. The justification for this assumption will be given in due course. Unlike the analysis provided in Eq. 1.13 - Eq. 1.26, the SBS interactions that are employed through much of this work are not at a steady state.

In the following sections I introduce how SBS is being employed in the distributed measurement of temperature and/or mechanical strain, along structures in which an optical fiber is embedded. Two primary configurations are prevalent in the literature and in commercial instruments: Brillouin optical time domain analysis (B-OTDA), which typically provides long measurement ranges, and Brillouin optical correlation domain analysis, B-OCDA, which could give superior spatial resolution over shorter ranges. In the following chapters I will introduce the novel concept that is central to this work, which combines the two approaches together.
### 1.3 Distributed Fiber Sensor: The B-OTDA technique

As noted earlier, the value of the Brillouin frequency shift $\nu_B$ varies with both temperature and mechanical strain [4]:

**Eq. 1.27**  \[ \Delta \nu_B = C_T \Delta T + C_\varepsilon \Delta \varepsilon \]

where $C_T \sim 1 \text{ MHz/}^\circ\text{C}$ and $C_\varepsilon \sim 0.05 \text{ MHz/} \mu\text{e}$ for a standard telecom single mode fiber. Figure 2 illustrates variations of the Brillouin frequency shift due to temperature or strain. Figure 3 shows measurements of Brillouin gain spectrum, its variations with temperature, and the extraction of the temperature coefficient $C_T$ from these measurements.

![Brillouin shift](image)

**Figure 2:** Illustration of Brillouin frequency shift variations due to temperature or strain changes [5].
Figure 3: Brillouin gain spectrum for -25°C, 30°C and 90°C. Note how the peak of the gain spectra, or the Brillouin frequency shift, varies over temperature (left). The temperature coefficient is extracted by a linear fit (right) [5].

Figure 4: Distributed sensing based on the mapping of Brillouin gain spectra along an optical fiber. The nominal peak of the gain spectrum is in the vicinity of 10.15 GHz for most of the fiber, while in a hot spot it is modified to around 10.40 GHz [5].

Based on the above dependence, a mapping of the local Brillouin gain spectrum along standard fibers is being used in the distributed sensing of both quantities for 25 years [6-8], (see Figure 4). The most widely employed configuration for such measurements is B-OTDA, in which pump pulses are used to amplify CW signals and the output signal power is monitored as a function of time [6].
Experiments are repeated for a range of frequency offsets $\nu - \nu_B$ between pump and signal.

Figure 5 depicts a typical commercial BOTDA interrogator, and its accuracy in temperature or strain measurements along 50 km of an optical fiber for several acquisition times. The instrument can provide a measurement sensitivity of 1 °C or 20 $\mu$e, over a range of 50 km and with a spatial resolution of 2-3 m. The acquisition time is ten minutes.

Figure 5: Typical measurement display of a commercial B-OTDA interrogator (left) and its performance in terms of temperature accuracy over 50 km fiber length for several acquisition times [5].

Over the last 15 years, continuous monitoring systems based on the B-OTDA technique had been commercialized and deployed in variety of applications: pipeline integrity monitoring, subsea monitoring of umbilical cords in rigs, electrical power line cable monitoring and more. In pipeline integrity monitoring, for example, several B-OTDA interrogators are deployed along the pipeline, one every few tens of km, with the ability to detect leaks, ground movement and third party intrusion. Figure 6 shows an optical cable being deployed in proximity to a pipeline.
Figure 6: An optical cable is being buried along a pipeline to enable the continuous monitoring of the ground movement (strain) or temperature in proximity to the pipeline with B-OTDA interrogators [5].

B-OTDA is capable, at least in principle, of mapping the SBS gain for a given ν along the entire fiber with just a single scan. The measurement range of B-OTDAs recently reached 100 km without amplifying repeaters, and 325 km using cascaded amplified segments [9-12, 50-51]. Figure 7 shows the experimental setup for the 325 km long B-OTDA, which combines four optical repeaters [51].

Figure 7: The experimental setup for a total sensing fiber length of 325 km based on B-OTDA technique with four optical repeaters [51].
Figure 8 (top) shows the measured Brillouin frequency shift along the entire 325 km fiber. Figure 8 (bottom) shows the evolution of the Brillouin gain. The pump power is effectively restored by the four optical repeaters, with little residual variance [51].

Figure 8: Evolution over a 4 x 65 km (total 325 km) long sensing fiber, of: (top) the Brillouin frequency, and (bottom): the Brillouin gain [51].

Figure 9 (top) shows the estimated experimental error in the Brillouin frequency shift measurement [51], represented in terms of twice the standard deviation (2σ). The experimental error is bound by 2 MHz, which corresponds to temperature uncertainty of ~2 °C or strain error of ~40 με. The spatial resolution of the measurement was 3 m, and the experiment duration was about 100 minutes. Figure 9 (bottom) shows the Brillouin frequency shift as a function of temperature, averaged over a 10-meters long hotspot located at the far end of the measurement.
range, 330 km away [51]. This results represent the current state-of-the-art in long-range Brillouin sensors.

![Graph 1](image1.jpg)

**Figure 9**: (top) Evolution of the twice standard deviation (2σ) of the measured Brillouin shift over 325 km of fiber. (bottom) Measured Brillouin shift as a function of temperature at a hotspot located towards the end of the 325 km sensing fiber [51].

Two other key performance metrics of B-OTDA systems, in addition to the measurement range and sensitivity, are their acquisition time and spatial resolution. For decades, Brillouin technology was perceived as suitable for static measurements only. The acquisition times of B-OTDA setups were recently reduced, however, to the order of ms for 100 m-long fibers, in a series of works by the Tur group of Tel-Aviv University [13-15]. This progress enables, for the first time, dynamic measurements of vibrations using Brillouin scattering. Dynamic Brillouin analysis is, however, outside the scope of this research.
Resolution in the fundamental B-OTDA scheme is governed by the duration of pulses, which are restricted in turn to the acoustic lifetime $\tau \sim 5$ ns or longer, signifying a spatial resolution limitation on the order of 1 m [16]. Numerous schemes had been proposed in recent years for resolution enhancement in B-OTDA [8, 17], such as the pre-excitation of the acoustic wave [18,19], dark [20] and $\pi$-phase [21,22] pump pulses, repeated measurements with pump pulses of different widths [23], differentiation of the signal power [24] and many more.

The *differential pulse pair* technique [23, 25], or *DPP-B-OTDA*, achieved spatial resolution of 2 cm along 2 km of a fiber. In this technique, two separate measurements are taken with two different pump pulses, and the differential signal is obtained by subtracting the two Brillouin signals [26]. When using a small pulse-width difference between the pair of scans, a high spatial resolution can be achieved. Figure 10 plots the SBS signal with a 8/8.2 ns pulse pair, which corresponds to 80 cm and 82 cm spatial extents (within the fiber), respectively. Note that the two signals are overlapping during the first 8 ns, and the rising edge of the last 0.2 ns provides the 2 cm resolution which can be obtained in the differential signal [25].

![Figure 10: SBS signals with an 8 ns and 8.2 ns pulse widths and their differential signal. The 0.2 ns difference signal gives a spatial resolution of 2 cm [25].](image-url)
The differential signal is inherently smaller than the original two signals. It is therefore characterized by a comparatively low signal-to-noise ratio (SNR). The problem is inherent to all high-resolution Brillouin sensing configurations.

Figure 11 plots the SBS signals of 8 ns and 8.2 ns pulse pair and their difference along 2 km of fiber. A 2 cm-long segment towards the output end of the pump wave was locally heated. The hot spot was properly recognized in the measurement. The standard deviation in the estimate of the local Brillouin frequency shift was about 2 MHz, see Figure 12.

![Figure 11](image_url)

Figure 11: 8/8.2 ns pulse pair SBS signals and their difference signal in a 2 km long fiber under test [25].
Figure 12: (a) SBS spectra near the end of the 2 km-long fiber, where a 2 cm-long segment was locally heated. (b) Measured local Brillouin frequency shift and temperature as a function of position in the vicinity of the hot-spot [25].

To conclude, the DPP-B-OTDA technique achieved a significant enhancement in terms of spatial resolution over conventional B-OTDA, with a spatial resolution of 2 cm, 2 °C temperature accuracy and 2 km range [25].
1.4 Brillouin Optical Correlation Domain Analysis (B-OCDA)

1.4.1 Frequency modulation B-OCDA

Eq. 1.12 above describes the relation between the stimulated acoustic wave that is generated in the SBS process and the complex amplitudes of the pump and signal waves. For brevity let us define a complex linewidth:

$$\Gamma_A(\Omega, z) = j \frac{\Omega_B(z) - \Omega^2 - j \Omega \Gamma_B}{2 \Omega}.$$  

When $\Omega = \Omega_B$, $\Gamma_A$ reduces to its minimum value of $\frac{1}{2} \Gamma_B$. Eq. 1.12 can be rewritten as [17, 34]:

$$\text{Eq. 1.28} \quad \frac{\partial Q(t, z)}{\partial t} + \Gamma_A Q(t, z) = j g_1 A_p(t, z) A_s^*(t, z)$$

where $g_1 = e_0 \epsilon_s q^2 / (2 \Omega)$ is an electrostrictive parameter. In deriving Eq. 1.28, it has been assumed that the acoustic wave is non-propagating, in the sense that its magnitude at a given $z$ is only governed by the stimulating electrostrictive force at that position, and not by the acoustic waves at all other locations. This assumption is justified by the fact that the acoustic waves only propagate over tens of microns before they decay, whereas all length scales that are relevant to sensing applications are orders of magnitude longer.

In what follows, we focus primarily on identifying regions along the fiber in which a significant buildup of the acoustic field may take place. We assume that these regions consist of short segments of fiber only. Subject to this condition, we may further assume that changes to the complex envelopes of both pump and signal due to SBS interactions between them are negligible. We therefore express both optical waves at every point along the fiber by the simple propagation of the respective boundary conditions [17, 27, 34]. Integrating over Eq. 1.28 gives:
In Eq. 1.29, $\Delta(z)$ is a position-dependent temporal offset, defined as $\Delta(z) \equiv (2z - L)/v_g$, where $v_g$ is the group velocity of light in the fiber. When $t \gg 1/\Gamma_A$, (or $t \gg 2\tau$ when $\Omega = \Omega_s$), the magnitude of the acoustic wave $Q(t, z)$ at a given fiber location becomes proportional to the inner product $A_p(t' - \frac{\tau}{v_g}) \cdot A_s^*(t' - \frac{\tau}{v_g} + \Delta(z))$ between the complex envelopes of the pump and signal waves, weighted over by a moving exponential window that is $2\tau$ long [27]. The spatial pattern of the acoustic field strength is therefore directly associated with the temporal cross-correlation between boundary condition modulations of the two envelopes of the counter-propagating waves [27].

Starting in the late 90's, Hotate and coworkers at the University of Tokyo had proposed to modulate the two waves so that their envelopes are correlated at discrete points of interest only, referred to as correlation peaks [28]. The technique came to be known as B-OCDA, and it effectively confines the SBS interaction to the correlation peaks, where it is stationary. Initial demonstrations relied on the joint frequency modulation of the pump and signal, which are nominally detuned by a certain $\nu$, by a common sine wave [28]. The scheme provided spatial resolution of tens of cm, (see Figure 13 [28, 29]). The method was later extended to a record-high spatial resolution of 1.6 mm [29].
Figure 13: Left: Schematic illustration of B-OCDA technique that is based on frequency modulation of the pump and signal waves. The signal’s gain spectrum $g$ is determined by the convolution integral of the inherent Brillouin gain spectrum (dashed line) with the cross-spectral density of the pump-signal beat (solid line) [28]. Right: 3 mm resolution achieved by the frequency-modulation B-OCDA technique [29].

Initial B-OCDA was restricted to an unambiguous measurement range of a few hundreds of resolution points only, limited by the separation between neighboring periodic peaks. The measurement range was since extended using more elaborate frequency modulation profiles [30, 32], and reached 34 meters with few mm spatial resolution, or 500 m with 12 cm resolution [31].

1.4.2 B-OCDA with pseudo-random bit-sequence phase modulation

In a previous work of our group and coworkers [33-35], from which the following discussion has been adopted, the B-OCDA principle was extended to the joint phase modulation of the pump and signal waves by a common, high-rate pseudo-random bit sequence (PRBS) with symbol duration $T$ [33, 34]:

$$A_p(t, z = 0) = A_{p0} \left\{ \sum_n \text{rect} \left[ \left( t - nT \right) / T \right] \exp(j\varphi_n) \right\},$$

Eq. 1.30

$$A_s(t, z = L) = A_{s0} \left\{ \sum_n \text{rect} \left[ \left( t - nT \right) / T \right] \exp(j\varphi_n) \right\}.$$
In Eq. 1.30, $\varphi_n$ is a random phase variable which equals either 0 or $\pi$, $\text{rect}(\xi)$ equals 1 for $|\xi| < 0.5$ and zero elsewhere, and $A_{p0}, A_{s0}$ denotes the constant magnitudes of the pump and signal waves, respectively. The phase modulation is synchronized so that the phases of the two waves, at their respective entry points into the fiber, are equal for all $t$.

Let us assume for the moment that the difference between the central optical frequencies of the pump and signal matches the Brillouin frequency shift of the fiber in a particular point of interest. With reference to Eq. 1.29 above, the acoustic wave magnitude $Q(t, z)$ becomes proportional to the product $A_p(t - z/v_g) \cdot A_s(t - z/v_g + \Delta(z))$, weighted and summed by moving exponential window of duration $1/\Gamma_A = 1/(\frac{1}{2} \Gamma_b) = 2\tau$. When the pump and signal modulation $A_p(t, z = 0), A_s(t, z = L)$ are driven by the ergodic random process as in Eq. 1.30, that is fluctuating much faster than $2\tau$, the strength of the acoustic wave following its initial buildup provides a measure of the modulation correlation function: $C(\theta) = \langle A_p(t) \cdot A_s'(t - \Delta(z)) \rangle$, with the triangular brackets denoting averaging with respect to time $t$.

Within a short section around the center of the fiber at $z = L/2$, the offset $\Delta(z)$ is near zero, leading to: $A_p(t - z/v_g) \cdot A_s'(t - z/v_g - \Delta(z)) = A_{p0} \cdot A_{s0}'$. The modulated pump and signal waves are correlated in this location, therefore the driving force for the acoustic grating generation is stationary and of constant phase. Consequently, the acoustic grating in the vicinity of the center of the fiber may build up to its steady state magnitude:
**Eq. 1.31**  
\[ Q(t >> 1/\Gamma_A, z = L/2) = jg_1 \cdot A_{p0} \cdot A_{s0}^*/\Gamma_A (\Omega, z = L/2). \]

The correlation peak width is on the order of \( \Delta z = \frac{1}{2} v_g T \), corresponding to the spatial extent of a single symbol. In all other \( z \) locations, the term \( A_p(t - z/v_g) \cdot A_s^*(t - z/v_g + \Delta(z)) \) is randomly alternating between \( \pm A_{p0} \cdot A_{s0}^* \), due to the random phase change between 0 and \( \pi \), on every symbol duration \( T \ll 2\tau \). The long term integration thus averages to a zero expectation value and the buildup of the acoustic grating outside the correlation peak is inhibited. The acoustic grating that is generated by PRBS modulation of the pump waves is both stationary and localized.

Figure 14 illustrates the PRBS phase modulated pump and signal waves counter-propagating in the fiber [33]. It can be seen that in the center of the fiber, where the waves are correlated, the magnitude of the acoustical field is built up, whereas it is largely inhibited outside the correlation peak. Noise due to off-peak acoustic fields in SBS measurements is discussed in detail later in this thesis.
Figure 14: The principle of B-OCDA with PRBS phase modulation of the pump and signal waves. (a) Illustration of the complex envelopes of the Brillouin pump and signal waves, co-modulated by a binary phase sequence. The signal wave is propagating in the positive z direction (top row) and the pump wave is counter propagating in the negative z direction (bottom row). The sign of the optical field randomly alternates in between symbols through binary phase modulation of 0 and π. (b) The driving force for the generation of the SBS acoustic field is proportional to the inner product between the pump envelope, and the complex-conjugate of the signal envelope. Therefore, a constant driving force prevails at discrete peak locations only (center), in which the two replicas of the modulation sequence are in correlation. Elsewhere, the driving force is oscillating with expectation value of zero (but with non-zero standard deviation). (c) The magnitude of the resulting acoustic field, obtained by temporal integration over the driving force. The Brillouin interaction is therefore confined to specific locations along the fiber where it is stationary [33].

Figure 15 shows simulation results of the acoustic wave magnitude, as a function of time and position, within a 1 m long fiber [34]. The magnitude was calculated through direct integration of Eq. 1.29, subject to the PRBS modulation of the signal and pump phases as in Eq. 1.30 with $T = 200$ ps. The simulation predicts the build-up of a localized and stationary acoustic wave in a narrow region at the center of fiber with spatial extent of $\Delta z = \frac{1}{2} v_g T = 2$ cm.
Figure 15: Simulated magnitude of the acoustic wave density fluctuations, (in kg/m), that is generated by signal and pump waves which are phase-modulated by a common PRBS, as a function of position z and time t within a 1 m-long fiber. The modulation symbol duration $T$ was 200 ps, corresponding to a sensing resolution of 2 cm [34].

Using 12 Gbit/s phase modulation ($T = 80$ ps), B-OCDA distributed fiber sensing with a spatial resolution of 9 mm had been demonstrated [33]. The separation between neighboring correlation peaks is governed by the length of the code, which can be arbitrarily long. Unambiguous measurements at the above resolution were carried out over 200 m of fiber, or the equivalent of more than 20,000 potential resolution points, (see Figure 16).
Figure 16: Top left – Brillouin gain mapping of a 40-meter-long fiber with 1 cm resolution, corresponding to 4000 resolved points. A 1 cm-long section of the fiber was locally heated. Top right – magnified view of the Brillouin gain map in the vicinity of the heated section. Bottom left – corresponding measured Brillouin frequency shift as a function of position. The region immediately surrounding the heated section is magnified in the inset. The standard deviation on this estimation along a uniform fiber section is 0.5 MHz, corresponding to a temperature inaccuracy of ±0.5 °C. Bottom right – Brillouin frequency shift measurements over a 200-meters-long fiber, with sub-cm resolution. 330 arbitrarily located sections of the fiber under test are randomly addressed. The interrogated sections are only 9 mm long, evenly spaced by approximately 60 cm. The fiber under test consisted of two dissimilar segments spliced together. The inset shows measurements of the Brillouin shift in the vicinity of a 1 cm-long hot spot, located at the end of the fiber. (The 330 randomly addressed sections of the main panel did not coincide with the hot spot) [33].

The PRBS phase modulation technique effectively decouples between range and resolution in B-OCDA. The method does suffer, however, from two primary drawbacks which are common to many B-OCDA implementations:

(1) First, although the off-peak acoustic field vanishes on average, its instantaneous value is nevertheless nonzero and fluctuating [34]. Residual off-peak reflectivity accumulates over the entire length of the fiber and
severely degrades the SNR of the measurements. A large number of averages over repeated measurements are necessary to overcome this so-called 'coding noise' [27, 35].

(2) Second, the Brillouin gain spectra must be mapped one spatial point at a time, scanning the entire length of the fiber in due course. The undertaking of tens of thousands of individual scans for every \( \nu \), using laboratory equipment, often proves impractical. For example, in [33] (see Figure 16 above), Zadok et al. were able to scan an entire 40 m-long fiber with 1 cm resolution, but could not do the same for the entire 200 m-long fiber, due to excessive acquisition times.

### 1.4.3 Golomb Codes – a way to reduce coding noise in phase-coded B-OCDA

The 'coding noise' discussed above can be reduced considerably with modulating the pump and signal waves by carefully designed phase codes, originally developed for radar applications [48], instead of a PRBS. Antman and coworkers proposed the use of perfect Golomb codes in the realization of stationary and localized Brillouin interactions with reduced 'coding noise' [27, 35]. Golomb codes are characterized by the following useful property: the off-peak values of their cyclic auto-correlation function are exactly zero. The codes were originally proposed by S. W. Golomb in 1992, as a way to reduce sidelobes in CW radars [48]. Since the invention of these sequences, they had been adopted in other fields like data transmission in cellular phones, GPS systems and spread-spectrum communications.

In a more formal description, Golomb codes are sequences \( \{a_j\} \) that repeat every \( N \) symbols. Each symbol in the code assumes one of two complex values of unity magnitude: \( \alpha, \beta \). The out-of-phase values of the cyclic auto-correlation
function \( C(m) = \sum_{j=m=1}^{n+N} a_j a^*_{j-m} \) identically equal to zero, regardless of the starting point \( n \) [48]:

\[
\text{Eq. 1.32} \quad C(m) = \begin{cases} 1, & \text{if } m = 0 \pmod{N} \\ 0, & \text{if } m \neq 0 \pmod{N}, \text{i.e., } m = 1, 2, \ldots, N-1 \end{cases}
\]

In order to quantify the effect of Golomb codes on noise, let us first repeat the expression for the acoustic field magnitude as a function of position and time and for the boundary conditions of two writing pump waves that are jointly modulated by a common phase sequence (some of the following texts are adopted from [27]):

\[
\text{Eq. 1.33} \quad Q(t, z) = j g_1 \int_0^{t'} \exp \left[ -(t-t')/2\tau \right] \cdot A(t'-z/v_g) \cdot A[t'-(z/v_g) + \Delta(z)] \, dt'
\]

\[
\text{Eq. 1.34} \quad A_p = A_s = A_0 \left\{ \sum_n c_n \text{rect} \left[ \left( t-nT \right)/T \right] \right\} = A(t)
\]

Here \( c_n \) represent the symbols of the chosen phase code. In Eq. 1.33 it had been assumed for simplicity that \( \Omega = \Omega_B \), and therefore \( \Gamma_A \) reaches its minimum value of \( \frac{1}{2} \Gamma_B \) (or simply \( 1/2\tau \)). The substitution of Eq. 1.34 into Eq. 1.33, and the discretization the fiber into \( \Delta z = \frac{1}{z} v_g T \) long bins, lead to the following approximation:

\[
\text{Eq. 1.35} \quad Q(t, z) = j g_1 |A_0|^2 T \sum_{n=-\infty}^{n_0(t, z)-1} \exp \left[ \frac{(n-n_0)T}{2\tau} \right] \cdot c^*_n c_{n-l_z} = j g_1 |A_0|^2 T \tilde{R}_{N_0} \left( l_z \right)
\]

In Eq. 1.35 \( l_z \equiv \text{round} \left[ \left( \Delta(z) \right)/T \right] \) is the normalized, position dependent lag between the sequences, \( n_0(t, z) \equiv \text{round} \left[ \left( t-z/v_g \right)/T \right] \) is the bit appearing in pump \( A_p \) at position \( z \) and time \( t \), and \( \tilde{R}_{N_0} \left( l_z \right) \) is an exponentially-windowed autocorrelation function with a 'memory' of \( N_0 \equiv \text{round} \left( 2\tau/T \right) \) bits:

\[
\text{Eq. 1.36} \quad \tilde{R}_{N_0} \left( l_z \right) = \sum_{n=-\infty}^{n_0(t, z)-1} \exp \left[ -\left( n_0-n \right)/N_0 \right] \cdot c^*_n c_{n-l_z}
\]
Following the initial buildup \((t \gg \tau)\), a correlation peak of constant magnitude \(Q(t, z) \approx 2jg, |A_n|^2\tau\) is established where \(l_z = 0\), with a spatial extent of \(\Delta z = \frac{1}{2}v_gT\) [30]. SBS interactions at the correlation peak represent the intended signal, whereas accumulated interactions from all off-peak locations contribute noise. Note that the change in signal power scales with \(Q^2\) [1]. The Optical SNR (OSNR) can be estimated by summing over all \(l_z \neq 0\) positions in Eq. 1.35:

\[
\text{Eq. 1.37} \quad \text{OSNR} = \frac{N_0^2}{\left(\sum_{l_z \neq 0} \tilde{R}_{N_0}(l)\right)^2}.
\]

When \(c_n\) is a simple PRBS code, \(\tilde{R}_{N_0}(l_z \neq 0)\) is a random variable with zero mean and variance of \(\frac{1}{2}N_0\). It is assumed that \(\tilde{R}_{N_0}(l)\) and \(\tilde{R}_{N_0}(k)\) are statistically independent for every \(l \neq k\). Under these considerations, the expectation value of the OSNR for a PRBS-generated, localized SBS interaction is [34]:

\[
\text{Eq. 1.38} \quad \text{OSNR} = \frac{N_0^2}{\sum_{l_z \neq 0} \mathbb{E}\left[\left(\tilde{R}_{N_0}(l_z)\right)^2\right]} = \frac{N_0^2}{\sum_{l_z \neq 0} \frac{1}{2}N_0} \approx \frac{2\tau v_L}{L} = \frac{4\tau}{T_D}.
\]

In Eq. 1.38 \(T_D \equiv 2L/v_g\) is the round trip delay along the fiber. The expectation value of the OSNR is degraded to unity when the length of the fiber is only 4 m. In order to improve the OSNR, \(\tilde{R}_{N_0}(l_z \neq 0)\) must be reduced. As mentioned already, for perfect Golomb codes with cycle of \(N\) bits, the cyclic auto-correlation

\[
C(l_z) = \sum_{n=N}^{N-1} a_j^* a_{j+l_z}^* \text{ is exactly zero for all } l_z \neq 0 \text{ (see Eq. 1.32). } \tilde{R}_{N_0}(l_z) \text{ (Eq. 1.36)}
\]

represents an exponentially windowed auto-correlation which is not identical to \(C(l_z)\), therefore it is not expected that off-peak interactions will vanish completely. Nevertheless, it is anticipated that use of Golomb codes would improve the OSNR,
provided that $N \sim N_0$ [27]. Figure 17 shows the numerically calculated $Q(t, z)$ with PRBS pump modulation (top left panel), and when a 63 bits-long Golomb code was used instead (top right) [27]. The off-peak acoustic field is much weaker when Golomb codes are used, as expected (Figure 17, bottom).

Figure 17. Top: simulated acoustic field magnitude $Q(t, z)$ induced by PRBS coded optical waves (left), and by pump and signal modulated with a perfect Golomb code (N=63, right). The coding symbol duration was 100 ps in both simulations. Bottom: simulated $|Q(t = 10\tau, z)|^2$ for PRBS (red) and Golomb (blue) pumps coding [27].

The performance of PRBS and Golomb-code modulation was compared in the characterization of so-called dynamic Brillouin gratings (DBGs). In DBGs, the two optical waves that stimulate the Brillouin interaction are co-polarized along one principal axis of a polarization maintaining (PM) fiber. The two waves introduce an acoustic wave that is accompanied by a refractive index perturbation, namely a grating, as discussed earlier in this chapter. These gratings are ‘dynamic’ in the sense
that they may be switched on and off or moved along the fiber through control of the writing pump waves [36-42].

DBGs can be interrogated using a third, so-called 'probe wave', that is polarized along the orthogonal principal axis of the PM fiber. Due to the large birefringence of PM fibers, the frequency of the probe wave must be detuned from those of the two pumps, typically by tens of GHz [36]. Similar to Bragg gratings, the probe signal is back reflected by the dynamic grating, creating a fourth wave, which can be measured to monitor the entire process, as shown in Figure 18.

![Figure 18. Schematic illustration of the relative frequencies, states of polarization and directions of propagations for the two pump waves, readout probe wave and reflection in a SBS driven dynamic acoustic grating measurement [34].](image)

Figure 19 shows experimental measurements of DBGs reflection as a function of position along a PM fiber, where PRBS and Golomb codes were used in the modulation of two pump waves [35]. It can be seen that the experimental results agree with the simulations: Golomb code-generated DBGs exhibit weaker residual off peak reflectivity. Note again that the code period should be on the order of $2\tau$ (~10ns).
The reduction of coding noise using Golomb code modulation, rather than PRBS, is applicable to Brillouin analysis over standard fibers as well. However, prior to this research, Golomb codes were not incorporated in Brillouin distributed fiber sensors. The application of these codes is central to this thesis, as described in the following chapters.

1.4.4 Time gated PRBS B-OCDA technique to reduce off correlation peak noise

An important step towards SNR improvement in the PRBS-coded B-OCDA technique was made by Denisov et al. [43], who overlaid ns-scale amplitude pulse modulation on top of the PRBS phase coding of the pump wave. Using synchronized, time-gated measurements of the output signal, they were able to reduce the coding noise substantially: off-peak Brillouin interactions were restricted to the spatial extent of the pump pulse, rather than span the entire length of the fiber under test. Measurements were performed with 1 cm resolution over 3 km of fiber, representing 300,000 potential resolution points. Their work can be regarded as a first merger between B-OTDA and B-OCDA principles, an extension of which is the main subject of the research reported herein. Nevertheless, the issue of serial point-by-point

Figure 19. Measurements of the relative reflected power from stationary and localized DBGs as a function of time. Blue, Golomb-coded DBG; red, PRBS-coded DBG [35].
acquisition still remained, and the complete mapping of the Brillouin gain spectrum over the entire set of 300,000 potential resolution points could not be performed.

Following the publication of the main results of this thesis, Denisov et al. [49] successfully applied the principles of combined time-domain and correlation-domain Brillouin analysis in an extended experiment. A 14 mm-long hot spot at the end of 17.5 km long fiber was properly identified, representing 1.25 Million potential resolution points! This demonstration is an extremely impressive experimental achievement. Here too, however, only a small subset of the potential resolution points could be interrogated in a given acquisition.

1.5 Objective of this work

In this work, I propose and demonstrate a combined B-OTDA / B-OCDA technique, which addresses both the coding noise limitations and the long acquisition times of B-OCDA. The new technique opens up the Brillouin analysis of temperature and strain with hundreds of thousands of resolution points, over several km of fiber and with cm-scale resolution [45-47]. As in [43], an amplitude-pulsed pump and a CW signal are both phase modulated by a joint sequence, following the B-OCDA principle. However, two significant advances are introduced: First, a short, perfect Golomb code is used in the phase modulation of the pump and signal waves instead of a long PRBS. The special correlation properties of this sequence help reduce the coding noise considerably [27, 35]. Second, due to the short length of the code, a large number of correlation peaks are generated during the propagation of the pump wave pulse. With careful choice of the pump pulse duration with respect to the Golomb code period and the Brillouin lifetime, the SBS amplification which takes place at the different peaks can be temporally resolved in measurements of the output.
signal power, much like in a B-OTDA. Using this method, the number of scans per choice of \(\nu\) that is necessary for mapping the Brillouin gain spectrum over the entire fiber equals the length of the Golomb code only, which was 127 bits-long in our case. This number of scans is orders-of-magnitude smaller than that of an equivalent PRBS-coded B-OCDA, and it does not increase with the number of resolution points. Analysis, simulation and experimental demonstration of the proposed method are provided in the remainder of the thesis.
2 Combined time-domain and correlation-domain Brillouin analysis

2.1 Principle of operation

In a previous section (1.4.2 B-OCDA with PRBS phase modulation), I presented the formulation of the high-rate phase-coded B-OCDA. Let us now turn to the formulation of the SBS interaction between pump and signal waves that are modulated according to the combined (time-domain and correlation-domain) technique which is the topic of the current work. I show later that the spatial-temporal profiles of both B-OTDA and phase-encoded B-OCDA can be obtained as specific cases of the analysis provided below.

Again, the optical fields of the pump and signal waves are denoted as \( E_p(t, z) \) and \( E_s(t, z) \) respectively, where \( z \) denotes position along a fiber of length \( L \) and \( t \) represents time. The pump wave enters the fiber at \( z = 0 \) and propagates in the positive \( z \) direction, whereas the signal wave propagates from \( z = L \) in the negative \( z \) direction. We denote the complex envelopes of the pump and signal as \( A_p(t, z) \) and \( A_s(t, z) \) respectively, and their optical angular frequencies by \( \omega_p \) and \( \omega_s \). The difference between the two frequencies: \( \omega_p - \omega_s = \Omega = 2\pi v \) is on the order of \( \Omega_B = 2\pi v_B \).

In the proposed scheme, the signal envelope at its point of entry into the fiber is modulated by a phase sequence \( c_n \) with a symbol duration \( T \) that is much shorter than the acoustic lifetime \( \tau \):

\[
\text{Eq. 2.1 } A_s(z = L, t) = A_{0s} \sum_n c_n \text{rect} \left( \frac{t - nT}{T} \right) = A_s(t)
\]
Here \( A_{0} \) is a constant magnitude, \( c_{s} \) is chosen as a prefect Golomb phase code of unity magnitude that is repeated every \( N \) symbols, and \( \text{rect}(\xi) \) equals 1 for \( |\xi| \leq 0.5 \) and zero elsewhere [27]. The pump wave envelope is also modulated by the same code, as in [27, 33-35]. Unlike the earlier works [27, 33-35], however, we present now an additional amplitude modulation by a single pulse that is overlaid on top of the phase sequence:

\[
A_{0}\left(z=0,t\right) = A_{0}\text{rect}\left(\frac{t}{\theta}\right)\sum_{n} c_{n}\text{rect}\left[\frac{t-nT}{T}\right] = A_{0}\left(t\right)
\]

In Eq. 2.2, \( A_{0} \) is a constant magnitude and \( \theta \) is the duration of the pump amplitude pulse. The phase sequence symbol duration \( T \) and the pulse duration \( \theta \) are chosen so that \( \theta \approx NT > \tau \).

We recall that the magnitude of the acoustic field at a given location is given by (see Eq. 1.27 above) [34]:

\[
Q(t, z) = j g_{1} \int_{0}^{t} \exp[-\Gamma_{A}\left(t-t^{'}\right)] A_{p}\left(t - \frac{z}{v_{s}}\right) A_{p}^{*}\left(t - \frac{z}{v_{s}} + \Delta(z)\right) dt^{'}
\]

Since the magnitudes of the pump and the signal envelopes are modulated in a randomly-like\(^1\) manner, we regard the acoustic field as a stochastic, ergodic process. It is therefore reasonable to examine the expectation value of the acoustic field, so that Eq. 2.3 becomes:

\[
\bar{Q}(t, z) = j g_{1} \int_{0}^{t} \exp[-\Gamma_{A}\left(t-t^{'}\right)] A_{p}\left(t - \frac{z}{v_{s}}\right) A_{p}^{*}\left(t - \frac{z}{v_{s}} + \Delta(z)\right) dt^{'}
\]

\[
= \frac{j}{\Gamma_{A}} g_{1} \cdot \text{ACR}_{p-s} \left[\Delta(z)\right]
\]

\(^1\) Here, the pump and signal envelopes are modulated with perfect Golomb series that are well designed and cannot be regarded as "random" sequence per se.
In Eq. 2.4, the overhanging bar sign denotes the ensemble average, and $ACR_{p,s}$ denotes the cross-correlation of the pump and signal envelopes. Ensemble and temporal statistics are taken to be equal. The spatial profile of the acoustic field is therefore closely associated with the cross-correlation between the two modulating envelopes. The relation only holds during the pump pulses, and provided that they are sufficiently long to exceed the duration of the exponential weighing window. Note that the Brillouin frequency shift might be position-dependent due to variations in the fiber, either intentional or not. The added value of the overlaying, pulsed amplitude modulation of the pump wave is examined below.

### 2.2 Simulations

Eq. 2.3 can be integrated numerically, subject to the boundary conditions of Eq. 2.1 and Eq. 2.2. Figure 20 shows the magnitude of acoustic field $|Q(z,t)|$ over a 6 m-long fiber section, subject to the modulation scheme of pump and signal described above. A uniform $v_B$ was assumed, and the frequency offset $\nu$ was chosen to match that value. A perfect Golomb code, ($N=127$, $T=200$ ps, see Appendix), was used in the phase modulation of both pump and signal, and a 26 ns-long amplitude pulse was superimposed on the phase-modulated pump wave. This pump pulse duration matches the code period. As expected in phase-encoded B-OCDA [33, 34], the acoustic field is confined to a discrete set of spatially-periodic correlation peaks, whose width $\Delta z = \frac{1}{2} v_s T$ equals 2 cm in this case. The separation between neighboring peaks is $N \cdot \Delta z$. Unlike the previous scheme [27, 33-35], however, the temporal duration of each correlation peak is restricted to the order of pump amplitude pulse $\theta$, and the peaks do not overlap in the time domain. The power of
the output signal, at any given instance, would therefore be affected by SBS amplification in a single correlation peak or by none at all.

Figure 20: Simulated magnitude of the acoustic wave density fluctuations (in normalized units), as a function of position and time along a 6 m-long fiber section. Both pump and signal waves are co-modulated by a perfect Golomb phase code that is 127 bits long (see Appendix), with symbol duration of 200 ps. The pump wave was further modulated by a single amplitude pulse of 26 ns duration, see Eq. 2.1 and Eq. 2.2. The acoustic field, and hence the SBS interaction between pump and signal, is confined to discrete and periodic narrow correlation peaks. The peaks are built up sequentially one after another with no temporal overlap.

Figure 21 shows the simulated output signal power as a function of time $|A_z(z = 0, t)|^2$. The trace consists of a series of amplification events, each of which can be unambiguously related to the SBS interaction at a specific correlation peak of known location. A single trace may therefore provide information on $L/(N \cdot \Delta z) \gg 1$ fiber positions. The locations of the correlation peaks can be offset in $\Delta z$ increments with proper retiming of the phase modulation of the pump and signal [33, 34]. The correlation peaks would return to their initial locations every $N$ steps, hence $N$ scans
only would be sufficient for the mapping of the Brillouin gain over the entire fiber, for each choice of \( \nu \). This number of scans does not depend on the fiber length, and is orders-of-magnitude smaller than the number of resolution points \( L/\Delta z \). The combined technique therefore retains the high resolution and long range of unambiguous measurement that is provided by phase-encoded B-OCDA, with an acquisition time that is potentially much reduced. In addition, use of perfect Golomb codes instead of PRBS phase modulation reduces the coding noise substantially [27, 35], and may help decrease the necessary number of averages.

![Figure 21](image.png)

Figure 21: Simulated output signal power as a function of time. Both pump and signal are modulated by a 127 symbols-long Golomb code with 200 ps symbol duration. The pump is also amplitude-modulated by a 25 ns-long single pulse. The simulated fiber under test is 20 m long. The simulated output signal was averaged over 128 repetitions. The trace consists of a series of amplification events, each of which can be unambiguously related to the SBS interaction at a specific correlation peak (see Figure 20).

For comparison, Figure 22 shows the calculated \( |Q(z,t)| \) for the phase-coded B-OCDA scenario, \( (\theta \to \infty, \text{ panel (a)}) \), and for the B-OTDA case where \( c_n = 1 \) for
all $n$, (panel (b)). The SBS interaction in B-OTDA at any given instance spreads over a comparatively large spatial extent, restricting resolution. Use of short codes in B-OCDA, on the other hand, leads to ambiguous measurements of the output signal power due to the simultaneous generation of multiple peaks.

Figure 22: Simulated magnitude of the acoustic wave density fluctuations (in normalized units), as a function of position and time along a 6 m-long fiber section. Panel (a): both pump and signal waves are co-modulated by a perfect Golomb phase code that is 127 bits long, with symbol duration of 200 ps. The simultaneous generation of multiple, periodic correlation peaks would lead to ambiguous measurement of the SBS amplification in monitoring the output signal power. Panel (b): The pump wave was modulated by a single amplitude pulse of 10 ns duration, whereas the signal wave was continuous (B-OTDA). Resolution limitations are illustrated.

### 2.3 Signal to noise ratio analysis

In the work presented in [52], Soto and Thevenaz provide a thorough analysis of the key factors that determine the performance of Brillouin distributed optical fiber sensors. An analytical expression was derived for the uncertainty in the estimates of the Brillouin frequency shift, as a function of various experimental parameters [52]:

\[
\sigma_v(z) = \frac{1}{SNR(z)} \sqrt{\frac{3}{4} \delta \cdot \Delta \nu_B}
\]
Here $\sigma_v(z)$ is the error in the estimated local value of the Brillouin frequency shift, $\delta$ is the frequency sampling step of the Brillouin gain profile measurements, $\Delta \nu_B$ is the Brillouin gain full-width at half maximum (FWHM), which is often estimated as $\Gamma_B/(2\pi)$, and $SNR(z)$ is the signal to noise ratio of the peak gain measurement at location $z$ along the fiber (see Figure 23).

![Brillouin gain profile](image)

**Figure 23.** Typical normalized Brillouin gain profile at a certain location $z$ in the fiber. The peak frequency of the gain profile is being estimated by a parabolic fit, and the uncertainty of its measurement dictates the Brillouin sensor temperature or strain accuracy. Noise ($\sigma$) on the signal, the full width at half maximum of the Brillouin gain line ($\Delta \nu_B$) and the frequency scanning step ($\delta$) are noted on the curve [52].

Eq. 2.5 shows that the higher the SNR in a specific measurement, the lower the error in the Brillouin frequency estimate. The SNR therefore plays an important role in the temperature or strain accuracy of Brillouin sensors, including the specific scheme that is described in this work. The SNR in the combined B-OTDA / B-OCDA method proposed in this chapter is given by:

$$SNR(z) \equiv \frac{\Delta P_r(\Omega = \Omega_B)}{\sigma},$$

**Eq. 2.6**
where the 'signal' \( \Delta P_s \) is defined as the difference (in W) in the output probe power following SBS amplification in a single correlation peak and at the frequency of maximum gain:

\[
\Delta P_s (\Omega = \Omega_p) = P_s(z + \Delta z) - P_s(z) \\
= P_s(z) \exp(g_0 P_p \cdot \Delta z) - P_s(z) \\
= P_s(z) \left[ \exp(g_0 P_p \cdot \Delta z) - 1 \right] , \\
\approx P_s(z) \cdot g_0 P_p \cdot \Delta z
\]

Eq. 2.7

and the noise standard deviation \( \sigma \) in the denominator of the SNR definition will be discussed later. In Eq. 2.7, \( P_s \) is the optical power of the signal wave, the correlation peak is introduced between \( z \) to \( z + \Delta z \), \( g_0 \sim 0.1 \text{ [W} \cdot \text{m}]^{-1} \) is the line-center Brillouin gain coefficient, and \( P_p \) is the pump power. We assume that the exponential signal gain is small, and may be approximated by the first order linear term. This assumption is justified since \( \Delta z \) is on the order of only 2 cm, and the expected Brillouin gain is less than 1%.

Let us evaluate the terms in the SNR (Eq. 2.6 and Eq. 2.7) and their practical limitations. First, \( P_s(z) \) is limited to the maximum optical input power that is allowed by the detector used in the measurements:

\[
P_s(z) \leq P_{\text{MAX}}^{\text{det}},
\]

Eq. 2.8

which leads to:

\[
\Delta P_s(\Omega = \Omega_p) \leq P_{\text{MAX}}^{\text{det}} \cdot g_0 P_p \cdot \Delta z.
\]

Eq. 2.9

Second, the pump power \( P_p \) might be limited due to several mechanisms [53]:
(i) **Non-local effects**: Non-local effects refer to a situation in which the measurement of SBS, in a certain location along the fiber and for specific choices of \( \Omega \), is affected by pump - signal interactions prior to that location. The pump power may be depleted due to these prior interactions, and therefore it might become weaker before reaching the specific location of interest. Consequently, weaker Brillouin amplification of the signal wave would take place at that point, for the particular \( \Omega \). This, in turn, may leads to distortion in the Brillouin gain profile and to an error in the estimate of the peak frequency. This pump depletion may be substantial when the pump-signal waves are interacting over a long fiber distance. However, in our technique pump depletion is negligible, since the SBS interaction is largely confined to several hundreds of correlation peaks, of a total length of only a few meters.

(ii) **Modulation instability** (MI), due to the combined effects of Kerr nonlinearity and chromatic dispersion. MI is the result of the interplay between anomalous dispersion and the Kerr effect [54], which causes exponential amplification of residual optical noise at specific frequencies, at the expense of the pump. MI might limit B-OTDAs over long fibers with strong pump power. The longest measurement range reported in this work is 1.7 km. MI is insignificant over this comparatively short range.

(iii) **Spontaneous and Stimulated Raman scattering**: Raman scattering, (named after C. V. Raman, the Indian Nobel Prize winner physicist, 1888-1970), is an inelastic scattering of a photon from an atom or molecule which involves vibrational state changes of that atom or molecule during the process [1]. Stimulated Raman scattering occurs when that scattered light ("signal") is interacting with the original light ("pump") along an optical fiber with the medium vibrational states as an intermediator. This effect transfers energy from the pump wave to the signal wave,
just similar to SBS but with a different mediator - vibrational states instead of acoustical phonons. There are two noticeable differences between the processes [55]: (i) the frequency shift of the scattered light in standard fiber is \(~13\) THz for Raman and \(~11\) GHz for Brillouin scattering; and (ii) the Raman scattered signal might be either co-propagating or counter-propagating with the pump wave. The forward-scattered Raman signal therefore interacts with the pump wave over the entire fiber length, unlike backward-only Brillouin scattering where the interaction length is limited to the pump pulse width. This suggests that Raman scattering may limit the pump power. However, Raman scattering efficiency in silica fibers is orders of magnitude smaller than that of SBS, with threshold power levels on the order of \(1\) W for tens of km of fiber. Therefore the maximum pump power is unlikely to be restricted by Raman scattering considerations.

(iv) **Spontaneous Brillouin scattering:** Spontaneous Brillouin scattering might compete with the stimulated one for pump power. A common method to mitigate the effects of spontaneous Brillouin scattering in optical communication systems is the phase modulation of the signal [56], in order to spread its power spectrum beyond the 30 MHz-wide Brillouin linewidth. Broadband phase modulation at 5 Gbit/s is inherent to the measurement scheme, elevating the spontaneous Brillouin scattering threshold by a factor of over 100. Therefore, this mechanism as well is expected to be negligible.

(v) **Self-phase modulation (SPM):** The refractive index of the fiber is modified by the intensity of the pump power due to the Kerr effect, and in turn affects the phase of the pump wave itself during propagation. This effect is known as SPM [1, 56]. The acquired nonlinear phase is given by [1]:

\[
\Delta \varphi_{NL} = \gamma P_p \cdot L
\]
Here $\gamma$ is the nonlinear coefficient, which equals $1.3 \text{[W} \times \text{km}]^{-1}$ in standard single mode fibers. The combined B-OTDA/B-OCDA method is based on a strictly designed phase coding of the pump and signal waves, and their phase accuracy and stability are of the essence for effective localization of the interaction and high resolution analysis. Let us assume arbitrarily that the maximum tolerable nonlinear phase is 1 rad:

Eq. 2.11  \[ \gamma P_p L \leq 1 \]

This leads immediately to a limitation on the pump power:

Eq. 2.12  \[ P_p \leq \frac{1}{\gamma L} \]

Applying the result of Eq. 2.12 in Eq. 2.9 leads to an upper bound on the attainable measurement signal:

Eq. 2.13  \[ \Delta P_s(\Omega = \Omega_B) \leq \frac{P_{\text{MAX}}^{\text{det}} \cdot g_0 \cdot \Delta z}{\gamma L} \]

Since $N_{\text{total}} = \frac{L}{\Delta z}$ is the total number of resolution points, we can rewrite Eq. 2.13 as:

Eq. 2.14  \[ \Delta P_s(\Omega = \Omega_B) \leq \frac{P_{\text{MAX}}^{\text{det}} \cdot g_0}{N_{\text{total}} \cdot \gamma} \]

In a standard single mode fiber: $\frac{g_0}{\gamma} \approx \frac{0.1}{1.3 \cdot 10^{-3}} \approx 100$, so Eq. 2.14 can be rewritten as:

Eq. 2.15  \[ \Delta P_s(\Omega = \Omega_B) \leq \frac{P_{\text{MAX}}^{\text{det}}}{N_{\text{total}}} \cdot 100 \]

The result of Eq. 2.15 is very important: it means that the Brillouin amplification signal $\Delta P_s(\Omega = \Omega_B)$ is practically limited by two factors: the total
number of potential resolution points, and the maximum allowed input power of the detector. In this respect, the limiting factors of the proposed hybrid B-OTDA / B-OCDA schemes are fundamentally different from those of standard B-OTDA protocols. Since SBS is much more pronounced in standard fibers than the Kerr effect, B-OTDAs are typically restricted by SBS-induced depletion and non-local effects. In our scheme, however, effective SBS takes place over a small fraction of the fiber length, whereas SPM accumulated over the entire measurement range. Hence SPM might become the foremost limiting factor in this scheme.

Applying the result of Eq. 2.15 into Eq. 2.6 gives the upper limit to the SNR:

\[ \text{SNR}(z) \leq \frac{100}{N_{\text{total}}} \frac{P_{\text{MAX}}^{\text{det}}}{\sigma}. \]

Measurement noise stems from two primary sources: Detector's thermal noise and shot noise. The standard deviations of the photo-current at the detector output due to both mechanisms are given by:

\[ \sigma_{\text{shot}} = \sqrt{2ei\Delta f} = \sqrt{2eR_{\lambda} P_{\text{MAX}}^{\text{det}} \Delta f} \]

\[ \sigma_{\text{thermal}} = \sqrt{\frac{4k_{B}T}{R_{L}}} F_{n} \Delta f = R_{\lambda} \cdot \text{NEP} \cdot \sqrt{\Delta f} \]

Here \( e \) is the electron charge, \( i \) is the average photo-current due to the detection of the signal power, \( \Delta f \) is the detector bandwidth, \( R_{\lambda} \) is the detector responsivity in [A/W] at a specific wavelength, \( k_{B} \) is Boltzmann's constant, \( T \) is the detector operating temperature in °K, \( R_{L} \) is the detection circuit equivalent load resistance in Ohm, and \( F_{n} \) is the noise-figure that represents any excess noise in the electronic circuitry of the photo-detector. NEP (in W/\( \sqrt{\text{Hz}} \)) stands for Noise
**Equivalent Power.** It is a commonly-used practical figure of merit of optical detectors, that expresses the optical power that yields an SNR of unity when measured at 1 Hz bandwidth. Eq. 2.16 can now be rewritten to give the final expression for the SBS gain measurement SNR:

\[
\text{Eq. 2.18} \quad \text{SNR}(z) \leq \frac{100}{N_{\text{total}}} \cdot R_{\lambda} P_{\text{MAX}}^{\text{det}} \cdot \frac{1}{\sqrt{2 e R_{\lambda} P_{\text{MAX}}^{\text{det}} \Delta f + R_{\lambda}^2 \cdot \text{NEP}^2 \Delta f}}.
\]

Eq. 2.18 shows that the SNR of the system is determined by the number of potential resolution points in the acquisition, the maximum optical input power that is allowed by the detector \((P_{\text{MAX}}^{\text{det}})\), shot noise and the detector's NEP. The magnitudes of the noise terms depend on the measurement bandwidth \(\Delta f\), which is governed in turn by the duration of the pump pulses. Substituting Eq. 2.18 into Eq. 2.5 provides an estimate for the uncertainty in the measurement of the local Brillouin frequency shift using combined B-OTDA / B-OCDA:

\[
\text{Eq. 2.19} \quad \sigma_v(z) \geq \frac{N_{\text{total}}}{100} \sqrt{\frac{2 e R_{\lambda} P_{\text{MAX}}^{\text{det}} \Delta f + R_{\lambda}^2 \cdot \text{NEP}^2 \Delta f}{R_{\lambda} P_{\text{MAX}}^{\text{det}}}} \cdot \frac{3 \cdot \delta \cdot \Delta V_B}{\sqrt{4 \cdot \Delta f}}.
\]

The detector I used in the experiment has a \(P_{\text{MAX}}^{\text{det}}\) of 1 mW, its NEP is 3 pW/\(\sqrt{\text{Hz}}\), its responsivity \(R_{\lambda}\) is on the order of 1 A/W, and its measurement bandwidth is \(\Delta f = 250 \text{ MHz}\). Shot noise is the dominant mechanism in these conditions.

Figure 24 shows the Brillouin frequency error \(\sigma_v\) as a function of fiber length for the above detector characteristics, and for \(\delta = 1 \text{ MHz}\) and \(\Delta V_B = 30 \text{ MHz}\). The spatial resolution is 2 cm. The analysis suggests that the measurements can, at least in principle, reach a range of about 2 km with a Brillouin frequency uncertainty of less
than 1.5 MHz, and without averages. It should be noted, however, that in most experiment that signal power at the photo-detector input might fall short of $P_{\text{MAX}}^\text{det}$, leading to elevated experimental errors in the estimate of the Brillouin shift. In addition, in a real distributed fiber sensing system, the sensing fiber is arranged in a loop and the effective physical length of the monitored path would be half of the above.

Figure 24: Brillouin frequency error $\sigma_v$ of Eq. 2.19 as a function of fiber length for the following detectors parameters: $P_{\text{MAX}}^\text{det} = 1 \text{ mW}$, $NEP = 3 \text{ pW/}\sqrt{\text{Hz}}$, $f_\Delta = 250 \text{ MHz}$; spatial resolution $\Delta z = 2 \text{ cm}$ which corresponds to Golomb symbol duration of 200 ps; $\Delta v_g = 30 \text{ MHz}$ and frequency scan step $\delta = 1 \text{ MHz}$.

The SNR can be improved by a factor of $\sqrt{N_{\text{avg}}}$, if the output signal is averaged over $N_{\text{avg}}$ repetitions taken at identical conditions. Another important conclusion can be drawn in that respect: an increase of the fiber length by a factor $M$, without changing resolution, would require $M^2$ as many averages to retain a desired SNR (and a desired Brillouin frequency accuracy). Since the time-of-flight of each measurement is also increased by a factor of $M$, the overall acquisition time of the
entire experiment would become $M^3$ times longer. This scaling law is not very favorable.

The restriction on the maximum allowed nonlinear phase accumulation was set in an arbitrary manner as 1 rad in Eq. 2.11. We may evaluate the SPM tolerance more closely using numerical simulations. To that end, the input pump wave of Eq. 2.2 was first propagated over a length $L$ of 3 km according to the nonlinear Schrödinger equation:

$$\text{Eq. 2.20} \quad \frac{\partial A_p}{\partial z} + j\frac{\beta_2}{2} \frac{\partial^2 A_p}{\partial t^2} - j\gamma |A_p|^2 A_p = 0$$

Here $\beta_2 = -20$ ps$^2$/km is the second-order chromatic dispersion parameter of the fiber, and linear losses are neglected. Propagation was modelled using the split-step numerical method. Next, the distorted, output pump wave was cross-correlated against an ideal, undistorted signal wave that is modulated according to Eq. 2.1, and the strength of the off-peak correlation sidelobes is observed for different pump power levels. A super-Gaussian pulse of order 4 was used: $A_p(t, z = 0) = \sqrt{P_p} \exp\left(-t^4/2\tau_p^4\right)$, with a width parameter $\tau_p$ of 10 ns (see Figure 25). The pulse shape and duration closely resemble those used later in experiments. The symbol duration of the underlying, Golomb-coded phase modulation was 200 ps.

Figure 25 shows the simulated magnitude of the stimulated acoustic field, obtained by the exponentially-windowed cross-correlation between the ideal probe wave and the SPM-distorted pump wave. Results are provided for different values of $\Delta\varphi_{NL}$ between 1 and 4 rad (pump power levels of 0.25-1 W). The elevation of coding noise with pump power is evident. The results suggest an upper limit of $\Delta\varphi_{NL}$ on the
order of 2 rad, a factor of two more tolerant than previously considered. This relaxation would imply a measurement range that is twice as long as well, for equal resolution, accuracy and detector parameters.

Figure 25. Simulated cross-correlations between a perfect Golomb code and a replica that is distorted by SPM, for several pump power levels. Top left: Temporal shape of the amplitude pump pulses used in the simulation. Both the pump wave and constant-magnitude probe were modulated by a 127 bits-long Golomb code with a symbol duration of 200 ps. Top right: Exponentially-windowed, cyclic cross-correlation between pump and probe, following propagation of the pump over 3 km of standard fiber. The pump power of 250 mW corresponds to a nonlinear phase \( \Delta \phi_{NL} \sim 1 \) rad. Bottom left and right: same as above, with pump power levels of 500 mW and 1000 mW (\( \Delta \phi_{NL} \) of 2 rad and 4 rad), respectively.

One manifestation of the effect of SPM on the coded pump wave is in the phases of those Golomb-code symbols which are in overlap with the rising or falling edges of the amplitude pulse. The phases acquired by those symbols vary
continuously, from zero to $\Delta \varphi_{NL}$, and therefore deviate from the designed binary values of the Golomb code. The cyclic auto-correlation property of the code is degraded accordingly. This observation suggests that the extent of coding noise due to SPM would be pulse shape-dependent. In principle, perfectly rectangular pump pulses might withstand larger nonlinear phases with little effect on coding noise. This trend is indeed observed in the numerical simulations.

Lastly, it must be commented that the SNR estimates provided above only take into consideration fundamental limitations, and therefore represent optimistic upper bounds on the performance of any practical realization of the combined B-OTDA/B-OCDA measurement protocol. The analysis does not take into account the accumulation of residual coding noise, even without significant SPM (as described in chapter 1.4.3. and Figure 17), which takes place due to the exponential windowing of the SBS process or due to any practical 'imperfections' of the phase modulation setup. Coding noise is made worse by the finite extinction ratio of the pump amplitude modulation, which introduces nonzero coding noise contributions from fiber segments that are outside the extent of the pump pulse. Last but not least, polarization-related fading of SBS, and the means for its mitigation, introduce a significant additional noise mechanism which is discussed at the end of chapter 3.1 hereunder. Nevertheless, the analysis carried out in this section provides useful estimates for the attainable performance of the proposed Brillouin sensing protocol, and its inherent tradeoffs and limitations.
3 Experimental Setup and Results

3.1 Experimental setup

Figure 26 shows the experimental setup for high-resolution, extended-range Brillouin analysis using the proposed, combined B-OTDA / B-OCDA technique. Both pump and signal waves were drawn from a single laser diode source at 1550 nm wavelength (New-Focus tunable laser, see Figure 27). An electro-optic phase modulator at the laser output was driven by an arbitrary waveform generator (AWG). The AWG (Tektronix model 7051, see Figure 28), was programmed to repeatedly generate a 127 bits-long perfect Golomb code (see Appendix), with a symbol duration on the order of 200 ps. The output voltage of the generator was adjusted to match $V_\pi \approx 3.7V$ of the modulator.

![Figure 26: Experimental setup for combined B-OTDA and B-OCDA distributed sensing.](image)
The phase-modulated light was split into pump and signal branches by a 50/50 fiber coupler. Light in the pump branch was amplitude-modulated by a sine-wave of frequency $\nu$ (~ 10.850 GHz), in suppressed-carrier format. The upper modulation sideband was retained by a narrow-band fiber-Bragg grating (FBG), whereas any residual carrier and the lower sideband were blocked. This upper sideband acts as a seed for the pump wave. Since it is derived from the same laser source as the signal wave, the difference in optical frequencies between the two remains stable. The pump wave was then amplitude modulated again by a second electro-optic modulator, driven by repeating pulses with a low duty cycle. The pulses duration of 26 ns was chosen to approximately match the period of the Golomb code, and their period of 4 $\mu$s exceeded the time-of-flight through the fibers under test. These pulses imitate the pump pulses in the B-OTDA technique. The pump pulses were then amplified by an erbium-doped fiber amplifier (EDFA) to an average power of 100 mW. A polarization scrambler was used to prevent polarization-related fading of the SBS interaction [44], see Figure 29 (see more below).

Figure 27: A tunable laser source (NewFocus, Venturi model TLB6600) was the light source for both the pump and signal waves.
Figure 28: Image of the arbitrary waveform generator used in the experiments. An 83 symbols-long perfect Golomb code can be seen. Sampling rate is ~5 GS/sec, or 200 ps symbol duration.

Figure 29: the polarization scrambler (Fiberpro model PS3000) used in the experimental setup to prevent polarization-related fading of the SBS interaction [44].

Light in the signal branch was delayed in a 25 km-long fiber imbalance [33]. The role of this path imbalance will be explained later in this section. The signal and pump waves were launched into opposite ends of a fiber under test. The signal wave at the output of the fiber under test was detected by a photo-detector of 250 MHz bandwidth (Figure 30), and sampled by a real-time digitizing oscilloscope. The
boundaries of the fiber under test are an isolator at one end and a circulator at the other end. A 2 cm-long hot spot, induced by a 10 Ω heating resistor, was placed towards the output end of the pump wave (nearby the isolator, see Figure 31).

Figure 30: The detector used in the experiments. MenloSystems model FPD 510 with maximum received optical power $P_{\text{det}}^{\text{MAX}}$ of about 1 mW, NEP of 3 pW/√Hz and bandwidth $\Delta f = 250$ MHz.

Figure 31: Heating element made of a high-current, 10 Ω resistor beneath an aluminum plate. A 2 cm long fiber section was attached to the aluminum flat, thereby creating a local hot spot towards the end of the fiber under test.

Arbitrary locations along the fiber under test were addressed as follows [33]:

The joint phase modulation introduced multiple correlation peaks along the fiber ring
that encompassed the pump branch, the signal branch, and fiber under test (see Figure 26). The peaks were separated by \( N \cdot \Delta z = \frac{1}{2} N_{T} \cdot T \approx 2.6 \text{m} \). Hence the position of all peaks, except for the central one, varied with the exact symbol duration. The \( L_{\text{delay}} = 25 \text{ km-long path imbalance along the signal branch guaranteed that off-centered correlation peaks were in overlap with the fiber under test. The positions of these peaks could be scanned through slight changes to the Golomb code symbol duration by offsets of: } \Delta Z = \left( L_{\text{delay}} / 2 \right) \cdot \left( \Delta T / T \right), \text{ where } \Delta T \text{ is the change in symbol duration.}

In the experimental setup, an 8 kbit/s variation in the nominal 5 Gbit/s phase modulation rate corresponded to an offset of the correlation peaks by 2 cm.

The fiber under test used in the experiment was a standard single-mode fiber of weak and random birefringence, which is not polarization maintaining. As Eq. 1.10 suggests, SBS originates from the optical interference between the pump and signal waves. Consequently, the interaction is the most efficient when the electric fields of the pump and signal are aligned, i.e., both have the same state of polarization (SOP) [44]. If the two waves have orthogonal SOPs, then the SBS interaction vanishes. In other words, the term \( A_{s} A_{p}^{*} \) in Eq. 1.11 must be generalized to represent a vector inner product rather than a scalar one. The SOPs of optical signals propagating along standard fibers vary at random, over a characteristic length scale of tens of meters. Therefore, the strength of the SBS interaction at a given correlation peak position may vary between the maximum that is predicted by scalar theory, and a minimum of zero. This polarization-related fading effectively restricts the analysis of fiber locations in which the two SOPs are nearly orthogonal.

In order to overcome this detrimental effect, a polarization scrambler was used in the pump arm of the experimental setup. The scrambler randomly changes the SOP
of the pump wave among the different repetitions of each measurement. Using this technique, the averaged trace that is acquired on the oscilloscope becomes polarization-independent. The method is associated with a penalty: the average SBS gain is reduced to half of that of the scalar case. In addition, the comparatively slow scanning rate of the scrambler mandates that at least 100 acquisitions or so are averaged, even in otherwise good SNR conditions.

3.2 Results

Two experiments demonstrated the proposed Brillouin analysis method. The First experiment used a 400 m long fiber under test (Figure 32 - Figure 34). A second experiment was taken with a 1700 m long fiber under test (Figure 35 - Figure 37).

3.2.1 Combined method demonstration with 400m long fiber

Figure 32 shows examples of the output signal as a function of time $|A_z(z = 0, t)|^2$. The fiber under test consisted of two segments, each about 200 m-long, with $\nu_B$ values at room temperature of 10.90 GHz and 10.84 GHz, respectively. A 2 cm-long hot spot was introduced towards the output end of the pump wave. Periodic peaks can be seen in the output probe power, separated by $NT \approx 26\text{ns}$ as expected. Each peak corresponds to the SBS amplification of the signal wave at a single correlation peak, as discussed in the previous section. In Figure 32(a) $\nu$ was set to match $\nu_B$ of the second fiber at room temperature. A single gain peak which is in overlap with the hot-spot appears weaker (see inset). That specific gain peak is more pronounced than all others when $\nu$ was changed to 10.89 GHz, the Brillouin shift in the hot spot (Figure 32(b), see inset). Each trace was averaged over 64 pump pulses, in order to overcome polarization scrambling variations, coding, detector and
shot noises. Note that the amplification peaks in the first fiber section disappear in the left-hand panel, due to the mismatch in Brillouin frequency shifts.

Figure 32: Measurements of the output signal power as a function of time, following propagation in a 400 m-long fiber under test that was composed of two sections, each of ~200 m length. The Brillouin frequency shifts of the two segments at room temperature were 10.90 and 10.84 GHz, respectively. Multiple peaks are evident, each corresponding to the SBS amplification in a specific correlation peak of the Golomb code. A 2 cm-long hot spot was located towards the output end of the pump wave. In both panels, one of the correlation peaks is in spatial overlap with the hot spot. The frequency offset between the pump and signal was set to match the Brillouin shift of the second section at room temperature (panel (a), 10.84 GHz), and the Brillouin shift at the temperature of the hot spot (panel (b), 10.89 GHz).

Figure 33 shows the SBS signal gain as a function of ν and z. The experimental procedure effectively reconstructed the Brillouin gain spectra at all 20,000 resolution points using only 127 scans for each choice of ν. The recovered values of ν_b(z) are shown in Figure 34. The estimated error of the measured Brillouin frequency is 1.7 MHz. The hot spot is well recognized (see inset).
Figure 33: Measured Brillouin gain map as a function of frequency offset between pump and signal, and position along a 400 m-long fiber under test. The fiber consisted of two sections, each approximately 200 m-long, with Brillouin shifts at room temperature of approximately 10.84 GHz and 10.90 GHz, respectively. A 2 cm-long hot spot was located towards the output end of the pump wave. The map was reconstructed using only 127 scans per frequency offset, according to the combined B-OTDA / B-OCDFA method. The complete map is shown on panel (a), and a zoom-in on the hot spot region is shown on panel (b).

Figure 34: Brillouin frequency shift as a function of position, as extracted from the experimental Brillouin gain map of Figure 33 above.
3.2.2 Hot spot measurements towards the end of a 1700 m long fiber

Figure 35 shows examples of the output signal power trace as a function of time, with $\nu$ adjusted to the Brillouin shift of the fiber under test at room temperature (top panel), and at the temperature of the hot spot (bottom panel). Only small segments of the traces, representing the output end of the pump wave, are shown for clarity. Each peak at the top panel corresponds to SBS amplification at a single correlation peak. The final peak is in overlap with the hot spot. The peak does not show at the top panel, but reappears in the bottom panel. The fiber was 1700 m long, therefore this experiment achieved over 80,000 resolution points. Yet, the entire set of resolution points was successfully interrogated using only 127 scans of correlation peaks positions. The reduction in acquisition time is be a factor of over 600.

Figure 36 (left) shows the map of SBS amplification as a function of $\nu$ and position. The map is magnified in the vicinity of the hot spot in Figure 36 (right), and the reconstructed local value of the Brillouin frequency shift is shown in Figure 37. The hot spot is clearly identified. The final 0.5 m-long segment of higher Brillouin shift is the fiber lead of an optical isolator.

![Figure 35: Measured output signal power as a function of time, taken with $\nu$ adjusted to the Brillouin shift of the fiber under test at room temperature (top panel), and at the temperature of the hot spot (bottom panel). Only short, magnified segments of each trace are shown, corresponding to the output end of the pump wave.](image-url)
Figure 36: Left – measured SBS gain as a function of frequency offset between pump and signal and position along the fiber under test. Gain spectra are acquired for 80,000 resolution points. Right – zoom-in of the gain spectra in the vicinity of the hot spot. The hot spot can be clearly seen.

Figure 37: Reconstructed values of the local Brillouin shift as a function of position. Inset shows a magnification of the trace in the vicinity of the hot spot. The final segment of higher Brillouin shift corresponds to the fiber lead of an isolator.

The results of both measurements provide solid experimental proof of the proposed, novel Brillouin sensing scheme and its added value.
4 Discussion and Summary

4.1 Summary of principle and results

In this work, I have proposed and demonstrated a new technique for distributed Brillouin fiber sensing of temperature and strain with a large number of high-resolution points. The method combines between B-OTDA and B-OCDA schemes. Similar to the phase-coded B-OCDA technique, both SBS pump and signal waves are repeatedly co-modulated by a short and high-rate phase sequence, whose symbol duration is on the order of hundreds of ps and its period is somewhat longer than the Brillouin lifetime. In addition, much like in B-OTDA setups, the pump wave is also amplitude-modulated by a single pulse, whose duration equals the period of the phase sequence. The method provides both high resolution and a comparatively long range of unambiguous measurements.

The combined B-OTDA/B-OCDA technique has two significant improvements with respect to the previous phase-coded B-OCDA arrangements: (i) Golomb phase codes are used instead of random sequences, and effectively reduce noise due to residual, off-peak Brillouin interactions; and (ii) The SBS amplification at a large number of correlation peaks is unambiguously interrogated by the single pump pulse, and resolved in the time domain. The number of scans that is necessary to reconstruct the Brillouin gain for a specific frequency offset $\nu$ equals the length of the Golomb code. The number of scans is smaller than that of previous phase-coded B-OCDA arrangements of equal range and resolution by over two orders of magnitude.
The combined technique is supported by numerical simulations of the stimulated acoustic field as a function of time and position, and of the output signal as a function of time, subject to the phase and amplitude modulation scheme of the pump and the signal as described above. As expected, the stimulated acoustic field is confined to a discrete set of spatially-periodic correlation peaks of cm-scale widths. The temporal duration of the acoustic field at each correlation peak is restricted to the pump amplitude pulse duration, and the peaks do not overlap in the time domain. The output signal trace consists of a series of amplification events, each of which may be unambiguously related to the SBS interaction at a specific correlation peak of known location. A single trace can therefore provide information on hundreds of fiber positions.

The locations of the correlation peaks can be offset in $\Delta z$ increments with proper retiming of the phase modulation of the pump and signal. The correlation peaks return to their initial locations following a number of steps that equals the length of the Golomb phase code: 127 steps in our case. Hence 127 scans are sufficient for the mapping of the Brillouin gain over the entire fiber, for each choice of $\nu$, and regardless than the number of resolution points $L/\Delta z$. The combined technique therefore retains the high resolution and long range of unambiguous measurement that is provided by phase-coded B-OCDA, with an acquisition time that is much reduced.

The SNR of the output signal measurements and its implications on the uncertainty in the estimate of the Brillouin shift were analyzed. It was found that both are limited by the SPM that is associated with a high-power pump wave, which distorts the precise values of the Golomb phase code as the pump is propagating along the fiber. Nevertheless the analysis suggests that, at least in principle, measurements
with few-MHz precision can be made over km ranges with cm resolution and without averaging.

The combined method was successfully demonstrated in two experiments in which Brillouin gain spectra were acquired over up to 1700 m of fiber with 2 cm resolution. The entire set of 80,000 resolution points was mapped in only 127 scans per choice of frequency offset \( \nu \). A 2 cm-long hot spot (\( \sim 65^\circ \)C), located towards the output end of the pump wave, was properly identified in the measurements. Each trace was averaged over 64 repetitions only, limited by the operation rate of the polarization scrambler involved in the setup. The overall net time-of-flight required, for 40 values of \( \nu \) and for the entire set of resolution points, was about 1 second. The estimate does not include latencies due to data transfer by laboratory equipment and off-line signal processing, which would be performed in real-time by a realistic, dedicated instrument. The uncertainty in the estimates of the local Brillouin shift was \( \pm 1.7 \) MHz. It can be improved by raising the power of the signal wave, closer to the upper limit of the photo-detector dynamic range, and with replacing the polarization scrambler arrangement by a polarization switch configuration [57, 58].

The spatial resolution in the experiments was limited to 2 cm by the rate of waveform generators available to us. The technique is scalable to resolution below 1 cm. Higher resolution measurements would be associated with weaker SBS amplification, and stronger coding noise due to longer Golomb codes. In this respect, it is important to note that off-peak interactions subject to Golomb-code modulation do not represent random noise, but rather a pattern that can be predicted. Yet, residual amplification variations due to off-peak interactions can be suppressed using averages over repeating measurements, provided that there is no temporal synchronization between the Golomb code cycles and the amplitude pulses of the pump.
In summary, the technique represents a significant advance towards practical high-resolution, long-range Brillouin analysis. The experimental results are at the forefront of high-resolution Brillouin sensing, and could not be obtained with previous phase coded B-OCDA techniques.

4.2 Follow-ups and ongoing work

Since the initial proposition and experimental demonstration of the combined B-OTDA / B-OCDA technique described in this thesis, the method became the 'work horse' of our group in numerous applications of high-resolution sensing. For example, Figure 38(left) shows a composite material beam, consisted of structural layers of glass fibers and epoxy resin, with optical sensing fibers embedded during production. The methods developed in my work were successfully employed in the repeating monitoring of the beam during its production and through the curing of the epoxy. Measurements were taken with a spatial resolution of 4 cm, and repeated every 20 minutes for over 30 hours. The local values of the Brillouin frequency shifts were estimated with ±1 MHz precision.

Figure 38(right) shows the Brillouin shift as a function of position and time elapsed since the installation of the sensing fiber. The analysis captured the initial heating of the beam during the curing of the epoxy resin, and showed that residual compressive strain remained in the sensing fiber [59]. The experiment included, for the first time in our group, the use of a polarization switch instead of a scrambler for faster acquisition with better SNR [59]. The experiment also demonstrated the robustness of the proposed method and setup. Measurements were taken continuously over 30 hours with no personnel present and without any calibrations or adjustments. In a different experiment, Brillouin analysis using the principles of this work
extracted the stiffness and elastic modulus of the composite material beam in a three-point-bending experiment [59].

![Composite beam with optical sensing fibers](image1)

**Figure 38.** Left – a composite beam made of structural layers of glass fibers and epoxy resin. Optical sensing fibers are embedded in the beam during its production. Right – map of the measured offsets in the Brillouin frequency (MHz) as a function of time (in hours) and position (in cm) along the sensing fiber. Data was taken every 20 minutes for over 30 hours, during and following the production of the beam, using the Brillouin analysis protocol that had been developed in this research [59].

As presented earlier in this work, SPM sets a limit on the power of a single amplitude pulse, and consequently on the number of resolution points that can be interrogated with sufficient SNR. Since the conclusion of my research, our group had suggested and demonstrated a significant extension of its principles which achieved a better SNR [60]: similar to the method reported herein, both pump and signal are jointly phase-modulated by a repeating, high-rate Golomb code (phase-coded B-OCDA). However, rather than using a single intense pump pulse, (as in B-OTDA), the pump is amplitude modulated by a long, lower-rate on-off-keying sequence. Brillouin interactions at the correlation peaks imprint weak replicas of the pump amplitude sequence on the intensity of the output signal. The Brillouin amplifications at individual correlation peaks are resolved by matched-filter post-processing of the
output signal, following a unique incoherent compression protocol that achieves maximum sidelobe suppression [61]. The SNR obtained in the compression of the extended pump pulse sequence is equivalent to that of many repeating single-pulse acquisition averaged together. Therefore, the acquisition time that is required to achieve sufficient precision is much reduced. Moreover, the peak power level of the pump sequence pulses may be lowered, and the onset of SPM is deferred.

My colleagues experimentally demonstrated the acquisition of Brillouin gain spectra over a 2.2 km-long fiber with a spatial resolution of 2 cm, or 110,000 resolution points, using a perfect Golomb phase sequence of 499 symbols (symbol duration 200 ps) and a pump amplitude modulation sequence of 2,224 bits (symbol duration 40 ns). Results are shown in Figure 39 (a). A 5 cm-long hot spot was detected successfully, (see Figure 39 (b), [60]). Very recently, the experiment was successfully repeated over an 8.8-long fiber, demonstrating the interrogation of an unprecedented 440,000 resolution points [62].

Figure 39. (a) Measured Brillouin gain (relative units), as a function of frequency offset between pump and signal and of position along a 2,200 m-long fiber. (b) A magnified view of a fiber section in the vicinity of a 5 cm-long hot spot, located towards the output end of the pump wave. The hot spot (and splice) are well recognized in the measurements [60].
On-going work is being dedicated to the following: a) An experimental, quantitative analysis of the limitations imposed by SPM; b) an optimization of the power levels of both pump and signal; c) system-level optimization of modulation extinction ratio, the treatment of polarization, etc.; and last but not least – d) the integration of a portable Brillouin analyzer prototype based on the principles of this research, for monitoring of composite beams, civil engineering structures, etc. outside the group research laboratory.

To conclude, in my opinion this research demonstrated yet again that the whole is greater than the sum of the parts. The careful and judicious combination between seemingly complementary and unrelated methods resulted in a new and better distributed fiber sensor.


5. Omnisens (www.omnisens.com), a Swiss based company which develops distributed fiber sensing products, such as B-OTDA interrogators.


35. Y. Antman, L. Yaron, T. Langer, M. Tur, N. Levanon, and A. Zadok, "Experimental demonstration of localized Brillouin gratings with low off-peak


51. F. Gyger, E. Rochat, S. Chin, M. Nikles, L. Thevenaz, "Extending the sensing range of Brillouin optical time-domain analysis up to 325 km combining four


Appendix

Perfect Golomb code

The Golomb code used in the experiments and simulations of this work is 127 bits long. All elements in the code are of unity magnitude.

- The phases of the following elements equal $\cos^{-1}(-63/64)$:
  \begin{equation}
  \{1 \ 2 \ 4 \ 8 \ 9 \ 11 \ 13 \ 15 \ 16 \ 17 \ 18 \ 19 \ 21 \ 22 \ 25 \ 26 \ 30 \ 31 \ 32 \ 34 \ 35 \ 36 \ 37 \ 38 \ 41 \ 42 \ 44 \\
  47 \ 49 \ 50 \ 52 \ 60 \ 61 \ 62 \ 64 \ 68 \ 69 \ 70 \ 71 \ 72 \ 73 \ 74 \ 76 \ 79 \ 81 \ 82 \ 84 \ 87 \ 88 \ 94 \ 98 \ 99 \\
  100 \ 103 \ 104 \ 107 \ 113 \ 115 \ 117 \ 120 \ 121 \ 122 \ 124 \}.
  \end{equation}

- The phases of all other elements equal zero.
Title

Pigmented birefringent and filamentary optical elements to localize and transmit optical energy, and how they behave when subjected to stress and vibration. The study examines the effects of mechanical vibration on the filaments, and how they respond to stress over time. The results are compared with those obtained from similar studies conducted in the past, and the implications for future research are discussed.

The study uses a novel method for measuring the effects of mechanical vibration on the filaments, and how they respond to stress over time. The results are compared with those obtained from similar studies conducted in the past, and the implications for future research are discussed.
The correlation is only present in a stable and fixed manner. In previous works by members of our research group and others, the -B-OCDA principle was expanded to include a shared phase of light and acoustic waves by means of a common sequence of bits at a high rate. This technique transfers the localization between the light and acoustic waves beyond the existing range of the -B-OCDA technique, and enables measurements of single-bit light and acoustic waves at a high spatial resolution.

Nonetheless, the value of the acoustic waves outside the correlation is zero, but the instantaneous values change with a deviation that is not zero. This phenomenon is known as 'encoding noise'. The localization of the waves at the time of the correlation accumulates for the entire length of the light wave, and increases significantly in relation to the light.

In the current work, I propose, analyze and demonstrate a new approach to light encoding. The method combines the principles of the -B-OTDA and -B-OCDA. It provides a solution to the noise and time limitations of the -B-OCDA technique in encoding. Just as in the previous method, the two optical fields pass through a common sequence of light pulses at a high rate, which results in light and acoustic waves at the points.

The method maintains high measurement resolution and long time ranges of single-meaningful measurements that remain in the -B-OCDA technique in encoding, and is improved by the use of longer light pulses.
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בשיטה זו, מספר החסידות نحوו עבורי את הפוסטים תдесяים ים השלוח אחד ושלוח הוף
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בקודיפא-מאות, מספר החסידות חדידה ניוה עלה כליב אחר אופנים של הסיב השלבアイテム.

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מדידת הסטטרוטוריה אשר המות. די על עם, היותו מרפא כי מידי˻ותיה של איסוף
דר בידיאון בדיק של 1 MHz ניתוח על פי חום של ממוקמת בורוקראיה ושל
מספר כש, ולא מיצוג על-פי מידי$hוורה:

השישה המוצעות הכסיות בנויים במפלס של חזר בריליאן על-פי בינארDCF
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مهפקולתהלנדסהשלאוניברסיטתבר-אילן.
חישת סיב-אופטיית מפולגת על בסיס אפקט בריליאן, בעל רזולוציה מרחבית добهة, טווח אור זום ומדידה מפתת

דוד אילן

עבוודת 2 מועמדת לתחום מדעים לספק בבלת נויר מורפומטר
בסקולטה להנחייה של אוניברסיטת בר-אילן

תשב"ה

רמת גן