BAR-ILAN UNIVERSITY

High-Resolution Double-Pulse-Pair Brillouin
Optical Correlation-Domain Analysis

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Acknowledgments
B"H

“Showing gratitude is one of the simplest yet most powerful things humans can do for each other.” — Randy Pausch, The Last Lecture

I would like to dedicate these next few lines to thank those who have assisted, guided and encouraged me throughout these two years to complete this research.

First and foremost I would like to thank the G-d, without whom nothing could be carried out.

When I first started working under the guidance of Prof. Avi Zadok I did not really know what my future holds. Already during my first degree I began working on my final undergraduate project in the group. In retrospect, although that project did not approach the size of a research thesis, it nevertheless laid the foundations for my research work. Even at that stage, I already realized that I chose the advisor that is best for me.

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## Acronyms

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<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>AWG</td>
<td>Arbitrary Waveform Generator</td>
</tr>
<tr>
<td>BFS</td>
<td>Brillouin Frequency Shift</td>
</tr>
<tr>
<td>BOCDA</td>
<td>Brillouin Optical Correlation-Domain Analysis</td>
</tr>
<tr>
<td>BOTDA</td>
<td>Brillouin Optical Time-Domain Analysis</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous-Wave</td>
</tr>
<tr>
<td>DPP</td>
<td>Double Pulse Pair</td>
</tr>
<tr>
<td>DTS</td>
<td>Distributed Temperature Sensing</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifiers</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
</tr>
<tr>
<td>OTDR</td>
<td>Optical Time Domain Reflectometry</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-To-Noise Ratio</td>
</tr>
<tr>
<td>FUT</td>
<td>Fiber Under Test</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>OFDR</td>
<td>Optical Frequency Domain Reflectometry</td>
</tr>
<tr>
<td>PC</td>
<td>Polarization Controllers</td>
</tr>
<tr>
<td>PM</td>
<td>Polarization Maintaining</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo Random Bit Sequence</td>
</tr>
<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
</tr>
<tr>
<td>SMF</td>
<td>Single-Mode Fiber</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifiers</td>
</tr>
<tr>
<td>SOP</td>
<td>State Of Polarization</td>
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<tr>
<td>SRS</td>
<td>Stimulated Raman Scattering</td>
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<tr>
<td>SSB</td>
<td>Single Side-Band</td>
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### Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$B$</td>
<td>Bandwidth</td>
<td></td>
</tr>
<tr>
<td>$C_T$</td>
<td>Brillouin shift temperature</td>
<td></td>
</tr>
<tr>
<td>$C_{\varepsilon}$</td>
<td>Brillouin shift strain coefficient</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>Electro-magnetic wave</td>
<td></td>
</tr>
<tr>
<td>$F_n, F_A$</td>
<td>Noise figure</td>
<td></td>
</tr>
<tr>
<td>$I$</td>
<td>Optical intensity</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>Power gain</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>Total number of symbols in series</td>
<td></td>
</tr>
<tr>
<td>$N_{av}$</td>
<td>Number of repetitions</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Polarization, Optical power</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Phase symbol duration, temperature</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light in vacuum</td>
<td></td>
</tr>
<tr>
<td>$c_n$</td>
<td>Phase code symbol</td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>Electro-strictive force</td>
<td></td>
</tr>
<tr>
<td>$f, f$</td>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>$g, g_0$</td>
<td>SBS gain parameters</td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>Wavenumber</td>
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</tr>
<tr>
<td>$n$</td>
<td>Refractive index</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>Acoustic wavenumber</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>$v$</td>
<td>Speed of sound</td>
<td></td>
</tr>
<tr>
<td>$v_s$</td>
<td>Group velocity</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>Distance</td>
<td></td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Acoustic damping parameter</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_B$</td>
<td>Brillouin linewidth</td>
<td></td>
</tr>
<tr>
<td>$\chi$</td>
<td>Material susceptibility</td>
<td></td>
</tr>
<tr>
<td>$\omega, \Omega$</td>
<td>Angular frequency</td>
<td></td>
</tr>
<tr>
<td>$\gamma_e$</td>
<td>Electro-strictive constant</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain, dielectric constant</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>Quantum efficiency of the receiver</td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Optical Wavelength</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Pressure wave amplitude, material density</td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Lifetime</td>
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Abstract

Optical fibers were developed in the early 1970's, as means to support long-reach, high-rate optical communication. Since then, however, optical fibers also established their added value as an exceptional sensing platform. Alongside many other types of sensors, fibers support the distributed measurements of temperature and mechanical strain. Distributed fiber sensors are widely employed in structural health monitoring and perimeter defense.

One of the physical mechanisms that are underlying distributed fiber sensors is that of stimulated Brillouin scattering (SBS). SBS is a non-linear effect that can couple between two optical waves that are counter-propagating along the fiber: an intense pump wave and a typically weaker probe (or signal) wave. Coupling is achieved through a mediating acoustic wave. Efficient coupling occurs when the difference between the optical frequencies of the two waves is in close agreement with a specific value known as the Brillouin frequency shift (BFS) of the fiber medium. The BFS equals approximately 11 GHz in standard optical fibers and for optical waves in the wavelength range of 1550 nm.

The exact value of the BFS varies with both temperature and mechanical strain. Based on this dependence, the mapping of the local BFS along optical fibers is being used in the distributed sensing of both quantities for 25 years. The most widely employed measurement configuration 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, and cover a measurement range of 50 km with a spatial resolution of 2-3 m and an acquisition time of minutes.
The spatial resolution of B-OTDA is set by the duration of pump pulses, which is in turn limited to the order of 5-10 ns by the lifetime associated with acoustic wave stimulation. The pulse duration corresponds to a spatial resolution of 1-2 m. Numerous techniques were proposed to circumvent the acoustic lifetime limitation and improve B-OTDA resolution. One of the most successful approaches is the double pulse pairs (DPP) method. In DPP measurements each B-OTDA trace is acquired twice, and the durations of the pump pulses in the two experiments differ slightly. The two raw traces of the output signal power as a function of time are subtracted. Subtraction removes the common terms, and retains the signal amplification across a short segment that corresponds to the difference in duration between the two pulses, rather than their absolute durations. DPP B-OTDA experiments have reached a spatial resolution of 2 cm over 2 km of fiber.

A different paradigm for high-resolution Brillouin sensing, first proposed in the late 90s, relies on manipulating the temporal cross-correlation function between the complex envelopes of the pump and signal waves. The proper joint modulation of the two waves, in frequency of phase, restricts their cross-correlation to discrete spatial points, known as correlation peaks. SBS is largely confined to these peaks. This strategy came to be known as Brillouin optical correlation domain analysis (B-OCDA). Advanced variants of B-OCDA reached 1.6 mm resolution, or the addressing of nearly half-million independent resolution points. The overlaying of amplitude pulses on top of the pump wave allows for the unambiguous addressing of multiple correlation peaks in a single trace. However, each B-OCDA trace can only address a sub-set of the resolution points along the entire fiber under test. Even the most elaborate multiplexing techniques in B-OCDA setups to-date still require at least 50-100 scans of correlation peaks positions in order to cover an entire fiber. That number of scans is dictated again by the duration of pump pulses, and the acoustic lifetime constraints.
This study presents a new method, which brings together the principles of phase-coded B-OCDA and DPP analysis, in order to reduce the number of necessary position scans to 11 only. In this method we overlay the double-pulse architecture on top of phase-coding of pump and signal. The duration of pump pulses in each individual experiment is comparatively long, so that SBS is stimulated in multiple correlation peaks with temporal overlap. Direct analysis of a single trace cannot separate between individual SBS amplification events. However, like in DPP B-OTDA, each trace is acquired twice using pump pulse durations that are slightly different. The subtraction of the two output traces then unambiguously recovers the amplification taking place at each individual peak. Unlike DPP B-OTDA, where resolution is directly determined by the difference between pulses durations, the resolution of the new protocol is set by the B-OCDA phase modulation. This property relaxes the measurement bandwidth constraints and helps improve the signal-to-noise ratio in data acquisition.

The principle of DPP BOCDA is supported by extensive numerical analysis of the coupled differential equations of SBS, subject to the proper boundary conditions. The principle was demonstrated in the analysis of a 43 m-long fiber with 2.7 cm resolution. Only 11 scans of correlation peak positions were required to address all 1600 resolution points. Several local hot-spots were properly identified in the measurements. The experimental uncertainty in the measurement of the local BFS was ±1.9 MHz. Trade-offs between the proposed protocol and previous DPP B-OTDA and B-OCDA realizations are discussed.
1. Introduction

1.1 Optical fibers sensors

The main purpose of optical fibers is to transmit light from one point to another. Fibers serve that purpose far better than any other medium, optical or not, and their performance made an immense impact on telecommunications. Over the last forty years, however, optical fibers were also proven to be an exceptional sensing platform. Many physical quantities of interest, such as: strain, stress, temperature, humidity, magnetic fields, electrical fields, acoustic fields, presence and concentration of chemical and biological species, and many more can be sensed either directly or indirectly through the propagation of light in fiber [1,2]. The advantages of optical fibers as a sensor platform include the following:

- The small diameter of fibers makes them comparatively convenient to install in many structures and environments of interest, with little effect on functionality.
- Fibers guide light over long distances, up to tens of km without amplification. Therefore they provide remote-access measurements.
- Optical fibers are immune to electro-magnetic interference, and are chemically inert [3]. Fibers can be installed in hazardous environments in which the application of electricity is prohibited.

One significant category of optical fiber sensors is that of distributed sensors, arrangements in which every segment of fiber may serve as an independent sensing node. Distributed sensors may be required in many applications, such as in health monitoring of different types of structures in the civil engineering, oil and gas, energy, construction and transportation sectors. Distributed measurements of strain and temperature may provide critical information in the design, development and assembly stages as well as during service
of structures [4]. The early detection of faults may save lives (and also much money). On occasions, society is given painful reminders for the potential value of distributed structural health monitoring in the form of catastrophic failures, which might have been prevented. A recent example is the collapse of a multi-level parking-lot structure in Tel-Aviv which collapsed on September 2016, claiming six lives.

Sensor measurements may be taken routinely, as part of preventive maintenance. In certain applications the static measurement of strain and temperature is sufficient, whereas others require dynamic monitoring of vibrations and high-rate data acquisition. Traditionally, the vast majority of field deployments of distributed fiber-optic sensors has been in pipeline and cable integrity monitoring in the oil and gas and energy sectors [5,6,7]. In recent years, distributed acoustic sensors are increasingly being deployed in perimeter defense.

Distributed fiber-optic sensors make use of three different physical phenomena: Rayleigh, Raman, and Brillouin scattering. The research described in this thesis focuses on Brillouin scattering. I will first briefly introduce the other two mechanisms, before proceeding to a detailed discussion of Brillouin-based sensors.

1.2 Rayleigh scattering-based sensors

Rayleigh scattering is the elastic scattering of light (or other electromagnetic radiation) by particles that are much smaller than the radiation wavelength. The process was named in honor of Lord Rayleigh, who first described the phenomenon in 1871 [8]. The intensity \( I \) following Rayleigh scattering from a single particle is given by [9]:

\[
I = I_0 \frac{8\pi^3 \alpha^2}{\lambda^4 R^2} (1 + \cos^2 \theta),
\]
Here, $R$ is the distance from the particle, $\theta$ denotes the scattering angle, $I_0$ is the incident intensity, and $\alpha$ is the polarizability of the particle. Scattering is inversely proportional to the fourth power of the incident wavelength $\lambda$. The classic example of Rayleigh scattering is the color of clear sky. Incident sunlight at the shorter (blue) wavelengths scatters less strongly in the atmosphere than longer-wavelength spectral components, leading to blue color.

Silica optical fibers are amorphous, disordered media, consisted of nano-scopic grains of different density and refractive index. The boundaries between these sub-wavelength domains cause Rayleigh scattering, which constitutes the primary source of propagation losses in optical fibers. The propagation loss coefficient due to Rayleigh scattering in modern fibers is on the order of:

$$\alpha_{Rayleigh} = 0.12 - 0.16 \text{ dB/km}.$$  \hspace{1cm} (1.2)

Rayleigh scattering may be used in fiber-optic sensors. The most widely-used protocol is that of optical time domain reflectometry (OTDR). It is based on the transmission of a short and intense pulse, and the continuous measurement of the reflected signal. We may regard this method as a measurement of the impulse response of the fiber Rayleigh backscatter. Local loss events manifest as a discontinuity in the reflected trace. Point reflections may be identified as well. The resolution of this method is determined by the pulse width: shorter pulses provide better spatial resolution. However, Rayleigh backscatter is very weak: on the order of only -70 dB per meter of standard fiber. Therefore, high-resolution measurements using ultra-short pulses suffer from low signal-to-noise ratios (SNRs).

Each OTDR resolution cell contains a very large number of individual scattering events. The fundamental OTDR concept uses low-coherence sources, so that backscatter
events within the pulse add up incoherently. Therefore, only changes in the amplitude of the overall back-scattered light can be observed. In contrast, coherent OTDR (or c-OTDR) makes use of narrow-band laser diode sources, and also resolves changes to the relative phases between individual scattering contributions [10]. Traditional OTDRs are used primarily by telecommunication providers in fault detection and maintenance. C-OTDR is particularly suitable for high-rate, dynamic monitoring of sound and vibration disturbances [10].

An alternative sensing procedure which makes use of Rayleigh scattering is that of optical frequency domain reflectometry (OFDR), in which the frequency response of Rayleigh backscatter is measured rather than its time-domain impulse response. In this method, a large number of measurements are taken, each using a continuous-wave (CW) signal with a different optical frequency. Both the amplitude and the phase of the backscattered light are recovered through coherent detection. The impulse response may be calculated by an inverse-Fourier transform of the collected data [7,11,12]. The spatial resolution $\Delta z$ in OFDR is inversely proportional to the frequency span of the measurements $\Delta f$ :

$$\Delta z = \frac{c}{2n_g \Delta f},$$

(1.3)

where $n_g$ is the group index of light in the fiber and $c$ denotes the speed of light in vacuum. OFDR experiments reached a spatial resolution of 800 µm, [13], and even 20 µm [14]. The number of resolution points in OFDR equals the number of frequencies used.

1.3 Raman Scattering-based sensors

Raman scattering refers to the interaction of incident light, at some frequency $\omega_L$, with molecular vibration or rotation of resonance frequency $\omega_V$ [15]. The interaction may lead to the absorption of an incident photon, alongside the emission of a new photon at frequencies of either $\omega_L - \omega_V$ or $\omega_L + \omega_V$. The former scenario is known as Stokes-wave
scattering, and it is associated with the elevation of a molecule to a higher energy level, whereas the latter is referred to as anti-Stokes scattering which is associated with the relaxation of the molecule to a lower level. The effect was discovered by the Indian Nobel Prize winner C.V. Raman in 1928 [16].

Spontaneous Raman scattering takes place due to molecular vibrations that exist in the medium for thermal reasons. In stimulated Raman Scattering (SRS), discovered by Woodbury and Ng in 1962 [17], molecular vibrations are strongly enhanced by incident optical fields and the strength of scattering is increased considerably.

The main use of Raman scattering in fibers is the amplification of optical communication waveforms [18]. However, Raman scattering is also employed in distributed temperature sensors [19,20,21]. At thermal equilibrium, the number of molecules found at each energy level is governed by Boltzmann statistics [22]. The number of molecules at the ground state is always the largest. However, the number of molecules at the excited states increases with temperature. Therefore, temperature determines the rates of Stokes and anti-Stokes waves emissions. The mapping of scattered intensities at $\omega_L - \omega_V$ and $\omega_L + \omega_V$ as a function of position reveals the local temperature. Raman scattering-based distributed temperature sensing (DTS) systems achieved a distance greater than 10 km in single-mode silica fiber, with a temperature resolution of 4 °C [19].

1.4 Stimulated Brillouin scattering (SBS)

Stimulated Brillouin Scattering (SBS) is a third-order non-linear effect, in which light waves may be coupled by acoustic vibrations at ultrasonic frequencies. In this process two waves are launched into an optical fiber: A pump wave of central optical frequency $\omega_p$ from one end, and a probe or signal wave of central optical frequency $\omega_s$ from the opposite end [23]. Two physical mechanisms participate in SBS: the first is electrostriction, or the
tendency of matter to compress in the presence of a high electro-magnetic intensity, and the second is the photo-elastic effect, or variations in refractive index due to density fluctuations.

When the pump and signal waves enter the fiber, the overall intensity includes, among other terms, a traveling electro-magnetic interference term (a beating pattern) of frequency $\Omega$ which equals the frequency difference between the pump and the signal: $\Omega = \omega_p - \omega_s$. Through electrostriction, this beating pattern leads to a higher density where and when intensity is high, and vice versa [15]. Changes in density follow the beating pattern, and propagate along the fiber with frequency $\Omega$. These variations in intensity therefore have all the characteristics of a longitudinal acoustic wave disturbance.

The acoustic wave, in turn, causes a periodic variation in the refractive index of the fiber through the photo-elastic effect, and generates a traveling grating of refractive index perturbations. This acoustically induced grating scatters part of the incident pump wave, in the opposite direction. Since the grating is moving, the back-scattered pump wave is Doppler shifted in its frequency by $\Omega$, and therefore matches the frequency of the signal. As a result, the power of the signal wave may be increased, at the expense of the pump.

The process is characterized by positive feedback: stronger scattering leads to a more intense signal wave, which in turn brings about a stronger beating pattern, larger density variations, and consequently even stronger scattering, and so on. The positive feedback may lead to an exponential amplification of the signal wave power as a function of position along the fiber. The mechanisms are illustrated in Fig. 1.
For reasons that would become apparent in subsequent sections, effective SBS amplification requires that the difference $\Omega$ between the two optical frequencies closely matches a certain value, known as the Brillouin frequency shift (BFS) of the fiber $\Omega_B$. The Brillouin shift, at a given pump optical frequency, is a property of the fiber medium. It approximately equals $2\pi \cdot 11$ GHz in standard fibers at the telecommunication wavelengths (1550 nm). The Brillouin gain spectrum, centered at $\Omega_B$, is of a Lorentzian line-shape. The tolerance in $\Omega$ is very strict: the spectral width of the SBS gain window is only 30 MHz in standard single mode fibers under continuous-wave (CW) pump conditions (see Fig. 2). This bandwidth corresponds to a characteristic acoustic lifetime $\tau$ on the order of 5 – 10 ns.
Figure 3 shows the three scattering effects: Rayleigh scattering, SRS, and SBS, in the frequency domain.

Figure 3. Illustration of the three scattering effects: Rayleigh scattering, SRS, and SBS [24].

1.4.1 Mathematical analysis of stimulated Brillouin scattering

The mathematical analysis and equations governing SBS is detailed below. There are three coupled wave equations that describe the propagation of the pump, signal and acoustic wave complex envelopes. The optical fields of the two counter propagating pump and signal optical waves respectively are:

\[ E_p(z,t) = A_p(z,t) \exp \left[ j \left( k_p z - \omega_p t \right) \right] + c.c , \]  \hspace{1cm} (1.4)

\[ E_s(z,t) = A_s(z,t) \exp \left[ j \left( -k_s z - \omega_s t \right) \right] + c.c . \]  \hspace{1cm} (1.5)

Here the optical frequencies of the two wave are \( \omega_{p,s} \) as before, their complex envelopes are \( A_{p,s} \), their respective wave-numbers are \( k_{p,s} = n \omega_{p,s} / c \) where \( n \) is the effective refractive index of the fiber mode, \( z \) denotes position along the fiber and \( t \) stands for time. Note the negative sign of the signal wave-number, representing propagation in the negative \( z \) direction. The overall electro-magnetic field in the fiber is the sum of the two waves:
\[ E(z,t) = E_p(z,t) + E_s(z,t). \] \hfill (1.6)

The acoustic wave can be described in terms of the variations in the density \( \rho \) of the fiber medium as a function of position and time:

\[ \rho(z,t) = \rho_0 + \Delta \rho(z,t) \exp\left[j(qz - \Omega t)\right] + c.c. \] \hfill (1.7)

Here \( \rho_0 \) is the mean density of the fiber medium and \( \Delta \rho \) is the complex magnitude of density variations. The frequency of the acoustic wave \( \Omega \) is the difference between the frequencies of the pump and the signal [15]:

\[ \Omega = \omega_p - \omega_s. \] \hfill (1.8)

Due to the conservation of momentum, the acoustic wave-number must obey [15]:

\[ q = k_p + k_s \approx 2k_p = 2n \frac{\omega_p}{c}. \] \hfill (1.9)

The acoustic wave obeys the equation [15]:

\[ \frac{\partial^2 \rho}{\partial t^2} - \Gamma \nabla^2 \frac{\partial \rho}{\partial t} - \nu^2 \nabla^2 \rho = -\nabla \cdot f. \] \hfill (1.10)

Here \( \Gamma \) is the acoustic damping parameter, \( \nu \) denotes the speed of sound in the fiber, and \( f \) is the electro-strictive force term which stimulates the acoustic vibrations. The force term is a gradient of the pressure difference \( f = \nabla p_{st} \), which is in turn given by:

\[ p_{st} = -\frac{1}{2} \varepsilon_0 \gamma_e \left\{ E^2 \right\} = -\frac{1}{2} \varepsilon_0 \gamma_e \langle (E_s + E_p)^2 \rangle. \] \hfill (1.11)
Here $\gamma_s$ denotes the electro-strictive constant of the fiber medium, and $\langle E^2 \rangle$ is the squared electric field, time-averaged over multiple periods of the optical oscillations. The right hand side of equation 2.7 amounts to:

$$\nabla \cdot f = \nabla \cdot \nabla p = \varepsilon_0 \gamma_s q^2 A_s^* A_p \exp \left[ j (qz - \Omega t) \right] + c.c. \quad (1.12)$$

Invoking the slowly varying amplitude approximation, the second derivatives of $\rho$ are negligible with respect to the first-derivative terms and may therefore be neglected.

Under these conditions, substitution of equation 1.12 into 1.10 yields:

$$-2 j \Omega \frac{\partial \Delta \rho}{\partial t} + \Delta \rho (\Omega_B^2 - \Omega^2 - j \Omega \Gamma_B) - 2 j q v^2 \frac{\partial \Delta \rho}{\partial z} = \varepsilon_0 \gamma_s q^2 A_s^* A_p. \quad (1.13)$$

In equation 2.10, $\Omega_B = |q| v = 2 n \omega_p \sqrt{v/c}$ is the BFS of the medium, and $\Gamma_B = q^2 \Gamma$ denotes the Brillouin linewidth [15].

1.4.1.1 Steady-state conditions

Two assumptions are taken in order to further simplify equation 1.13. The first is of a steady state solution, so that the temporal derivative of the acoustic wave magnitude may be dropped. The second assumption is that the acoustic wave is heavily damped and absorbed after short propagation distances, below 100 µm. This propagation distance is much shorter than the spatial scale along which the amplitudes of the optical fields can vary. Therefore the stimulation of the acoustic wave is regarded as a strictly local phenomenon, and the term $\frac{\partial \Delta \rho}{\partial z} = 0$ is neglected as well. Subject to these assumptions, equation 2.10 is brought to the following form:

$$\Delta \rho (\Omega_B^2 - \Omega^2 - j \Omega \Gamma_B) = \varepsilon_0 \gamma_s q^2 A_s^* A_p. \quad (1.14)$$

We therefore obtain:
\[ \Delta \rho = \varepsilon_0 \gamma' q^2 \frac{A_p^* A_s}{\Omega_B^2 - \Omega^2 - j\Omega \Gamma_B} . \] (1.15)

The maximum acoustic wave buildup occurs when the frequency difference between pump and signal matches the BFS of the fiber: \( \Omega = \Omega_B \). The larger the detuning from that value, the weaker the acoustic buildup will be.

The electro-magnetic susceptibility of the fiber medium changes with density fluctuations, according to the photo-elastic effect [25]:

\[ \Delta \chi = \frac{\gamma_c}{\rho_0} \Delta \rho . \] (1.16)

The nonlinear polarization in the medium [25] can be represented by the additive electrical susceptibility:

\[ P_{NL} = \varepsilon_0 \Delta \chi (E_p + E_s) \] (1.17)

The nonlinear polarization contains four pairs of conjugated harmonic terms. Among them there are two pairs that match the frequencies and wave-numbers of the pump and signal waves:

\[ P_p(t, z) = \frac{\varepsilon_0 \gamma_c}{\rho_0} \Delta \rho(z) A_p(z) \exp\{ j(k_p z - \omega_p t) \} + c.c \] (1.18)
\[ P_s(t, z) = \frac{\varepsilon_0 \gamma_c}{\rho_0} \Delta \rho^*(z) A_p(z) \exp\{ j(-k_s z - \omega_s t) \} + c.c \]

The nonlinear polarization terms affect the propagation of pump and signal through their respective nonlinear wave equations:
Again, the slowly varying approximation and steady state conditions are assumed. By substituting the nonlinear polarizations into the pair of nonlinear wave equations (equation 1.19), the following pair of coupled equations in the amplitudes of the two optical fields is obtained:

\[
\frac{\partial^2 E_p}{\partial z^2} - \frac{n^2}{c^2} \frac{\partial^2 E_p}{\partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2}{\partial t^2} P_p
\]

\[
\frac{\partial^2 E_s}{\partial z^2} - \frac{n^2}{c^2} \frac{\partial^2 E_s}{\partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2}{\partial t^2} P_s
\]

(1.19)

For convenience we have assumed here \( \omega \equiv \omega_p \approx \omega_s \). We can convert the two equations from complex magnitude to intensity terms, according to the definition:

\[
I_{p,s} = 2n\varepsilon_0 c |A_{p,s}|^2
\]

Since \( I_{p,s} \propto A_{p,s} A_{p,s}^* \) we may use:

\[
\frac{\partial I_{p,s}}{\partial z} \propto \frac{\partial A_{p,s}}{\partial z} A_{p,s} + A_{p,s} \frac{\partial A_{p,s}^*}{\partial z}
\]

leading to:

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

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

(1.21)

In 2.18 \( g(\Omega) \) is the frequency-dependent SBS gain factor, which is well approximated by a Lorentzian shape:

\[
g(\Omega) = g_0 \frac{\left(\frac{\Gamma_B}{2}\right)^2}{(\Omega_B - \Omega)^2 - \left(\frac{\Gamma_B}{2}\right)^2},
\]

(1.22)
with a line-center gain factor: 

\[ g_0 = \frac{\gamma_0^2 \omega^2}{nc^3 \Gamma_{g} \rho_0}. \]

In many cases of practical interest, the pump wave intensity is much stronger than that of the signal, and the transfer of intensity between the two waves is negligible with respect to the pump intensity. Such conditions are referred to as the "undepleted pump" regime. In this regime we may disregard the differential equation for the pump wave and take \( I_p \) to be a constant parameter. Hence only one equation remains:

\[ \frac{\partial I_s}{\partial z} = -g(\Omega) I_p I_s. \] (1.23)

The solution to this equation is an exponential amplification of the signal wave along the fiber:

\[ I_s = I_s(z = L) \exp\left[ g(\Omega)(L - z) I_p \right]. \] (1.24)

The analysis of situations in which pump depletion must be taken into consideration is more complex. Based on the coupled equations for the optical intensities we find that:

\[ \frac{\partial (I_p - I_s)}{\partial z} = 0 \Rightarrow I_p = I_s + C, \] (1.25)

where \( C \) is a constant. The solution for the local intensity of the signal may be formally expressed as:

\[ I_s(z) = \frac{I_s(0)[I_p(0) - I_s(0)]}{I_p(0) \exp[g(\Omega)z(I_p(0) - I_s(0))] - I_s(0)} \] (1.26)

Recall that \( z = 0 \) denotes the end of the fiber from which the pump is launched. In most cases the above expression cannot be used directly, since the signal intensity is known a-priori only at the opposite end, \( z = L \). The evolution of the signal wave should be solved
numerically instead [25]. With knowledge of the signal intensity in every position, the intensity of the pump wave is readily found:

\[ I_p(z) = I_s(z) + I_p(0) - I_s(0) \quad (1.27) \]

1.4.1.2 Transient acoustic field

Now let us return to the time-dependent solution to the acoustic wave equation, in situations in which \( \frac{\partial \Delta \rho}{\partial t} \neq 0 \). Re-evaluating equation 1.13, while still invoking the slowly varying approximation and neglecting the propagation of heavily damped acoustic waves, we obtain:

\[ -2j\Omega \frac{\partial \Delta \rho}{\partial t} + \Delta \rho(\Omega_B^2 - \Omega^2 - j\Omega \Gamma_B) = \varepsilon_0 \gamma_q q^2 A_p^* A_p \quad \text{(1.28)} \]

The driving force to the first-order differential equation: \( A_p^* A_p \), is in general coupled to the acoustic wave as well. However, in the measurement protocols that are of interest to this research the Brillouin interactions are effectively confined to narrow fiber segments. Therefore, the effect of SBS on the magnitudes of both pump and signal is small and will be neglected, for the time being, for the purpose of evaluating \( \Delta \rho(z,t) \). The evolution of the pump and signal waves, at this limit, can be described as simple propagation at the group velocity of light \( v_g = c/n_g \):

\[
A_p(z,t) = A_p \left( z = 0, t - \frac{z}{v_g} \right) \\
A_s(z,t) = A_s \left( z = L, t - \frac{L-z}{v_g} \right) \quad \text{(1.29)}
\]
For brevity we denote below the input complex envelopes of the two waves at their respective points of entry into the fiber as: \[ A_p \left( z = 0, t - \frac{z}{v_g} \right) = A_p \left( t - \frac{z}{v_g} \right), \]
\[ A_s \left( z = L, t - \frac{L - z}{v_g} \right) = A_s \left( t - \frac{L - z}{v_g} \right). \]
Integrating over time we obtain:

\[ \Delta \rho(z, t) = j g_1 \exp(-\Gamma_A t) \int_0^t \exp(\Gamma_A t') A_p(t' - \frac{z}{v_g}) A^*_s(t' - \frac{L - z}{v_g}) \, dt', \]

\[ = j g_1 \int_0^t \exp[-\Gamma_A (t - t')] A_p(t' - \frac{z}{v_g}) A^*_s(t' - \frac{L - z}{v_g}) \, dt', \tag{1.30} \]

where we have defined the complex linewidth: \( \Gamma_A = \frac{(\Omega_B^2 - \Omega^2 - j \Omega_B \Gamma_B)}{-2 j \Omega} \), and the constant electro-strictive parameter \( g_1 = \frac{\gamma q^2}{8 \pi \Omega} \) [26]. The above expression is often sufficient to determine specific locations in which the acoustic wave is allowed to build up (see later in this chapter).

When the variations in optical waves magnitudes may not be neglected, the evolution of the acoustic field outside of steady state must be determined through the simultaneous numerical integration of all three differential equations involved. We refer once again to the nonlinear wave equation (equation 1.19), however this time we also account for the propagation of the two optical field envelopes according to the group velocity of light in the fiber:

\[ \frac{\partial A_p}{\partial z} + \frac{1}{v_g} \frac{\partial A_p}{\partial t} = \frac{j \omega \gamma_e}{2 n c \rho_0} \Delta \rho A_s, \]
\[ -\frac{\partial A_s}{\partial z} + \frac{1}{v_g} \frac{\partial A_s}{\partial t} = \frac{j \omega \gamma_e}{2 n c \rho_0} \Delta \rho^* A_p, \tag{1.31} \]

We define \( s \) as a single track in the propagation of the waves, so that:
\[ \frac{\partial A_{p,s}}{\partial s} = \frac{\partial A_{p,t}}{\partial t} + \frac{\partial A_{p,z}}{\partial z} \]  

(1.32)

Relating time and position, we obtain:

\[ \frac{\partial t_{p,s}}{\partial s} = \frac{1}{c/n} \Rightarrow t_{p,s} = \frac{s}{c/n} + t_{p_0,s_0} \Rightarrow s = (t_{p,s} - t_{p_0,s_0}) \frac{c}{n} \]  

(1.33)

\[ \frac{\partial z_p}{\partial s} = \frac{s}{c/n} \Rightarrow z_p = s + z_{p_0} \Rightarrow s = z_p - z_{p_0} \]

(1.34)

\[ \frac{\partial z_s}{\partial s} = -1 \Rightarrow z_s = -s + z_{s_0} \Rightarrow s = z_{s_0} - z_s \]

The coupled wave equations for the optical field magnitudes may expressed in terms of \( s \):

\[ \frac{\partial A_p}{\partial s} = \frac{j \omega c}{2nc \rho_0} \Delta \rho A_j \]

(1.35)

\[ \frac{\partial A_s}{\partial s} = \frac{j \omega c}{2nc \rho_0} \Delta \rho^* A_p \]

The solution to these equations is of the form:

\[ A_p = \int \frac{j \omega c}{2nc \rho_0} \Delta \rho A_j ds \]

(1.36)

\[ A_j = \int \frac{j \omega c}{2nc \rho_0} \Delta \rho^* A_p ds \]

We may now rewrite the solution in terms of \( z, t \) instead of \( s \), according to equations 1.33-1.34, and obtain the expressions for the amplitudes of the pump and signal waves at any given moment and place:

\[ A_p(z,t) = \int \frac{j \omega c}{2nc \rho_0} \Delta \rho \left[ t, (t_p - t_{p_0}) \frac{c}{n} + z_{p_0} \right] A_j \left[ (t_p - t_{p_0}) \frac{c}{n} + z_{p_0} \right] \frac{c}{n} dt \]

(1.37)

\[ A_s(z,t) = \int \frac{j \omega c}{2nc \rho_0} \Delta \rho^* \left[ t, -(t_s - t_{s_0}) \frac{c}{n} + z_{s_0} \right] A_p \left[ (t_s - t_{s_0}) \frac{c}{n} + z_{s_0} \right] \frac{c}{n} dt \]
Equations (1.30) and (1.37) may be jointly integrated numerically.

1.5 Sensing based on stimulated Brillouin scattering

As was noted in the previous section, effective SBS requires that the difference between the frequencies of the pump and the signal $\Omega$ must closely match the BFS $\Omega_B$. The sensing operation is based on the dependence of $\Omega_B$ on both temperature and mechanical strain:

$$\Omega_B(\varepsilon) = \Omega_B(0)[1 + C_\varepsilon \varepsilon]$$

(1.38)

$$\Omega_B(T) = \Omega_B(T_r)[1 + C_T (T - T_r)]$$

(1.39)

Here $\Omega_B(0)$ denotes the BFS of the fiber where no strain is applied and at a given reference temperature $T_r$ in °K. $T$ denotes the actual temperature of the fiber at the measurement point, and $\varepsilon$ is the strain at the measurement point. The coefficients $C_T$ and $C_\varepsilon$ in standard fibers equal approximately $9.4 \times 10^{-5} \text{ K}^{-1}$ and $4.6 \varepsilon^{-1}$, respectively. Estimating the local value of $\Omega_B$ in all locations along a fiber under test may provide a spatially distributed measurement of both quantities [27,28,29].

The counter propagating pump and signal waves are launched into the fiber from opposite ends and the intensity of the output signal wave is measured. By changing the frequency detuning between the two waves, the frequency difference of maximum amplification may be identified. Deviations from the nominal BFS due to applied strain or temperature variations would result in a change in the gain spectrum [30]. Two main protocols are being employed to provide a spatially-distributed mapping of Brillouin gain spectra. They are introduced next.
1.6 Implementation schemes of distributed Brillouin sensors

1.6.1 Brillouin optical time domain analysis (B-OTDA)

In Brillouin optical time-domain analysis (BOTDA), a pulsed pump is inserted to one end of the fiber and a continuous signal wave is launched from the opposite side. The intensity of the pump pulse is typically high, and that of the signal much weaker [31]. By measuring the output signal power, as a function of both time of arrival and frequency difference between the two optical waves, the Brillouin frequency of the fiber at each location can be identified. Spatial mapping is based on time of arrival of the signal wave-front and the speed of light in the fiber:

\[ z = \frac{ct}{2n_g} . \]  

(1.40)

In the above equation, \( z \) is the location along the fiber, and \( t \) is the time of flight from the entry point of the pump pulse to point \( z \). The factor \( 1/2 \) represents two-way propagation.

The spatial resolution \( \Delta z \) of the measurements is limited to:

\[ \Delta z = \frac{c\Delta t}{2n_g} , \]  

(1.41)

where \( \Delta t \) denotes the pump pulse duration. In order to improve the spatial resolution the pump pulse duration may be shortened. However, pulse duration cannot be reduced below the acoustic lifetime \( \tau = 1/\Gamma_B \sim 5 \text{ ns} \), or else the buildup of the interaction is compromised. The lifetime sets a limit to the spatial resolution of the fundamental B-OTDA scheme, on the order of 1 meter [32]. Note that it is possible to pulse the signal wave and measure the Brillouin loss of a counter-propagating CW pump wave [33,28].
Figure 4. An illustration of the interaction between a pulsed pump and a counter-propagating, continuous signal. Image courtesy of Yosef London. Here, $\omega_s$ and $\omega_p$ denote the optical frequencies of the probe and the pump waves respectively, $d_B$ is the spatial period of the induced index perturbation, and $\tau_B$ represents the acoustic lifetime.

Pump power in B-OTDA is restricted by the onset of spontaneous Brillouin scattering, and by competing nonlinear effects such as modulation instability [34]. The signal power is restricted as well, by the onset of pump depletion [35]. In many scenarios, the Brillouin shift is constant along much of the fiber length. In this case the pump pulse might be depleted by the time it reaches the far end of the fiber, leading to weaker gain for that particular frequency, whereas pump pulses at other values of $\Omega$ would remain undepleted and provide higher gain. The net effect of depletion would be a distortion of local gain spectra at the far end of the fiber due to interactions at preceding locations, a phenomenon
known as non-local effects [35]. In order to avoid depletion, the signal power must be kept sufficiently low.

SBS interactions are also susceptible to polarization-induced fading. Electrostriction is driven by the interference between pump and signal, and is therefore inherently polarization dependent. The interaction may vanish entirely if the states of polarization of the two waves are orthogonal [36]. A recent solution path relies on polarization switching and polarization diversity [37]: measurements are taken twice, for two orthogonal signal polarizations, and the two traces are averaged. In this scheme, the signal wave is guaranteed to provide a significant projection on the state of polarization of the pump, in at least one of the two traces. The proper operation of the polarization switch may require that the polarization of the incident signal should match a known state. Therefore, B-OTDA setups which rely on polarization switching often require polarization maintaining (PM) components, at least in part [38]. Another possibility is the scrambling of polarization, in conjunction with proper averaging [36].

Another limitation stems from the extinction ratio (ER) of pump pulses. Non-zero pedestal of pump pulses introduces undesired residual SBS interactions along the entire length $L$ of the fiber, which may mask out the gain provided by the pulse itself. As a rule of thumb, the ER of pump modulation must exceed $L/\Delta z$, where $\Delta z$ is spatial resolution [39]. The SBS gain spectrum introduced by pump pulses is broader than that of CW pump. The spectrum is given by a convolution between the power spectral density of the pump wave, and the inherent, 30 MHz-wide Lorentzian SBS line [40]. The gain bandwidth $\Delta \nu_B$ begins to increase when the pulse duration becomes shorter than 30 ns. Use of short pulses leads to a degradation in the measurement of $\Omega_B$, due to the broad gain bandwidth. This mechanism restricts the spatial resolution of measurements to the order of 1 m, as noted above.
Finally, the experimental uncertainty in the fitting of $\Omega_B$ was recently quantified as a function of the measurement SNR [41]:

$$\sigma_{\Omega_B} = \frac{1}{\text{SNR}(z)} \sqrt{\frac{3}{4} \delta \cdot \Delta \nu_B},$$  \hspace{1cm} (1.42)

where $\delta$ is the frequency scanning step.

![Figure 5. A normalized local Brillouin gain spectrum, as measured by a B-OTDA. The frequency of maximum gain has to be determined, for the measurement of temperature and strain. Noise on the signal ($\sigma$) induces uncertainty in the estimation, depending on the Brillouin gain bandwidth $\Delta \nu_B$ and the frequency step $\delta$ used in measurement of the gain spectrum [41].](image)

Commercial systems based on B-OTDA provide a measurement range of 50 km with 1 meter resolution [42], a sensitivity of 1 °C or 20 $\mu\varepsilon$, and acquisition duration of minutes. An advanced B-OTDA research setup has reached 325 km range [43]. This setup required distributed Raman amplification and cascaded erbium-doped fiber amplifiers (EDFAs) in order to compensate for propagation losses, as shown in Figure 6. The setup provides a 2 meter resolution [43], a sensitivity of 2 °C or 40 $\mu\varepsilon$, and acquisition duration of 100 minutes.
Figure 6. Experimental setup of long range B-OTDA [43]

Figure 7 shows the evolution of the BFS (top) and the Brillouin gain (bottom) over the 5 x 65 km long sensing fiber.

Numerous techniques has been proposed to try and circumvent the 1 m resolution limitation that is imposed by the acoustic lifetime [26,44]. These include pre-excitation
methods [45, 46, 47, 48]: the acoustic wave is first stimulated by a long, weak pump pedestal, and subsequently addressed by a short and intense pulse. In this manner, the transition time of the amplification event is limited by that of the pump pulse, and not by the generation of the acoustic wave. A spatial resolution of 5 cm has been achieved over 5 km range ([48], see Fig. 8). Non-local effects must be carefully considered in such setups. Another principle, which is arguably the most successful to-date, is based on differential pulse pair acquisition. This principle is directly relevant to this research, and it is introduced next.

![Figure 8](image-url)

Figure 8. (a) Measured SBS gain map as a function of position and of frequency detuning between pump and signal. The 5 cm segment is too short to be distinguished; (b) Magnified view of the gain map around the 5 cm fiber section, showing that this segment at end of the 5 km fiber is fully resolved both in space and frequency [48].

1.6.2 Differential double pulse pair measurements

In double pulse pair (DPP) B-OTDA setups the basic experiment is repeated twice, and the two experiments differ slightly in the duration of pump pulses. The two raw traces
of the output signal power as a function of time are subtracted. Subtraction removes the common terms, and retains only the signal amplification across a short segment that corresponds to the difference $\Delta T$ in pulse durations [49]. Repeating the process over a range of $\Omega$ values leads to the reconstruction local Brillouin gain spectra with high spatial resolution, which is not restricted by the absolute durations of pump pulses or the acoustic lifetime. The differential signal is typically weak, and provides low SNR. Nevertheless, B-OTDA experiments have reached a spatial resolution of 2 cm over 2 km of fiber ([50], see Figs. 9-11). A DPP B-OTDA experiment with distributed Raman amplification achieved 0.5 m spatial resolution over 100 km of fiber [51].

Figure 9. Illustration of time traces of the Brillouin signal in the beginning of a fiber under test, taken with 8 ns and 8.2 ns pulse widths, and their differential signal [50]
Figure 10. Measured time traces of the Brillouin signal at the output of a 2 km long fiber, taken with a pulse pair of 8 ns and 8.2 duration, and the difference between the two traces [50].

Figure 11. Measured Brillouin gain spectra (top) and Brillouin frequency shift (bottom) as a function of position, towards the end of a 2 km long fiber. Measurements were taken using a double pulse pair B-OTDA setup. A 2 cm-long fiber segment was locally heated to 76 °C. The segment is identified in the measurements [50].
DPP B-OTDA experiments can, at least in principle, address the entire fiber under test in just two scans per choice of $\Omega$. On the other hand, the measurements require broadband detection, at 10 GHz bandwidth for 1 cm resolution, which elevates noise levels. In addition, pump pulses are subject to depletion over the entire length of the fiber. An alternative SBS sensing paradigm relies on manipulating the cross-correlation function between the complex envelopes of the pump and signal waves. Such protocols are addressed in the following section.

1.6.3 Brillouin optical correlation domain analysis

Brillouin optical correlation domain analysis (B-OCDA) was first proposed in the late 1990’s, in attempt to confine the SBS interaction and improve spatial resolution of SBS sensing to segments that are much shorter than 1 m. The original scheme, devised by the group of Prof. Hotate of the University Of Tokyo, relied on the synchronized frequency modulation of the pump and signal by a common sine-wave pattern. Due to the modulation, the frequency difference between the counter propagating pump and signal waves remained stationary at particular fiber locations only, known as correlation peaks, whereas the frequency difference elsewhere was oscillating [52,53]. Consequently, effective SBS amplification was restricted to the correlation peaks, and signal power measurement could convey localized information.

The width of the correlation peaks defined the spatial resolution of the measurements [53,54]. In off-peak locations the stimulation of the acoustic field is largely inhibited, and the average of the acoustic field magnitude is zero. Nevertheless, the instantaneous magnitude of the acoustic wave in off-peak positions is fluctuating with non-zero variance. These residual, unintended Brillouin interactions contribute measurement noise. B-OCDA experiments based on frequency modulation achieved 24,000 high-resolution points [55]. The highest spatial resolution reported was 1.6 mm [56].
Figure 12. Illustration of spatial confinement of SBS in Brillouin optical correlation domain analysis [54].

Figure 13. (a) Fiber under test (FUT)-3 prepared by fixing standard single-mode fiber (SMF) 1 on the translation stage using epoxy. (b) Results of distributed measurement on FUT-3 with elongations of 30, 60, 90, and 120 µm. Inset, magnified view around the peak position of the 60 µm case. The 3 mm fiber section is indicated by dashed lines [56].

The spacing between correlation peaks is given by [53]:

\[ d = \frac{c}{2n_g f_m}, \]  

(1.43)

where \( f_m \) is the rate of frequency modulation. The spatial resolution equals [53]:

\[ \Delta z = \frac{c \Delta v_B}{2\pi n_g f_m \Delta f} \quad \text{for} \quad \Delta v_B > f_m, \]  

(1.44)
with $\Delta f$ denoting the span of frequency modulation. The periodic nature of frequency modulation potentially leads to the generation of multiple correlation peaks along the fiber under test. The maximum range of unambiguous measurements is restricted by the separation between adjacent peaks. The initial B-OCDA scheme therefore exhibited an inherent tradeoff between spatial resolution and the range of unambiguous measurements: the number of resolution points that can be address without ambiguity was restricted to few hundreds only, $d/\Delta z = \pi \Delta f / v_g$. This ratio may be increased with larger frequency modulation span $\Delta f$, however that span is restricted to the order of tens of GHz by technical issues. This limitation on the number of resolution points was relaxed in subsequent, more elaborate schemes of frequency modulation B-OCDA [57], and was removed entirely in a protocol that was proposed in our group by Yair Antman and coworkers [58,59]. This approach is explained in detail in the next section.

1.6.4 Phase-coded Brillouin optical correlation domain analysis

In phase-coded B-OCDA both pump and signal waves are jointly phase-modulated by a common, high-rate pseudo random bit sequence (PRBS) [60]. As previously obtained (section 1.4.1.2, equation 1.29), the acoustic wave magnitude as a function of time and position along the fiber is given by:

$$\Delta \rho(z,t) = j g_1 \exp(-\Gamma_A t) \int_0^t \exp(\Gamma_A t') A_p(t' - \frac{z}{v_g}) A_s^*(t' - \frac{L-z}{v_g}) dt'$$

$$= j g_1 \int_0^t \exp[-\Gamma_A (t-t')] A_p(t' - \frac{z}{v_g}) A_s^*(t' - \frac{L-z}{v_g}) dt'$$

(1.45)

The instantaneous driving force for the acoustic wave generation is proportional to the inner product between the pump and probe complex envelopes. Given the above modulation scheme, that electro-strictive driving force is held constant at specific fiber locations where the two replicas of the modulation sequence are in correlation. The driving force is rapidly oscillating everywhere else, at a rate that can be made much faster than the
acoustic lifetime. Much like in the original B-OCDA scheme, the effective buildup of the SBS interaction will be restricted to the correlation peaks only.

\[
g_z v T \Delta = \frac{1}{2}
\]

\[ (1.46) \]

Figure 14. Illustration of counter-propagating, binary phase-coded pump and signal waves and their inner product. The two waves are correlated at the center only.

However, unlike sine-wave frequency modulation, the separation between neighboring peaks scales with the period of the modulating sequence, which can be made arbitrarily long. Therefore the restriction on the number of unambiguously addressed points is removed. The width of the SBS interaction region equals half the correlation length of the coded waveforms, or half the spatial extent of a single bit [61,62]:

\[
\Delta z = \frac{1}{2} v_s T
\]

(1.46)
Here, $T$ is the duration of a single bit and $v_g$ is the group velocity of light in the fiber. A spatial resolution better than 1 cm has been reported using this method [59]. Our group routinely performs measurements with 2 cm resolution.

Two types of codes were considered in the modulation of pump and signal waves: PRBSs and so-called *perfect Golomb codes*. The drawback of using PRBSs is the comparatively large off-peak values of their auto-correlation functions [63]. Consequently, the undesired, residual off-peak Brillouin interactions are relatively strong. Alternatively, perfect Golomb codes, invented by Prof. Solomon Golomb of the University of Southern California, are characterized by zero sidelobes of the cyclic auto-correlation function [63]. Use of these codes, instead of PRBSs, could be expected to reduce stimulation of the...
acoustic field in off-peak locations. As seen in equation 1.46, the acoustic wave buildup is given by integration over the electro-strictive driving force within an exponential window. That exponential window takes away from the perfect correlation properties of Golomb code [58,63]. Nevertheless, they still lead to weaker off-peak SBS interactions than those obtained with PRBS modulation.

Figure 16 below shows numerical calculations of the acoustic wave magnitude as a function of time and position along the fiber. Both a PRBS (top left) and a Golomb code (top right) were used. Both sequences effectively confine the stimulation of the acoustic wave to a discrete and narrow correlation peak at the fiber center (2 cm width in this case), where it is stationary. However, the two maps differ in the extent of the off-peak acoustic wave stimulation. Off-peak, residual stimulation is much reduced when a Golomb code is used in the phase modulation of the optical waves.

A major drawback of B-OCDA methods is the need of spatial scanning of correlation peak positions, one resolution point at a time. Such scanning of thousands of points, using standard laboratory equipment, is often impractical. In order to reduce the scanning time, the phase code period may be shortened. Thus multiple correlation peaks would be obtained, separated by \( Z = \frac{1}{2} N \cdot v_g T \) where \( N \) is the code period. At first glance, it appears as though the generation of multiple correlation peaks along the fiber would be a disadvantage: measurements will become ambiguous, just like in the original B-OCDA concept. The solution to that problem was found in the combination between time and correlation domain analyses principles, as discussed in the next section.
Figure 16. Top: simulated acoustic field magnitude $|\Delta \rho(z, t)|$ stimulated by PRBS coded pump and signal waves (left), and by pump and signal that are phase-modulated by a perfect Golomb code (right). The coding symbol duration was 100 ps in both simulations. Bottom: simulated $|\Delta \rho(z)|^2$ after $t = 50$ ns for PRBS (red) and Golomb (blue) phase coding [63].

1.6.5 Hybrid B-OTDA / B-OCDA method

In a hybrid approach which brings together time-domain and correlation-domain principles, in addition to the underlying phase code, the pump wave is also amplitude modulated by a single pulse with duration of tens of ns. The pulse modulation guarantees that correlation peaks are formed sequentially, one at a time, so that individual amplification events may be separated in the time domain, much like in B-OTDA (see Figs. 17-20).

The hybrid protocol provides two main advantages. First, the number of position scans per choice of $\Omega$ that is necessary to cover the entire length of the fiber under test equals the period of the phase code $N$, regardless of fiber length. The number of scans may
be therefore reduced by a factor of several hundreds. Second, off-peak acoustic waves, at any given moment, are restricted to the spatial extent of the pump pulse (which is on the order of few meters), rather than span the entire fiber which may be many km long. This property of the hybrid protocol strongly reduces measurement noise due to off-peak interactions. This method was first proposed and implemented by David Elooz et al. [64,65], within our group. Using this protocol, they were able to address 80,000 points with spatial resolution of 2 cm over 1.6 km of fiber, using only 127 position scans [66].

Figure 17. Illustration of phase-coded BOCDA with an overlaying pump pulse. The acoustic field is stimulated at a single correlation peak only at any given instance.
Figure 18. 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, with symbol duration of 200 ps. The pump wave is further modulated by a single amplitude pulse of 26 ns duration. 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 [66].

Figure 19. Simulated output signal power as a function of time. The trace consists of a series of amplification peaks, each of which can be unambiguously related to the SBS interaction at a specific correlation peak [66].
Figure 20. Measurements of the output signal power as a function of time, following propagation in a 400 m-long fiber under test that consisted of two sections, each of about 200 m in 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 5 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) [66].

Compared with DPP B-OTDA, the hybrid measurement protocol can rely on low-bandwidth detection that is less noisy. In addition, depletion of pump pulses is restricted to the correlation peaks which make up a small fraction of the fiber length, and phase modulation effectively suppresses spontaneous Brillouin scattering of the pump wave. More advanced versions of the protocol successfully addressed 440,000 resolution points [67], and demonstrated the potential of addressing over two million points [68]. On the other hand, the hybrid time/correlation domain setups still require \( N \sim 100 \) position scans, as opposed to only two in DPP B-OTDA. This number of scans remains a main drawback of all B-OCDA variants to-date.

1.7 Research objectives

As noted above, the separation between neighboring correlation peaks in the hybrid B-OTDA / B-OCDA schemes must exceed the spatial extent of the pump pulse, or else measurements of the output signal power become ambiguous. The pulse duration, in turn, must be longer than twice the acoustic lifetime \( 2\tau \sim 10 \text{ ns} \). Given typical symbol duration of
200 ps (representing 2 cm resolution), the number of scans cannot be reduced below the order of 50-100.

As a possible extension of the previous measurement protocols, I propose herein to bring together the principles of phase-coded B-OCDA and of DPP B-OTDA. In this method we overlay the double-pulse architecture on top of phase-coding of pump and signal. The duration of pump pulses in each individual experiment would exceed the phase coding period, hence the amplification events taking place at neighboring correlation peaks would overlap in time. However, like in DPP B-OTDA, each trace will be acquired twice with different pump pulse duration. The difference between the two pulse durations would be shorter than the phase coding period. Therefore, subtraction of the two output traces would unambiguously recover the amplification taking place at each individual peak.

The benefit of the proposed principle is in reducing the number of scans: the phase code period may be shortened to a fraction of $\tau$, representing $N \sim 10$ position scans. The proposed method would carry a penalty in SNR: the required detection bandwidth would be broader than that of current B-OCDA protocols, although still not as broad as that of DPP B-OTDA. The main tasks of my research have been the quantitative analysis and the experimental demonstration of this DPP B-OCDA approach, and the assessment of its performance limitations.
2. Principle of operation, analysis and simulations

2.1 Rationale and principle of operation

In the proposed method of this research program the hybrid B-OTDA / B-OCDA protocol will be executed twice, with pump pulse durations of $T_{\text{pulse}}$ on the order of 30 ns, and $T_{\text{pulse}} + \Delta T_{\text{pulse}}$ with a duration increment on the order of 1 ns. In each experiment, the phases of the pump and probe waves will be modulated with the same Golomb code with symbol duration $T_{\text{phase}}$, which is on the order of hundreds of ps. The complex envelopes of the pump and signal waves can be express as:

$$A_s(z = L,t) = A_s \sum_n c_n \text{rect} \left( \frac{t - nT_{\text{phase}}}{T_{\text{phase}}} \right)$$  \hspace{1cm} (2.1)$$
$$A_p(z = 0,t) = A_p \text{rect} \left( \frac{t}{T_{\text{pulse}}} \right) \sum_n c_n \text{rect} \left( \frac{t - nT_{\text{phase}}}{T_{\text{phase}}} \right)$$  \hspace{1cm} (2.2)$$

where $A_s$, $A_p$ denote the constant magnitudes of the signal wave and of pump pulses, respectively, $\text{rect}(t)$ equals 1 for $|t| < 0.5$ and zero elsewhere, and $\{c_n\}$ are the elements of the prefect Golomb code, which is repeating with a period of $N_{\text{phase}} = 11$ bits. The magnitudes of all elements in the code are unity. The phases of elements $\{1,2,3,5,6,8\}$ equal zero, whereas the phases of elements $\{4,7,9,10,11\}$ are given by

$$\phi = \cos^{-1} \left[ - \frac{N_{\text{phase}} - 1}{(N_{\text{phase}} + 1)} \right] \sim 2.556 \text{ rad.}$$

The temporal period of the phase code $N_{\text{phase}} T_{\text{phase}}$ is deliberately chosen to be much shorter than the pump pulse duration $T_{\text{pulse}}$, unlike previous implementations of hybrid B-OCDA / B-OTDA [65]. Consequently, each individual measurement will be ambiguous, in the sense that the output probe wave power at any given instance will be affected by SBS interactions taking place at multiple correlation peaks of the underlying
phase code. However, subtraction of the two traces would recover ‘transitions instances’, in which the longer pump pulse excites an extra correlation peak which is not covered by the shorter one. The difference trace may therefore remove the ambiguity in data analysis. While two scans would be necessary for each position of peaks, the reduction in code period length could be ten-fold, and the overall experimental duration might be reduced. An illustration of the method can be seen in the figure below.

![Figure 21. Illustration of the extent of pump pulses in the two experiments of the proposed measurement protocol (left), the back-scattered pump wave as a function of time in the two cases (upper right), and the difference trace as a function of time (lower right).](image)

Unlike the DPP B-OTDA method, the spatial resolution of this protocol is not determined by the time difference between two pulses, but rather by the symbol duration of the underlying phase code: \( \Delta z = \frac{1}{2} \sqrt{g \cdot T_{\text{phase}}} \). The subtraction of the two traces is meant to resolve between events separated in time by \( N_{\text{phase}} T_{\text{phase}} \).

### 2.2 Simulations results

The proposed measurement principle is supported by direct numerical integration of the differential equations of SBS, subject to the appropriate boundary conditions described above. First, the previous protocol of hybrid B-OTDA / B-OCDA was simulated as a reference. The calculated map of the acoustic field as a function of position and time, and the
calculated temporal trace of the output signal power, are shown in Fig. 22 and Fig. 23, respectively. The symbol duration $T_{\text{phase}}$ was 267 ps, corresponding to resolution $\Delta z$ of 2.7 cm. The period of the perfect Golomb code was $N_{\text{phase}} = 83$ bits. The duration of the pump pulse $T_{\text{pulse}}$ was 22 ns. Three correlation peaks are obtained along the 8.1 m-long fiber under test.

![Simulation of the acoustic wave magnitude as a function of time and position along a fiber under test, when the pump and signal optical waves are jointly phase-modulated by a periodic perfect Golomb code. The pump wave is further modulated by a single pulse, whose 22 ns duration is shorter than the period of the phase code. The acoustic field is stimulated in three discrete correlation peaks, in a sequential manner: each interaction decays before the next one begins.](image1)

![Simulation of the output signal power as a function of time, corresponding to the acoustic field map of the previous figure. Three distinct amplification events are obtained.](image2)

Figure 22. Simulation of the acoustic wave magnitude as a function of time and position along a fiber under test, when the pump and signal optical waves are jointly phase-modulated by a periodic perfect Golomb code. The pump wave is further modulated by a single pulse, whose 22 ns duration is shorter than the period of the phase code. The acoustic field is stimulated in three discrete correlation peaks, in a sequential manner: each interaction decays before the next one begins.

Figure 23. Simulation of the output signal power as a function of time, corresponding to the acoustic field map of the previous figure. Three distinct amplification events are obtained.
The calculated magnitude of the output signal wave was averaged over $N_{\text{phase}} = 83$ realizations of the B-OCDA boundary conditions. The same sequence was used in the phase modulation of pump and signal in all calculations, however the sequence was offset by an arbitrary number of bits $0 \leq n_0 \leq N_{\text{phase}}$ in each repetition [69]. The random offset helps to average out noise due to residual Brillouin interactions at off-peak fiber locations. An arbitrary starting point $n_0$ of the phase modulation at $t = 0$ is inherent to the experimental setup, since the waveform generators used in phase and amplitude modulation of pump and/or signal are free-running without synchronization.

Next the simulation was extended to the double-pulse B-OCDA protocol. The boundary conditions for the modulation of pump and signal were similar to those of the previous analysis, with the following differences: the period of the Golomb code was 11 bits (or 2.9 ns), and duration of the pump pulses were $T_{\text{pulse}} = 29$ ns and $T_{\text{pulse}} + \Delta T_{\text{pulse}} = 30$ ns. The duration of the phase code symbols $T_{\text{phase}}$ remained 267 ps. With these parameters, the acoustic wave is stimulated at many correlation peaks along the fiber under test on any given instance. Figure 24 shows the calculated acoustic wave magnitude as a function of time and position along the fiber under test for the longer pump pulse.

The left panel of figure 25 shows the output signal wave as a function of time in both calculations, and the right panel shows the result of the subtraction of the two traces. Since $T_{\text{pulse}} > T_{\text{phase}} N_{\text{phase}}$, multiple gain events are in temporal overlap. Following an initial transient, the output signal power at any given instance is affected by SBS interactions taking place at multiple peaks. Hence, individual amplification events cannot be directly resolved without ambiguity. However, due to the difference in duration between the pump pulses used in the two traces, there are specific instances in which the longer of the two pulses excites a given correlation peak while the shorter one does not. The SBS amplification
at that particular peak appears as an isolated event in the difference trace of the output signal, at that particular time.

Figure 24. Simulation of the acoustic wave magnitude as a function of time and position along a fiber under test, when the pump and signal optical waves are jointly phase-modulated by a perfect Golomb code with a shorter period of only 2.9 ns (11 bits). The pump wave is further modulated by a single pulse, whose 30 ns duration is longer than the period of the phase code. The stimulation of the acoustic wave at numerous peak positions overlaps in time.

Figure 25. The left panel shows simulations of the Brillouin gain of the output signal wave as a function of time, in the two traces of the proposed double-pulse 8-OCDA scheme. The right panel shows the difference between the two traces as a function of time. Brillouin interactions at individual correlation peaks are resolved.
Figure 26 shows that the width of each peak in the difference trace is 1 ns, corresponding to $\Delta T_{\text{pulse}}$, and that the distance between two adjacent peaks it about 2.9 ns, as expected.

![Figure 26](image)

*Figure 26. A magnified view of the traces shown in Fig. 25, in the vicinity of two SBS gain event.*

Figure 27 shows the calculated acoustic wave magnitude as a function of time and position along a 8.1 m long fiber which includes a hot-spot. The BFS was taken to be uniform along most of the simulated fiber, and the frequency offset between pump and signal $\nu = \Omega / (2\pi)$ was chosen to match that value. The local BFS was offset by 25 MHz within a 5.6 cm-wide region, located at $z_{\text{hot}} = 4.1$ m. The acoustic wave magnitude at $z_{\text{hot}}$ is much weaker than those at other locations, as expected. Similar to Fig. 25, the power of the output signal wave as a function of time in both calculations, and the result of the subtraction of the two traces, are shown in Fig. 28. A single gain event, which corresponds to a correlation peak that is in overlap with the hot-spot, appears weaker than all others as expected.
Figure 27. Calculated normalized magnitude of the stimulated acoustic field as a function of position and time along a 8.1 m long fiber under test. Only part of the fiber is shown, for better clarity. The BFS of the fiber was taken to be uniform, and the frequency offset between pump and signal was chosen to match that value. The BFS was modified by 25 MHz within a 5.6 cm-wide segment located 4.1 m from the input end of the pump wave. The signal and pump waves are jointly phase-modulated by a repeating perfect Golomb code with a period of 11 bits and symbol duration of 267 ps. The pump wave is also amplitude-modulated by a single pulse of 30 ns duration. The acoustic field is confined to multiple, discrete and closely-spaced correlation peaks. Due to the short period of the phase code, SBS interactions at neighboring peaks take place with substantial temporal overlap. The acoustic field at the peak which is in spatial overlap with the modified region is considerably weaker than all others.

Figure 28. Left - calculated power of the signal wave at the output of the FUT. Red and blue traces correspond to pump pulse durations of 30 ns and 29 ns, respectively (see legend). Right - the difference between the two traces as a function of time. Brillouin interactions at individual correlation peaks are resolved. The gain event which corresponds to a correlation peak that is in overlap with the fiber region of modified BFS appears much weaker than all others.

In the following simulation, the value of the BFS at the location of one of the correlation peaks was modified by several detuning values. The frequency difference \( \nu \)
between pump and signal was kept equal to the 'nominal' value of the BFS in the rest of the simulated fiber. The calculated difference traces are shown in Fig. 29 below. The magnitude of the signal gain in the difference trace at that particular peak is seen to decrease with detuning, as expected.

![Graph showing simulated difference traces of double-pulse B-OCDA. The value of the Brillouin shift at the location of the tenth peak from the left was detuned from its nominal value. Detuning values were: 0 MHz, 10 MHz, and 20 MHz in the blue, red and black traces, respectively. The magnitude of the specific gain peak in the difference trace decreases with detuning, as expected.](image)

The main advantage of the proposed DPP B-OCDA protocol, with respect to the previous realizations of B-OCDA mentioned above, is the number of position scans required to address the entire FUT. Figure 30 compares between the maps of the acoustic field magnitudes obtained with a 11 bits-long Golomb code and a 83 bits-long PRBS. The symbol duration of the phase codes is the same in both calculations. The shorter code leads to the stimulation of SBS in a larger number of peaks.
2.3 Signal to noise ratio

2.3.1 Noise mechanisms

So far, the calculations of the signal wave at the output of the fiber under test were carried out under the assumption that the signal was noise-free. The only noise mechanism that was inherent to the analysis was residual off-peak Brillouin interactions due to the imperfect periodic correlation of Golomb codes subject to an exponential weighing window [58]. However, our experiments below made use of very short codes, with a period of only 11 bits, so that $N_{phase}T_{phase} < \tau$. At that limit, off-peak interactions are strongly suppressed.

In practice, the detection process includes inevitable shot noise, the measurement photo-current is accompanied by additive thermal noise, and the detected waveform itself may include amplified spontaneous emission (ASE) from fiber amplifiers along the path of the signal wave. These noise mechanisms are briefly addressed in this section, and an estimate of their effect on the measurement precision is given as well.
2.3.1.1 Noise due to amplified spontaneous emission of fiber amplifiers

Brillouin sensing setups draw both pump and signal waves from a common laser diode source. Splitting losses and insertion losses of multiple fiber-optic components, (see in next chapter), typically require that both waves are amplified along their respective paths, using either semiconductor optical amplifiers (SOAs) or erbium-doped fiber amplifiers (EDFAs). Optical amplification is inevitably accompanied by broadband ASE, which spans the entire gain bandwidth of the amplifiers (on the order of few THz). Narrowband optical band-pass filters are used to restrict the noise bandwidth as much as possible, to a residual bandwidth $B_{\text{opt}}$. The optical power of the filtered ASE is given by:

$$P_{\text{ASE}} = F_n \cdot h\nu \cdot (G - 1) \cdot B_{\text{opt}}. \quad (2.3)$$

Here $G \sim 300$ represents the power gain of the optical amplifier, $F_n \sim 5$ denotes the noise figure of the amplifier, and $h\nu = 1.28\text{e-19 J}$ is the photon energy at 1550 nm wavelength. For $B_{\text{opt}}$ of about 10 GHz, $P_{\text{ASE}}$ is on the order of 2 $\mu$W (-27 dBm). For comparison, the power of the amplified signal wave going into the detector, $P_s$, is typically on the order of 100 $\mu$W (-10 dBm).

Let us define $\text{SNR}_{\text{ASE}}$ as the ratio between the average photo-current squared, achieved in the detection of $P_s$, and the variance in the photo-current that is induced by $P_{\text{ASE}}$. When using a narrow-band filter $B_{\text{opt}}$, the primary noise term in the photo-current is due to the beating between the optical field of the SBS signal wave and the optical field of ASE (a term known as signal-spontaneous beating [70]). Let us assume that the electrical bandwidth of the detector and its associated circuitry is $B_{\text{Elect}} \sim 0.7$ GHz. In this condition, $\text{SNR}_{\text{ASE}}$ may be approximated by [71]:

$$\text{SNR}_{\text{ASE}} \sim \frac{P_s}{P_{\text{ASE}}}.$$
The SNR due to ASE is on the order of 350.

2.3.1.2 Shot noise

Shot noise stems from the quantum nature of the photo-detection process. The collected photo current consists of a series of elementary charges \( e \), each generated in response to the absorption of a single photon. The timing of each event is random, and uncorrelated with those of other events. The number of charges \( N \) collected within any finite duration \( T_{\text{det}} \) therefore becomes a random variable. It can be shown that \( N \) obeys Poisson statistics [71]:

\[
p(N) = \frac{N^N}{N!} \exp(-N),
\]  

which is entirely defined by its mean value:

\[
\bar{N} = \frac{\eta P T_{\text{det}}}{h}.
\]  

Here \( \eta \) is the quantum efficiency of the photo-receiver. It can be verified directly that the expectation value of \( N \) is indeed \( \bar{N} \), and that its variance also equals \( \bar{N} \). Therefore, the SNR associated with shot noise equals:

\[
\text{SNR}_{\text{shot}} = \frac{\eta P T_{\text{det}}}{h\nu} = \frac{\eta P}{2h\nu \cdot B_{\text{Elect}}}.
\]

Here we denoted the electrical bandwidth associated with photo-detection over duration \( T_{\text{det}} \) by \( B_{\text{Elect}} = \frac{1}{2T_{\text{det}}} \). \( B_{\text{Elect}} \) is on the order of 1 GHz. A comparison between the expressions for \( \text{SNR}_{\text{shot}} \) and \( \text{SNR}_{\text{ASE}} \) above suggests that shot noise is negligible in most systems that involve optical amplification.
2.3.1.3 Thermal noise

The current generated by the photo-detector flows along a finite load conductor of resistance $R_L$. Random thermal motion of free electrons in this conductor contributes noise currents, which add to the intended, photo-detected signal. The extent of this so-called thermal noise is independent of the detected optical power. The SNR associated with thermal noise is given by [72]:

$$SNR_{thermal} = \left( \frac{\eta e}{h\nu} \right)^2 \frac{P_s^2}{(4k_B T / R_L) \cdot F_A \cdot B_{Elect}}$$

(2.8)

Here $k_B = 1.38 \times 10^{-23}$ J/°K is Boltzmann's constant, and $F_A \sim 10$ is a noise figure associated with the electrical amplification within the detector circuitry. Trans-impedance photo-receivers exhibit load resistors on the order of Mega-Ohm, leading to $SNR_{thermal}$ in access of $10^7$ in the detection of $P_s$ above. Even with a load resistor of 50 Ohm, the SNR associated with thermal noise in our measurements is expected to be larger than 1,000.

2.3.1.4 Overall signal-to-noise ratio assessment and its implications

The discussion of the above sections suggests that the dominant noise mechanism in the detection of the signal wave is due to ASE. However, the expression given above for $SNR_{ASE}$ cannot be used directly, for the following reason: The quantity of interest in SBS sensing is not the signal power $P_s$ itself, but rather the changes $\Delta P_s$ in $P_s$ due to SBS over a short segment of length $\Delta z$. These changes are considerably smaller than $P_s$. When the frequency detuning between pump and signal matches the BFS, we may expect:

$$\Delta P_s = P_s \exp\left( g_0 P_p \Delta z \right) - P_s \approx g_0 P_p P_s \Delta z$$

(2.9)
Here $P_p$ is the power level of pump pulses. The measurement noise in DPP B-OCDA is increased by a factor of 2, due to the subtraction between two traces. The SNR in measurement of the quantity of interest $\Delta P_s$ therefore may be approximated as:

$$SNR_{tot} \approx \left( \frac{g_0 P_p \cdot \Delta z}{2} \right)^2 SNR_{ASE} \approx \left( \frac{g_0 P_p \cdot \Delta z}{2} \right)^2 P_s \frac{\text{Tot AES}}{4F_n \cdot h \cdot (G - 1) \cdot B_{Elect}}$$ (2.10)

The pump power in long-range Brillouin sensors experiments is limited by the onset of modulation instability due to the interplay of Kerr effect and chromatic dispersion [72], spontaneous Brillouin scattering and Raman scattering, to the order of few hundreds of mW. The experiments carried out in this research involved short fiber segments, only few tens of meters long. Even in these experiments, $P_p$ cannot be increased beyond few Watts due to saturation of amplifiers, finite extinction ratios of modulators etc. Typical values for the gain coefficient at standard single-mode fibers are on the order of $g_0 = 0.1 \, \text{[W} \cdot \text{m}]^{-1}$. With $\Delta z = 2 \, \text{cm}$, the factor $g_0 P_p \cdot \Delta z$ is bound by few percent, at most. Therefore, the experimental signal-to-noise ratio $SNR_{tot}$ may be as low as 0.07.

An expression relating the experimental uncertainty in the estimate of BFS and the measurement SNR was derived by Soto and Thevenaz in 2013 [41]. The expression was given in Chapter 1, and it is repeated here for convenience:

$$\sigma_{\Omega_s} = \frac{\sqrt{3}}{\sqrt{4 \cdot \delta \cdot \frac{\Gamma_p}{2\pi} \cdot \frac{1}{SNR_{tot}}}}$$ (2.11)

Here $\delta = 1.5 \, \text{MHz}$ is the step-size in the scanning of the frequency offset between pump and signal waves. Note that the SNR in the original publication was defined as the square root of the quantity used in this discussion. The above formula suggests a very large experimental error of $\pm 22 \, \text{MHz}$, which cannot be tolerated. The SNR improves, however, with the number of repetitions $N_{av}$ in the acquisition of the output signal wave. 512
repetitions were used in our experiments. Averaging is expected to reduce the experimental error to the order of ±1 MHz. As shown in the next chapter, the uncertainty in the experimental BFS measurements is not far from this prediction.
3. Experiments and results

3.1 Setup and main components

An illustration of the measurement setup designed to implement the proposed double-pulse B-OCDA method is shown in the figure below. Light from a continuously-operating laser diode source at 1550 nm wavelength passed through an electro-optic phase modulator. The modulator was driven by the output voltage of an arbitrary waveform generator (AWG), programmed to repeatedly generate an 11 bits long perfect Golomb code. The duration of phase coding symbols was 267 ps, corresponding to B-OCDA spatial resolution of 2.76 cm, as in the simulations of the previous chapter. The magnitude of the voltage waveform was amplified to match the phase values of the Golomb code. An optical coupler at the output of the phase modulator divided the incoming light in two branches: 99% of the incident power was directed to the pump path, and 1% was routed to the signal path.

Figure 3.1. Schematic illustration of the experimental setup. SOA: semiconductor optical amplifier; EDFA: erbium-doped fiber amplifier; SSB Mod.: singles side-band electro-optic modulator; Phase mod.: electro-optic phase modulator.
The signal wave propagated through a fiber path imbalance, necessary for the precise scanning of correlation peaks positions along the section of fiber under test (see details in section 3.1.2 below, and in [59]). The delay line was followed by a polarization scrambler, required to eliminate polarization-induced fading of SBS in case the pump and signal are orthogonal to each other at a particular location [36]. Lastly, the signal wave was launched into one end of the fiber under test (FUT).

The pump wave passed through a single side-band (SSB) electro-optic modulator, driven by a sine wave of frequency $\Omega$ from the output of a microwave synthesizer. The modulator was biased to provide a single offset replica of the phase modulated waveform, centered at an optical frequency of $\omega_0 + \Omega$ where $\omega_0$ is the optical frequency of the laser diode source. The opposite, lower sideband and the original carrier were suppressed by about 20 dB. Light at the pump branch was amplitude-modulated by repeating, low-duty cycle pulses in a SOA with a period of 2 $\mu$s, and amplified further by a high-power EDFA to an average power of 0.4 W (estimated pulse peak power of about 10 W). Last, the pump pulses were routed through a circulator into the opposite end of the FUT.

The section of fiber under test was 43 m-long. The signal wave at the FUT output was amplified by a second EDFA, and detected by a broadband photo-receiver. An optical bandpass filter was used to suppress the amplifier ASE. The figure below shows an image of the measurement setup in our group laboratory.
Electro-optic modulator

In optical communication systems, the electro-optic modulator is responsible for superimposing information onto an optical carrier wave. This information can change the phase, amplitude, frequency or polarization of incident light. There are, therefore, several types of modulators, categorized according the type of modulation they impose on the propagating light wave. We use both phase and amplitude modulation in our setup.

Electro-optic phase modulator:

Phase modulation can be implemented based on the electro-optic effect in LiNbO$_3$ crystals. In this effect, the refractive index of the material changes with the application of an external voltage $V$ [72]:

$$\Delta n = -\frac{1}{2} n_0^3 r_{33} \frac{V}{d}$$

(3.1)
In the above equation \( d \) is the distance between electrodes surrounding a waveguide in the crystal, and \( r_{33} \) is an electro-optic coefficient of the crystal \((r_{33} = 30.9 \times 10^{-12} \text{[m/V]})\). Changes in refractive index modify the accumulation of phase along a waveguide of length \( l \):

\[
\Delta \varphi = \frac{2\pi}{\lambda} \Delta n \cdot l = -\frac{\pi}{\lambda} n^3 r_{33} \frac{V}{d} l = -\pi \frac{V}{V_\pi}
\]

(3.2)

Here \( V_\pi \) is defined as the voltage necessary to induce a phase shift of \( \pi \) radians. The phase modulator element also provides the basis for amplitude modulation, as discussed next.

**Electro-optic amplitude modulator:**

Amplitude modulation can be realized in a Mach-Zehnder interferometer (MZI) configuration (Fig. 33). Incoming light is split in two waveguide paths, each consisted of a LiNbO\(_3\) phase modulator, and combined together at the output. Incident power is divided equally between the two arms. The drive voltages for the two embedded phase modulators are \( V_{1,2} \).

![Diagram of a LiNbO\(_3\) Mach-Zehnder interferometer amplitude modulator](image)

**Figure 33. A schematic illustration of a LiNbO\(_3\) Mach-Zehnder interferometer amplitude modulator [72]**

The output field magnitude can be written as:

\[
E_{\text{out}} = \frac{1}{2} E_0 \exp \left( j \Delta \varphi \right) \left[ \exp \left( j \frac{\Delta \varphi_{12}}{2} \right) + \exp \left( -j \frac{\Delta \varphi_{12}}{2} \right) \right] \exp \left( j \omega t \right)
\]

(3.3)
Here $E_0$ is the magnitude of the incident field with a carrier optical frequency $\omega_0$, $\Delta \varphi_{1,2}$ are the electro-optic modulation phases at the two arms, $\Delta \varphi_{1,2} = (\Delta \varphi_1 - \Delta \varphi_2)$ and $\Delta \varphi = \frac{1}{2}(\Delta \varphi_1 + \Delta \varphi_2)$. The output power is given by:

$$P_{out} = |E_{out}|^2 = \frac{1}{2} \left[ 1 + \cos (\Delta \varphi_{1,2}) \right] |E_0|^2 = \frac{1}{2} \left[ 1 + \cos \left( \pi \frac{(V_1 - V_2)}{V_x} \right) \right] |E_0|^2 \quad (3.4)$$

Power transmission is complete when the two drive voltages are equal (constructive interference between light propagated in the two arms), whereas transmission is blocked when the difference between the two drive voltages is set to $V_x$ (destructive interference).

**Single-Sideband modulation**

In standard electro-optic modulators, of either phase or amplitude, modulation introduces two spectral sidelobes, above and below the frequency of the optical carrier. In many setups, such as ours, only a single sideband (SSB) is useful, while the complementary sideband disrupts the measurements. Many SBS sensor setups use narrowband optical filters to select a single sideband following modulation. Alternatively, SSB modulators generate only an SSB to begin with. The device consists of two independent MZI amplitude modulators, and the input electrical waveform is therefore driven twice into the device. A phase shift of 90° must be introduced between the two replicas. In addition, the carrier wave itself may be suppressed with a careful choice of a DC bias to the modulators.

Our setup employs an SSB modulator to generate the pump wave from a replica of the signal. The device is driven by an electrical sine wave from a microwave generator at frequency $\Omega \approx \Omega_p$, and adjusted so that only the shorter-wavelength (higher-frequency) sideband is retained. An example is shown in the figure below. The opposite sideband and the optical carrier are effectively suppressed, by a factor on the order of 20 dB.
Figure 34. An optical spectrum analyzer measurement of an optical carrier following SSB modulation by a sine wave of frequency on the order of 10 GHz. The right-hand (longer wavelength) sideband is retained, to be used as an SBS probe wave. The optical carrier itself and the opposite sideband are largely suppressed. Note that roles were reversed in the DPP B-OCDA experiment, and the shorter-wavelength sideband was retained instead.

3.1.1 Polarization control

Control over the state of polarization is required in several positions along the measurement setup. First, electro-optic modulators support the propagation of one linear state of polarization and block the orthogonal one. Manual polarization controllers (PCs) were used to adjust the incoming polarization to the state supported by modulators. Further, the SBS interaction itself is polarization dependent, and may vanish entirely if the states of polarization of pump and signal are orthogonal [36].

Polarization-induced fading can be mitigated using a polarization switch: a device that can toggle the polarization of an optical wave between two orthogonal states. The SBS sensing experiments is carried out twice, using both polarizations, and the recorded traces are averaged [37]. The scheme therefore implements polarization diversity. However, the switching operation requires that at least part of the setup is constructed from polarization maintaining fibers, a requirement we could not meet. Instead, a polarization scrambler (Fig. 35) was used to switch the instantaneous state of polarization (SOP) of the signal wave between random states that were evenly distributed on the Poincare sphere, at a rate of 100,000 states per second [36]. The comparatively slow scrambling rate mandates that at
least 128 repetitions of each trace are averaged, even if the measurement SNR is otherwise sufficient.

![Figure 35. The polarization scrambler used in the experimental setup.](image)

### 3.1.2 Scanning of correlation peaks positions

The intuitive approach to shifting the positions of correlation peaks would be to introduce a variable delay to the phase coding of either pump or probe waves in increments of a single bit. This solution would require the separate and synchronous modulation of the two waves with two phase modulators. Alternatively, the positions of correlation peaks can be moved through slight modifications to the exact bit duration. An illustration is provided in Fig. 36.

![Figure 36. Illustration of shifting the position of correlation peaks through small-scale changes to the exact bit duration.](image)

The FUT and the fiber paths leading to it from the input ends of the pump and signal form a fiber loop. A so-called zero-order correlation peak is formed at the center of that
loop, in a position denoted below as \( z = 0 \). Multiple, higher-order correlation peaks are formed at positions 

\[ z_m = \frac{1}{2} m \cdot N_{\text{phase}} \cdot v_s T, \]

where \( m \) is a positive or negative integer. The locations of all these peaks, other than \( m = 0 \), change with symbol duration:

\[
\frac{\Delta z_m}{z_m} = \frac{\Delta T_{\text{phase}}}{T_{\text{phase}}} = -\frac{\Delta f_{\text{phase}}}{f_{\text{phase}}} \tag{3.5}
\]

Here \( \Delta f_{\text{phase}} \) represents a variation of the clock rate \( f_{\text{phase}} \) driving the phase modulator, and \( \Delta T_{\text{phase}} \) is the corresponding variation in the symbol duration \( T_{\text{phase}} \).

A proper B-OCDA experiment requires that the offsets \( \Delta z_m \) in the exact positions of all correlation peaks \( z_m \) are equal. However, the precise offsets depend on \( m \). Differences may be arbitrarily reduced when a long delay line imbalance is placed in either the pump or the signal paths. The path imbalance guarantees that high-order peaks are in overlap with the fiber segment of interest: \( m >> 1 \). Let us denote the length of the fiber under test as \( L \), and that of the delay line as \( L_{\text{delay}} \). The location of the point of measurement that is nearest to the center of the loop is:

\[
z_1 = \frac{L_{\text{delay}} - L}{2} \tag{3.6}
\]

The clock-rate increment that is necessary to achieve \( \Delta z \) resolution at that position is given by:

\[
\Delta f_1 = -\frac{f_{\text{phase}} \Delta z}{z_1} = \frac{2f_{\text{phase}} \Delta z}{L - L_{\text{delay}}} \tag{3.7}
\]

Similarly, the measurement point that is the most further away from the center is located at:

\[
z_2 = \frac{L_{\text{delay}} + L}{2} \tag{3.8}
\]

The offset in that location subject to the above \( \Delta f_1 \) would be:
\[ \Delta z_2 = \frac{z_2}{z_1} \Delta z = \frac{L_{\text{Delay}} + L}{L_{\text{Delay}} - L} \Delta z \]  \hspace{1cm} (3.9)

Near-uniform scanning of positions therefore requires that \( L_{\text{delay}} \gg L \). A 2.2 km-long fiber path imbalance was used in our experiments, alongside a 43 m-long FUT. The phase modulation clock rate \( f_{\text{phase}} \) was 3.75 GHz, and the necessary step size \( \Delta f_{\text{phase}} \) for a spatial resolution of 2.67 cm was 92.764 kHz.

### 3.2 Results

In a proof-of-concept DPP B-OCDA experiment, the entire FUT was scanned using \( N_{\text{phase}} = 11 \) positions of correlation peaks. For each set of positions, the frequency difference \( \nu = \Omega/(2\pi) \) between pump and signal was scanned between 10.72 GHz to 10.82 GHz in 1.5 MHz steps. A pair of traces was recorded at each frequency, using pump pulses of \( T_{\text{pulse}} = 30 \) ns or \( T_{\text{pulse}} - \Delta T_{\text{pulse}} = 29 \) ns duration as discussed in the previous chapter. Each trace was averaged over 512 repetitions. The photo-current from the detector at the output signal path was sampled by a real-time, digitizing oscilloscope at 5 GHz bandwidth. The sampled data was digitally filtered off-line to a bandwidth of 0.7 GHz, to improve the SNR. Three 8 cm wide hot-spots were placed along the FUT, by attaching the fiber coil to a hot plate (see Fig. 37). The separations between the first hot-spot and the second, and between the second and third ones, were 40 cm and 4.7 m respectively.
Figure 37. Image of part of the fiber under test, coiled and placed on top of a hot-plate to introduce three local hot-spots.

Figure 38 (bottom left) shows an example of a single pair of output signal traces taken at $\nu = 10.765$ GHz, a value that is close to the BFS of the FUT at room temperature. Only parts of the complete traces are shown for better clarity. The displayed section includes a single hot-spot. Both traces consist of series of overlapping gain events. Figure 38 (bottom right) shows the result of the subtraction between the two traces. The difference trace consists of a series of individual gain events that are separated by $N_{\text{phase}}T_{\text{phase}} = 2.9$ ns. The duration of each event is $\Delta T_{\text{pulse}} = 1$ ns, and it represents the SBS amplification in a single correlation peak of width $\Delta z$. Measurements are resolved even though the temporal separation between adjacent peaks is shorter than the Brillouin lifetime, and much shorter than the pump pulses durations. A single gain event, which corresponds to a correlation peak that is in overlap with the location of the hot-spot, appears much weaker than all others. Note the similarity between the experimental, bottom panels of Fig. 38 and the simulated results (Fig. 28, repeated at the top panels of Fig. 38 for convenience).
Figure 38. Bottom Left – example of a pair of measurements of the output signal wave, taken for $\nu = 10.765$ GHz which is close to the BFS of the FUT at room temperature. Only parts of the traces are displayed for better clarity. The sections of the traces displayed are in overlap with a single hot-spot. The pump pulse durations were 30 ns (red trace) and 29 ns (blue trace). Both traces consist of series of overlapping SBS gain events. Bottom Right – result of the subtraction between the two traces of the left panel. The difference trace consists of a series of amplification events that are unambiguously associated with individual correlation peaks. A single gain event, which corresponds to a correlation peak that is in overlap with the hot-spot, is much weaker [73]. The top left and top right panels present the results of a corresponding simulation (repeat of Fig. 28).

The magnitude of the SBS gain at each peak was estimated as follows: the instantaneous maximum reading of each gain event in the difference trace of Fig. 38 (right) was identified, and the trace was integrated over a 1 ns-wide window centered at that maximum. Upon completion of the spectral scanning over all values of $\nu$, the position of all correlation peaks were shifted by $\Delta z$ as explained above and the spectral scan was carried out again. The correlation peaks returned to their original location following 11 shifting steps.

Figure 39 shows the measured SBS amplification as a function of frequency offset $\nu$ and position $z$. The SBS gain map consists of 1,600 resolution points that were addressed using only 11 pairs of traces per choice of $\nu$. The entire FUT was covered in the measurements. A magnified view of the SBS gain map in the region containing the three hot-
spots is provided in Fig. 40. The three hot spots are clearly identified at positions around 28 m and 33 m.

Figure 39. Measured normalized SBS gain (arbitrary units), as a function of correlation peak position and frequency offset between pump and signal waves [73].

Finally, Fig. 41 (left) shows the measured BFS as a function of position. Magnified view of the fiber segment containing the three hot-spots is provided in Fig. 41 (right). All three hot-spots are identified in their correct locations.
Figure 41. Measured Brillouin frequency shift as a function of position. Right – magnified view of the region containing the three local hot-spots [73].

The experimental error in the measurement of the BFS can be evaluated based on the variations between its values in adjacent resolution cells [65]:

\[
\sigma_v \approx \sqrt{\frac{1}{2} \left( \left< V_B(z + \Delta z) - V_B(z) \right> \right)^2}_z
\]

(3.10)

where \( \left< \right>_z \) denotes averaging over position \( z \). \( \sigma_v \) of the experiment equals ±1.9 MHz. This value is not far from the estimate given in chapter 2, based on SNR considerations. The evaluation assumes that changes in the measured BFS over short segments of \( \Delta z \) length, outside the hot-spots, represent measurement noise rather than physically meaningful variations. This evaluation of the experimental error therefore represents a pessimistic upper bound. The experimental error increased to 3 MHz when the number of averaged acquisitions of each trace was reduced from 512 to 256.
4. Summary and discussion

The motivation for my research has been to try and reduce the number of position scans necessary in phase-coded B-OTDA by an order of magnitude. We were able to do so through the combination between B-OCDA and DPP acquisition principles. The measurement protocol is an extension of previous, time-gated B-OCDA setups, in which both pump and signal waves are jointly modulated by a repeating, high-rate phase code and the amplitude of the pump wave is also modulated by a pulse. The phase code was short, and its period was much shorter than the duration of pump pulses. Hence SBS was stimulated in a large number of correlation peaks in each trace. However, individual gain events overlapped in time. Unambiguous measurements were recovered by taking each trace twice, with pump pulse durations that slightly differed, and subtracting the two traces of the output signal. The number of positions scans that is necessary to cover the entire FUT equals the number of bits in the phase code, and it is independent of the fiber length.

In a proof-of-concept experiment, a 43 m-long FUT was analyzed with a spatial resolution of 2.7 cm. All 1,600 resolution points were addressed using only 11 scans of the correlation peaks positions, the smallest number of any B-OCDA experiment. Previous B-OCDA setups required at least 50-100 position scans, and sometimes even thousands of scans. The accuracy in the measurement of the BFS was 1.9 MHz. Three local hot-spots were properly identified in the measurements. The spacing between adjacent peaks positions was only 30.4 cm. Such close spacing cannot be applied in direct, single-pulse B-OCDA due to acoustic lifetime limitations.

4.1 Comparison with other Brillouin sensing protocols

The DPP B-OCDA setup represents a middle-ground between earlier, time-gated B-OCDA protocols [65,74,69,68] and DPP B-OTDA [50], with respect to the trade-off between SNR and number of position scans. Previous B-OCDA protocols of cm-scale resolution
required at least 100 scans of correlation peaks positions to cover the entire FUT, but on the other hand typically involved detection at 100 MHz bandwidth or lower. The measurements reported in this work required only 11 pairs of position scans, with detection at 0.7 GHz bandwidth. On the other extreme, DPP B-OTDA covers the entire FUT with a single pair of scans, but requires detection at several GHz bandwidth [50]. A similar trend may be expected with respect to pump depletion. The pump pulse is depleted along the entire length of the FUT in DPP B-OTDA. Depletion is confined to a shorter effective length $L/N_{\text{phase}}$ in DPP B-OCDA, and to a length that is shorter still in previous time-gated B-OCDA setups.

The uncertainty in the BFS estimate of all three protocols is governed by the SNR of the SBS gain measurement [74]. In systems that are limited by shot noise, additive detector noise or amplifier noise, the SNR scales inversely with the detection bandwidth. The degradation in SNR must be compensated by a larger number of repetitions $N_{av}$ in the averaging of each trace. Therefore, subject to equal power levels of pump and signal, similar amplifier and detector noise performance and the same spectral scanning, DPP B-OCDA should require fewer averages than DPP B-OTDA, but more averages than previous time-multiplexed B-OCDA setups. Noise due to residual off-peak SBS interactions is expected to be lower in the DPP B-OCDA measurements than in previous B-OCDA setups, due to the use of shorter perfect codes.

In principle, the overall number of traces required to achieve a given precision: namely the product of $N_{av}$, the number of frequency offset values $\nu$ and the number of positions scans, should be similar for all three protocols. The preference of one approach over others would depend on convenience and on availability of components. In some practical systems, however, other considerations might mandate a certain minimum number of $N_{av}$. For example, in our experiment the averaging over 512 repeating acquisitions was

65
required due to the operation rate of the polarization scrambler. Use of polarization switching [37,68], or polarization diversity schemes [76], is expected to reduce this number.

Both time-multiplexed B-OCDA and DPP B-OTDA have reached a measurement range of several km with cm-scale resolution, addressing hundreds of thousands of points [50,65,74,77,69,68]. There is no fundamental limitation that should prevent the currently proposed DPP B-OCDA principle from reaching comparable range. However, these efforts are beyond the scope of the present work.

4.2 Limitations

The measurement parameters of DPP B-OCDA are restricted by several considerations. The duration of pump pulses $T_{\text{pulse}}$ must be several times longer than the acoustic lifetime: on the order of 25 ns or longer, so that the stimulated acoustic fields at the correlation peaks positions may reach their maximum, steady-state values. The specific choice of 30 ns, however, was arbitrary.

The difference between the durations of the two pulses used in each measurement, $\Delta T_{\text{pulse}}$, must be shorter than the phase code period $T_{\text{phase}} N_{\text{phase}}$, or else the analysis of the difference trace would become ambiguous as well. The electronic bandwidth of the detection circuitry, $B_{\text{Elect}}$, must be broad enough to accommodate gain events of duration $\Delta T_{\text{pulse}}$. Hence, choice of a short $\Delta T_{\text{pulse}}$ would unnecessarily increase the detection bandwidth and measurement noise. An arbitrary value of 1 ns was used in this research. Given the code period $T_{\text{phase}} N_{\text{phase}}$ of 2.9 ns, a larger difference between pulse durations could have been used. Optimization of $\Delta T_{\text{pulse}}$ and $B_{\text{Elect}}$ was not carried out within the scope of this research. Similarly, use of even shorter phase codes would reduce the number of positions scans necessary, but increase the detection bandwidth and elevate the noise levels.
The extinction ratio in the amplitude modulation of pump pulses needs to be high. Non-zero pedestal of pump pulses introduces undesired residual SBS interactions along the entire length $L$ of the fiber, which may mask out the gain provided by the pulse itself. As a rule of thumb, the extinction ratio of pump modulation must exceed $L/\Delta z$. Other limitations are not fundamental, and have to do with the specific implementation chosen for the proposed principle. The comparatively slow scrambling of polarization requires many averages. The scanning of peaks positions through clock rate variations requires a delay imbalance that is 10-100 times longer than the FUT.

4.3 Future work

Several improvements can be made in the implementation of the proposed principle. The first one is the employment of polarization switching and diversity, rather than scrambling, in the mitigation of polarization-induced fading of the local SBS interactions. Our group had used polarization switching in other B-OCDA experiments before [38]. The number of repetitions required in the averaging of each trace was much reduced. I expect a similar benefit in the DPP B-OCDA setup.

Other potential improvements are the use of even shorter phase sequences, such as a 5 bits Golomb code, to reduce the number of positions scans even further. Resolution can also be improved, towards 1 cm. In both these cases, the detection bandwidth would have to be broadened, and the SNR may be degraded. The number of averages is expected to increase accordingly.

Last but not least, DPP B-OCDA can be performed over km-scale fibers, addressing hundreds of thousands of resolution points with a small number of position scans. Previous measurements with km-scale range and cm-resolution were limited by either pump depletion, long measurement duration or the complexity associated with the collection and processing of vast amounts of data. Our group previously performed B-OCDA over 8.8 km of
fiber with 2 cm resolution, addressing all 440,000 points. That experiment was limited by complexity and acquisition duration. DPP B-OCDA reduces the number of position scans, and does not involve the complicated dual-hierarchy coding scheme of our previous work, hence its extension to an even larger number of resolution points should be feasible.

On the other hand, DPP B-OCDA is more prone to depletion than our previous setups. Depletion takes place over an effective length of $L/N_{\text{phase}} = L/11$. As mentioned earlier in this section, DPP B-OTDA experiments are susceptible to depletion over the entire length $L$ of the fiber under test. DPP B-OTDA was successfully carried out over 2 km with 2 cm resolution. Drawing on this previous example, it is reasonable to expect that B-OCDA measurements could be performed over 20 km of fiber before being restricted by depletion. As new middle-ground between previous time-domain and correlation-domain protocols, the configuration proposed in this research has good potential to improve upon the current state-of-the-art in terms of the number of resolution points addressed, and perhaps raise the bar above 1 million points.
5. Bibliography

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A section of optical fibers was first developed in the late 1970s, as a means to transmit communication over long distances and at high speeds. Since then, optical fibers have proven themselves as highly successful sensors. Besides other applications, optical fibers allow for a fiber-mapping of mechanical and temperature deformations. These measurements are widely used in monitoring facilities and in the protection of various areas.

One of the physical mechanisms used in optical fibers is stimulated Brillouin scattering (SBS). Stimulated Brillouin scattering is a nonlinear effect that occurs between two optical fields propagating in opposite directions: a strong signal (pump) and a weaker signal. The mixing is done by an acoustic wave. Effective mixing occurs when the optical frequencies of the two fields match a specific value called Brillouin frequency shift (BFS). The value of this shift, in standard optical fibers for optical signals at a wavelength of 1550 nm, is 11 GHz.

The accurate value of the Brillouin frequency shift changes according to temperature and local mechanical deformations. Therefore, mapping the Brillouin frequency shift over a fiber is used to measure both these quantities. The most common method is Brillouin optical time domain analysis (B-OTDA). In this method, a pulse of optical power is used to increase the signal. Commercial devices based on this principle allow for the measurement of fibers over 50 km, with a spatial resolution of 1-2 meters and a temporal resolution of ±1 μs. The measurement time is several minutes. Coordinate B-OTDA or DPP (double pulse-pair, DPP) methods have been developed to avoid this limitation. The accuracy of the method is one kelvin or two parts per million. Data collection time is several minutes.
This method, the hologram-based mixed signal transmission, makes it possible to transmit the hologram of the signal on the fiber. The hologram is created by the interference of two coherent light waves. The wavefronts of these waves are characterized by their phase and frequency. The hologram is recorded by using the interference pattern of the two waves. The recorded hologram can be read by using the reference beam, which is the same as the original wave. The hologram can be used to reconstruct the signal, which is the original wave that was used to create the hologram. The hologram can be stored and retrieved by using the reference beam. The hologram can be used to transmit the signal over long distances, without the need for再生 or amplification. The hologram can be transmitted through optical fibers, and it can be read by using the reference beam. The hologram can be used to transmit the signal in real-time, and it can be used to transmit the signal in a secure manner. The hologram can be used to transmit the signal in a wide range of frequencies, and it can be used to transmit the signal in a wide range of distances. The hologram can be used to transmit the signal in a wide range of applications, such as communication, data transmission, and optical communication.
עקרון המדידות המוצע נマー באינדיקציה נומרית מקיפה של המשוואה הדיפרגנטיאלית המוצמדת של פיצורי בריליוואן מאוליגר. הנקודות הניתן לשיפוע המשתיים העקרון משודד במדידת ניסיון של סיב באורכם 43 מטרים ברזולוציה מרחבית של 2.7 מ"מ 11 סרטי מרחביות בבלד של מיקום שכ入り הקורלציה הסופיקע-분מטים את כל 1,600 נקודות הרזרולציה לאורך הסיב. המספר קוננוקט אחד לבין הסיב הוא ובית ברזולוציה המידה. הדיוק במדידה של חישוף בריליוואן המוקדנה היא הידifestyles שפחתה בבלד ולבין שיפוע מידה קיימות רוב在这种 הנעוץ לפי אפנון הפאה של מעוננים B-OCDA. בכמה זה מס perpetrת להervative רוחב הפאה הדירוג.
עבדת זו נעשתה בהדרכה של פרופ' אבי צדוק من הפקולטה להנדסה של אוניברסיטת בר-אילן.
אוניברסיטת בר-אילן

מדידות פיזור ברייאון מיולץ במרחבי הקואליציה

באמצעת שימור בפולים כפואל

אראל שלומי

עובדה זו מונפקת מחקק מחברות יהודים הקבלת תואר מוסמך לפכولوجي להקדמה של

אוניברסיטת בר-אילן

רמחן ג'ණ

תשע"ו