Noise-based Brillouin optical correlation domain analysis with mm resolution

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Submitted in partial fulfillment of the requirements for the Master's Degree in the Faculty of Engineering, Bar-Ilan University

Ramat-Gan, Israel 2014
This work was carried out under the supervision of Prof. Avi Zadok
Faculty of Engineering, Bar-Ilan University.
In many research groups, each researcher is immersed in his own topic, without much interaction with his fellow group members, at least at the research level. Here this is definitely not the case. The research which I present here is based on the previous work of members of our group and was successful only because of the many discussions and from hands on help that I had.

First and foremost my thanks goes to Prof. Avi Zadok. He has done over and above what is expected from a supervisor. While he provided an environment where research can be done without external distractions, which is very important, his friendliness and support in all areas is more impressive and has taught me a thing or two in what is known as Derech Eretz.

My thanks also goes to Yair Antman, Yosef London, David Elooz and Shahar Levy (pre-detection filtering!) who all have helped me in the research, be it through using their previous work or by their help in the lab.

I want to thank Prof. Michael Rosenbluh who supported aspects of my research in its initial stages. Dov Friedman from the workshop also helped a lot.

To the rest of my research group both past and present was supportive and helpful throughout; Dr. Arkady Rudnitsky, Eyal Preter, Yoni Stern, Idan Bakish, Ran Califa, Nadav Arbel, Asaf Ben-Amram, Dvir Munk, Daniel Kravitz, Daniel Grodensky Tali Ilovitch, Kun Zhong, and Ofir Klinger.
To the administration of the Faculty of Engineering in Bar-Ilan University, and especially to Mrs. Dina Yeminy and Mrs. Adi Rozen-Hevroni, I would like to express my gratitude for their support throughout this research.

I also appreciate the support given for this research from the Chief Scientist’s Office of the Israeli Ministry of Economy through two different MAGNETON programs.

Obviously, I would like to thank my parents and family for, well, basically everything.

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<th>Description</th>
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<tbody>
<tr>
<td>AM</td>
<td>Amplitude modulation</td>
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<tr>
<td>ASE</td>
<td>Amplified spontaneous emission</td>
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<tr>
<td>B-OCDA</td>
<td>Brillouin optical correlation domain analysis</td>
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<tr>
<td>B-OTDA</td>
<td>Brillouin optical time domain analysis</td>
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<tr>
<td>BPF</td>
<td>Band pass filter</td>
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<td>DAS</td>
<td>Distributed acoustic sensing</td>
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<td>DPP</td>
<td>Differential pulse width pair</td>
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<td>DSB</td>
<td>Double sideband</td>
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<td>EDFA</td>
<td>Erbium doped fiber amplifier</td>
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<td>FBG</td>
<td>Fiber Bragg grating</td>
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<td>FUT</td>
<td>Fiber under test</td>
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<td>FWHM</td>
<td>Full width half maximum</td>
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<td>MFD</td>
<td>Mode field diameter</td>
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<td>OFDR</td>
<td>Optical frequency domain reflectometer</td>
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<td>OSA</td>
<td>Optical spectrum analyzer</td>
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<tr>
<td>OTDR</td>
<td>Optical time domain reflectometer</td>
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<tr>
<td>PBS</td>
<td>Polarization beam splitter</td>
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<td>PC</td>
<td>Polarization controller</td>
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<td>PCF</td>
<td>Photonic crystal fiber</td>
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<td>SBS</td>
<td>Stimulated Brillouin scattering</td>
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<td>SMF</td>
<td>Single mode fiber</td>
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<td>SNR</td>
<td>Signal to noise ratio</td>
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<td>SOA</td>
<td>Semi-conductor optical amplifier</td>
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<td>SSB</td>
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<td>Symbol</td>
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</tr>
<tr>
<td>$c$</td>
<td>Speed of light in vacuum</td>
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<td>$\lambda$</td>
<td>Optical Wavelength</td>
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<tr>
<td>$n$</td>
<td>Refractive index</td>
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<tr>
<td>$\Lambda$</td>
<td>Periodicity of Bragg grating</td>
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<td>$\Omega$</td>
<td>Angular frequency</td>
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<tr>
<td>$v$</td>
<td>Frequency</td>
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<td>$v$</td>
<td>Speed</td>
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<td>$\gamma_e$</td>
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<td>Boltzman constant</td>
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<td>$\Gamma_B$</td>
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<td>$h$</td>
<td>Reduced Planck constant</td>
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<td>Pressure wave amplitude</td>
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<td>Brillouin shift temperature</td>
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<td>$C_{\epsilon,s}$</td>
<td>Brillouin shift strain</td>
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PUBLICATIONS

JOURNAL PUBLICATIONS:


CONFERENCE PAPERS:


ABSTRACT

Distributed optical fiber sensors provide unique answers to many different sensing problems. They are now in the forefront of structural health monitoring research and are also integrated in security systems. There are a number of different methods used to implement distributed fiber sensors, each one with its own special attributes. One such method utilizes optical Brillouin scattering, an effect that is sensitive to both temperature and strain along the optical fiber. This method has several advantages over Rayleigh and Raman scattering-based sensor systems. These include measurement ranges of hundreds of km, mm-scale spatial resolution, micro-strain and/or sub-°C sensitivity, insensitivity to losses, and comparatively simple post-processing of data. Distributed Brillouin analysis systems are being commercially deployed in increasing volumes, primarily in long-reach monitoring in the energy and oil and gas sectors.

Two main techniques have been developed for distributed fiber sensors, based on Brillouin scattering: Brillouin optical time domain (B-OTDA) analysis and Brillouin optical correlation domain analysis (B-OCDA). Recent progress has been made in both techniques to enhance the spatial resolution of the sensors. Currently the highest resolution reported is 1.6 mm, using a B-OCDA technique over a range of a few cm, while the highest resolution for longer-range B-OTDA measurements has been 2 cm over 2 km.

With similarity to many radar systems, high resolution measurements require some form of spectral broadening of the interacting optical waves. All Brillouin sensors reported to-date rely on the output of a coherent laser source, the
standard workhorse of most optical fiber systems. A broad variety of amplitude, frequency and phase modulation protocols are being employed for resolution enhancement, reported in scientific literature and commercial systems. These protocols require high-rate pattern generators, microwave generators and electro-optic modulators, operating at increasingly high bandwidths. A spatial resolution of 4 mm, for example, requires a bandwidth of 25 GHz. The necessary state-of-the-art equipment is expensive, and often unavailable.

This research introduces a conceptually new manner of implementing a high-resolution Brillouin scattering based distributed fiber sensor. The main difference between this proposed technique and its predecessors is in the use of Amplified Spontaneous Emission (ASE) as the common source of all optical signals in the system. By using ASE there is no longer a need to broaden the optical bandwidth of the signal in order to enhance resolution; in fact, the opposite is true as the bandwidth of ASE must be narrowed. The outcome of this change in paradigm is that the resolution limit is no longer set by equipment constraints: ASE-based sensors could provide sub-mm resolution in appropriate, highly nonlinear media. On top of its research novelty, the use of ASE opens up new possible applications, such as distributed sensing along planar lightguide circuits.

The ASE based Brillouin sensor is demonstrated in theory, numerical simulations and experiments. Aspects of measurement signal-to-noise ratio, measurement range and system complexity are thoroughly investigated. Experiments demonstrate spatial resolution of 3-4 mm along a measurement range of 5 cm. A 4 mm-long hot spot is recognized in the measurements. The experimental
uncertainty in the reconstruction of the local Brillouin shift is equivalent to an error of $\pm 1.5^\circ C$ or $\pm 30 \mu s$. Potential extensions of the work are discussed.
1 INTRODUCTION:

1.1 MOTIVATION:

In many sensing applications, the physical quantity of interest must be acquired from many points. For instance, if we are interested in the gradient of strain along a wing, then one strain gauge is not enough. We must have a number of gauges in order to get a good estimate of the strain throughout the wing. In other scenarios, we might be interested in monitoring the state of a long pipeline which might leak, at least potentially, at any given point. For these types of applications the use of point sensors is very cumbersome and costly. Each sensor must be able to communicate with the data hub, and in many cases must also have its’ own power supply. Instead, these applications call for distributed solutions, in which every segment of a continuous, long element, such as an optical fiber, serves as an individual sensing nerve.

Research in the field of distributed sensors has intensified in the past few years, both due to new needs that have been identified and to new technologies that can enable such systems [1, 2, 3]. The primary applications of distributed sensors are in the monitoring of large structures, such as pipelines, bridges, and passenger jets. Distributed sensors can provide critical information regarding the performance of structures under different circumstances, and identify the onset of faults at an early stage. Techniques that are based on point sensors are difficult to scale towards the monitoring of large structures.

Fiber optic based distributed sensors are especially suited for structural health monitoring systems [1, 2, 3]. The small size of the fibers allows them to be
embedded within a structure under test with little extra weight and little effect on functionality. Optical fibers can carry light over arbitrarily long distance, are immune to electromagnetic interference, and can withstand harsh environments [4]. Specifically, distributed fiber sensors are being rapidly adapted and incorporated within advanced composite materials, for aerospace and civil engineering applications [3].

The following sections include a detailed review of distributed fiber sensors principles and technologies. The vast majority of commercially available sensor systems offer a measurement range of many km and meter-scale spatial resolution\(^1\) [5-9]. Fewer works and systems provide cm-resolution or better [5-9]. In this research we propose, simulate, and demonstrate a method for ultra-high resolution, fiber optic-based distributed sensing. A spatial resolution of 3.2 mm is demonstrated experimentally. Analysis and simulations indicate that the method is scalable towards sub-mm resolutions in appropriate photonic media. Among other possibilities, the technique could allow for distributed measurements within integrated, planar light-guide circuits, a possibility that is not considered to-date due to the resolution restriction of available sensing platforms.

\(^1\) A word of caution is needed in relation to the term 'resolution'. When talking about resolution in relation to distributed sensors the intention is to the smallest detectable disturbance and not necessarily the ability to discern between two adjacent disturbances. This definition for resolution is different from the one used in microscopy and is perhaps misleading, however, since this is the term used in the literature it has been adopted throughout this work.
1.2 DISTRIBUTED FIBER BASED SENSORS:

1.2.1 OVERVIEW:

Sensors come in many shapes and sizes. It is difficult to place all sensors under one definition, but if we try it would be something like: "A device that receives and responds to a signal or stimulus" [10]. From this broad definition we can infer that sensors are relevant to almost every aspect of our modern lives. From the motion sensor that opens the door at the supermarket to the sensor that detects supernovas in the most advanced astronomical telescopes, sensors are integral parts of the modern world.

In general we will be talking about sensors that react to an analog physical phenomenon by producing electrical signals that can then be processed digitally. Sensors of this sort can be passive or active, simple or complex [10]. By passive it is meant that no external power source is needed for the electrical signal to be emitted, whereas in an active sensor an external energy source is needed in order for it to work. By simple it is meant that the electrical signal is a direct outcome of the energy produced by the interaction of the stimulus and the device. In complex devices the energy must undergo various transformations through transducers until it produces an electrical signal.

For over thirty years, numerous principles of distributed fiber optic sensors have opened the door for cost-effective sensing schemes that can be embedded into working components. The oldest systems were of OTDRs (Optical Time Domain Reflectometers), which measure optical Rayleigh backscatter and could indicate lossy connectors and defects along a fiber. Other widely observed quantities of
interest are temperature and mechanical strain. Measurement of both is commercially available, ranging from systems with sub-mm resolution along hundreds of meters [11] to systems that cover 100 km with meter-scale resolution [12]. Acquisition times were reduced to the extent that measurements may be taken hundreds of times per second, providing distributed acoustic sensing (DAS)[13]. On-going research efforts continue to increase the measurement range [14,15], reduce acquisition times, and improve sensitivity [16] and spatial resolution [14,15,17].

Optical Fiber Sensors rely on the fact that the optical and / or mechanical properties of the fiber waveguide are sensitive to environmental factors. There are a number of different parameters that can affect different optical properties, and each forms the basis of a unique sensing system. Such systems fall under the 'complex' category of sensors since a photo-detector is needed to translate the optical signal into an electrical signal which in turn has to be interpreted in order to understand what the environmental conditions were that caused the light to behave in such a manner. In this research we will be focusing on a method of sensing in optical fibers that utilizes the Brillouin scattering interaction in order to read temperature and strain along the fiber.

1.2.2 TYPES OF DISTRIBUTED FIBER SENSORS:

Four main types of distributed fiber sensors are available for research and applications [3]. They are based on Rayleigh back-scatter, stimulated Raman scattering, stimulated Brillouin scattering (see **figure 1**), and fiber Bragg gratings. The first three are 'truly distributed' whereas the fourth is discrete in nature but is
often called 'quasi-distributed'. The physical properties that are measured by these sensors are mostly strain, temperature, and acoustic waves. The focus of this work is Brillouin scattering sensors, therefore in the next few sections I only briefly review the other three sensing methods and relate to their merits and drawbacks. I hope this overview would provide an uninitiated reader with a basic idea as to when and where the different methods could be useful. The discussion emphasizes high-resolution implementations, where relevant, since this research addresses such a setup. In the subsequent section I proceed to an in-depth review of Brillouin scattering based sensor techniques.

![Figure 1: Spectrum of Rayleigh, Brillouin and Raman scattering (from [18])]()
proportional to that of the incident light. Rayleigh scattering sets the limit to linear losses of telecommunication silica fibers at 1550 nm wavelength, at about 0.2 dB/km. This value hasn’t improved much since 1979.

![Figure 2: illustration of Rayleigh scattering [1]](image)

The density fluctuations of the fiber medium are analogous to the refractive index changes that are induced in fiber Bragg gratings. While index perturbations of a Bragg grating are periodic and induced intentionally, those responsible for Rayleigh scattering are a random by-product of the making of glass. Nevertheless, the non-orderly perturbations give rise to a local reflectivity pattern that has a distinct spectral dependence, even if one cannot usually predict it in advance. Much like with Bragg gratings, the application of strain or temperature change stretches the spatial pattern of index variations, leading to a spectral offset in the unique reflectivity spectrum of each fiber segment [19].

An approximate mathematical representation of the optical wave that is a result of Rayleigh scattering within a fiber is represented by the following equation [1]:

$$\Psi(z, \beta) - \Psi(0, \beta) \approx \frac{BE_0}{2i} \int_0^z \frac{\Delta n(\zeta)}{\varepsilon} e^{2i\beta \zeta} d\zeta$$

\[eq. 1.1\]

Here $\Psi(z, \beta)$ is the amplitude of the backscattering from a specific position in the fiber with a propagation constant $\beta$. $\Psi(z, \beta) - \Psi(0, \beta)$ is the increment in the
back-scattered optical field due to Rayleigh backscatter along a segment of length $z$, $\beta = \omega \sqrt{\mu_0 \epsilon}$ is the propagation constant of the mode in the fiber at a specific frequency $\omega$, and $\Delta \epsilon$ represents the variations in local dielectric constant that accompany the density fluctuations. It is apparent that the Rayleigh scattering is related to the Fourier transform of the density fluctuations in the medium. In an OFDR (optical frequency domain reflectometer), a Rayleigh scattering-based sensor (see figure 3) coherently measures the amplitude and phase of the reflected field over a broad range of frequencies, and then performs the inverse Fourier transform to recover the local map of density variations.

![Figure 3: Illustration of the principle of operation of an OFDR](image)

The spatial resolution in measurements of local density perturbations is determined by the range of the wavelength sweep, where a 90 nm-wide range translates into a 10 micron spatial resolution [20]. The resolution of commercial systems is in the millimeter scale [20].
OFDR sensors provide the highest spatial resolution of all distributed fiber sensors that are commercially available. However, there are several drawbacks associated with their employment. First and foremost, the reconstructed spatial pattern of density perturbations must be compared with a reference pattern of the specific fiber, taken at strain-free conditions and at a known temperature, in order to recover strain or temperature variations. Such a reference is not always available. In particular, the initial placement of the test fiber within a structure to be tested might introduce initial strain that would not be detected in subsequent measurements. Second, the reflectivity of Rayleigh back-scatter from short fiber segments is extremely weak: on the order of -100 dB for a millimeter of standard fiber. The acquisition of such weak reflected waveforms in the presence of noise is challenging. Last, coherent detection of the phase of reflected waveform is limited to measurement ranges that are shorter than the coherence length of the optical source. Despite these difficulties, Rayleigh back-scatter based distributed fiber sensing is an emerging research field, one that is also widely acknowledged and embraced by industry.

In OTDR there is no frequency sweep, rather a short pulse of light is sent through a fiber and the reflected light from Rayleigh scattering is measured. This method has a resolution determined by the length of the pulse and can detect losses and refractive index changes. OTDR systems with comparatively low resolution on the order of 1 m are widely employed by telecommunication service providers, for maintenance and fault location. By using elaborate detection and pulsing schemes high resolutions of 1 cm have been reported, however, the complexity of such high-resolution setups is inhibiting [21].
Raman scattering stems from the interaction of light with molecules that are excited to different vibrational energy levels [1,18]. The interaction involves the absorption of an incident photon, and could lead to two potential outcomes: the emission of a lower-energy ('Stokes') photon with the excitation of the molecule to a higher vibrational level, or the emission of a higher-energy ('anti-Stokes') photon alongside the decay of the molecule to a lower level [1,18]. The emitted waves can be shifted in wavelength by as much as 200 nm from the original incident light wavelength (as shown in figure 1).

Figure 4: Illustration of Raman (stokes and anti-stokes) and Rayleigh scattering (from [22])

The ratio between the intensities of Stokes and anti-Stokes waves in Raman scattering is given by:

$$\frac{I_{AS}}{I_S} = \left( \frac{\lambda_S}{\lambda_{AS}} \right)^4 \exp\left( -\frac{h\omega_M}{k_B T} \right)$$ \hspace{1cm} \text{eq. 1.2}$$

Here, $I_{S,AS}$ are the intensities of the Stokes and anti-Stokes waves, respectively, $\lambda_S$ and $\lambda_{AS}$ denote the Stokes and anti-Stokes wavelengths, respectively. $h = h / 2\pi$ where $h$ is the Planck constant. $k_B$ is the Boltzmann constant, and $\omega_M$ is the
frequency of the quantum mechanical oscillator describing the molecule. Most importantly for our purpose, $T$ denotes temperature. Temperature can therefore be extracted from measurement of this ratio. In advanced setups a resolution of 24 cm has been achieved with a maximum range of 135m [1,23]. In other techniques, where dispersion compensation and wavelength dependent attenuation have been taken into account, ranges of up to 40 km have been reached, albeit with a sensitivity of 5 degrees over 17 meters [1,24]. Unlike Rayleigh scattering or Brillouin scattering sensors, Raman-scattering based sensors provide unambiguous temperature measurements that are unaffected by strain. The main drawback of the method is the extremely weak scattering. Also, the large difference in wavelengths between Stokes and anti-Stokes waves requires careful considerations of chromatic dispersion and wavelength-dependent losses.

### 1.2.2.3 SENSORS BASED ON FIBER BRAGG GRATINGS:

Bragg gratings are periodic refractive index perturbations that can be written into the cores of standard fibers with UV illumination. The periodicity of the grating determines the central wavelength that will be reflected [3]:

$$\lambda_B = 2n_{\text{eff}} \Lambda$$

**eq. 1.3**

Here $\lambda_B$ is the wavelength of peak reflectivity, $\Lambda$ is the period of the grating and $n_{\text{eff}}$ is the effective refractive index of the fiber mode. The relation defines what is known as the Bragg wavelength [25]. The reflectivity is governed by the length of the grating and the magnitude of index variations.
Figure 5: Illustration of spectral transmission and reflection from cascaded fiber Bragg gratings (from [13])

Strain or temperature applied to the fiber stretches or squeezes the grating, modifying the Bragg condition accordingly. Measurements of the wavelength of peak reflectivity therefore provide a very sensitive reading, with a wavelength shift of about 1.2 $\text{pm/}\mu\text{e}$ at 1550 nm wavelength [25]. An analogous modification of the Bragg condition occurs subject to temperature variations due to the thermo-optic effect, resulting in 10 $\text{pm/}^\circ\text{C}$ sensitivity for temperature at 1550 nm wavelength [25].

Fiber Bragg gratings are point sensors. However, by imprinting gratings of different periods in different locations along a fiber, and using a wideband light source, strain and temperature may be interrogated at numerous points. NASA has patented a system with hundreds of gratings multiplexed along a single fiber [26]. The main drawbacks of the method are that: a) it is not truly continuous; b) it requires intervention in the form of grating inscription, and the inscription often involves the removal of the fiber polymer coating, leaving the fibers mechanically weaker; and c) in order to resolve small changes in strain or temperature, sensitive
spectrum analyzers and/or tunable lasers are needed. Nevertheless, fiber Bragg gratings are simple and reliable, and have been widely deployed for decades. In addition, shift in Bragg reflectivity often serves as an indirect measure of a different physical quantity [26,27] which causes strain or index variations, such as electrical or magnetic fields, presence of chemical and biological species of interest, etc.

1.2.2.4 DISTRIBUTED ACOUSTIC SENSING

Other systems that use FBG’s, Brillouin and Rayleigh backscatter are distributed Acoustic Sensing (or DAS) systems. When using Rayleigh backscatter, DAS would be similar to classic OTDR in that it measures the back reflectance of an optical pulse sent through a fiber. However, in DAS the pulse has a very high repetition rate, which is only limited by the two-way time-of-flight along the fiber. The high repetition rate allows for detection of changes to the refractive index induced by the absorption of acoustic waves by the fiber. Currently 50 km fibers can be scanned at up to 2000 KHz rates [28], where every 10-meter segment of the fiber (as determined by the length of the optical pulse) becomes a microphone. With enough digital signal processing at the output, the DAS system can learn to identify different sounds and their sources. The primary difficulty of this method are the very low powers that need to be detected and the huge amount of data that has to be processed in real time at very high rates.

DAS can also be implemented using Brillouin scattering and FBGs. In Brillouin scattering-based systems, KHz-rate detection was reported over hundreds of meters [29]. FBGs are used in underwater acoustic sensing and in ultrasonic
structural monitoring [28]. More emphasis is placed on high repetition rates of DAS systems than on high spatial resolution.

1.3 SUMMARY:

In this chapter I have discussed the motivation behind distributed fiber sensors and described some of the main methods that are used. Each of the methods described has its' advantages and drawbacks. In the next chapter I give an in-depth review of stimulated Brillouin scattering-based distributed sensors: their underlying physics and engineering of their implementations. I elaborate specifically on the resolution limitations of Brillouin sensors. In this research I demonstrate a technique that provides a new way of reaching high resolutions with Brillouin based systems.
2 STIMULATED BRILLOUIN SCATTERING (SBS) DISTRIBUTED SENSORS

2.1 INTRODUCTION:
In this section I provide an in depth explanation of the physical mechanisms of stimulated Brillouin scattering (SBS), and methods used in distributed fiber sensors that are based on the effect. First, the coupled wave equations that govern the effect are introduced. Next, the two main configurations used in SBS-based sensing, the Brillouin optical time-domain analysis (B-OTDA) and the Brillouin optical correlation-domain analysis (B-OCDA), are described. The main advantages and drawbacks of both techniques will be pointed out, with emphasis on spatial resolution. The discussion provides sufficient background for the subsequent introduction of a new B-OCDA configuration used in this research.

2.2 STIMULATED BRILLOUIN SCATTERING:
Stimulated Brillouin scattering (SBS) in optical fibers is a nonlinear interaction between a relatively intense pump wave and a weaker, counter-propagating probe (or signal) wave, which are coupled by a stimulated acoustic field [18]. The term 'stimulated' implies that the interaction is not determined by pre-existing conditions of the medium, but rather the medium itself is being modified by the combination of the two light waves that are propagating through it. The stimulated acoustic field itself actually enhances the interaction between the two optical waves, thus initiating a positive feedback process as shown in figure 6. The mechanisms underlying the positive feedback are discussed in detail below.
Effective coupling between the two optical waves requires that the difference between the optical frequencies matches the Brillouin frequency shift of the fiber, \( \nu_s \sim 10-11 \text{ GHz} \) (at standard single mode fibers and at 1550 nm wavelength). Precise frequency matching is necessary, as the linewidth of the process for continuous pump waves is only about 30 MHz. The exact value of the Brillouin shift is primarily a property of the fiber medium, however it changes with both strain and temperature, as discussed in detail later. Monitoring the variation in the local values of the Brillouin frequency shift forms the basis of SBS-based distributed fiber sensors.

2.2.1 PHYSICAL MECHANISMS:

Two physical mechanisms enable the coupling between the pump and probe waves. The first is electrostriction: the tendency of materials to become compressed in the presence of high electro-magnetic intensity [18]. The second is the acousto-optic effect (a subcategory of photo-elasticity): in this effect the
refractive index of a medium is changed due to density variations caused by a pressure wave. The acoustic wave therefore induces a periodic disturbance in the index of refraction, hence an effective grating is generated in the medium. The stimulated grating causes scattering of light in a manner that is similar to a Bragg grating.

In SBS, the combined intensity of the two counter-propagating waves builds up a beating pattern in the medium that generates, through electrostriction, an acoustic density wave. The frequency of this acoustic wave equals the difference between the optical frequencies of the pump and probe wave. Through photo-elasticity, the acoustic wave generates a travelling refractive index grating. When the light waves interact with the refractive index grating, that they themselves generated, scattering occurs. Because of the nature of the grating there is direct coupling between the amplitudes of the light waves and the acoustic wave.

Due to conservation of momentum, the pump wave is back-scattered in the opposite propagation direction, namely in the propagation direction of the probe. The frequency of the scattered pump wave is downshifted by the frequency of the traveling acoustic wave because of the Doppler Effect, and thus matches the frequency of the probe. When proper conditions are met, as discussed below, an exponential amplification of the probe wave may take place.

The generation of the acoustic wave is most efficient when its frequency, or the difference between optical frequencies of pump and probe, matches the following value [18]:


$$\Omega_{\text{acoustic}} = \Omega_B = \frac{2 \omega_{\text{pump}} n}{c} v_{\text{sound}} \quad \text{eq. 2.1}$$

Where $n$ is the refractive index, $c$ is the speed of light in vacuum, $v_{\text{sound}}$ denotes the speed of sound, and we have approximated that the wave numbers of pump and signal as equal: $k_{\text{pump}} \approx k_{\text{signal}}$. This value is known as the Brillouin shift $\Omega_B$. It is dependent on the temperature and the strain according to the following relations [30]:

$$\Omega_B(\varepsilon) = \Omega_B(0) \left[ 1 + C_i \varepsilon \right] \quad \text{eq. 2.2}$$

$$\Omega_B(T) = \Omega_B(T_r) \left[ 1 + C_i (T - T_r) \right] \quad \text{eq. 2.3}$$

Where $\varepsilon$ is strain, $C_i$ equals approximately $4.6 \left[ \text{e}^{-1} \right]$ in regular SMF fibers. $T_r$ is a reference temperature, and $C_i$ is approximately $9.4 \times 10^{-5} \left[ K^{-1} \right]$.

2.2.1 COUPLED WAVE EQUATIONS:

We present here the mathematical basis for stimulated Brillouin scattering. The SBS process may be described as an interaction between two counter propagating light waves and the acoustic wave that is generated by the beating of the two waves. Scattering in this manner is strongly dependent on a number of parameters that are not only determined by the medium but also by the pump and probe waves – parameters which we can manipulate. The mathematical description of this positive feedback process is through three coupled equations, representing the amplitude of the pump, probe and acoustic wave respectively.

Let $E_1$ and $E_2$ denote the optical fields of the pump and probe waves, respectively [18]:
\[ E_1(z, t) = A_1(z, t)e^{i(k_1z-\omega_1t)} + c.c \quad \text{eq. 2.4} \]
\[ E_2(z, t) = A_2(z, t)e^{i(-k_2z-\omega_2t)} + c.c \quad \text{eq. 2.5} \]

Here \( k_{1,2} = 2\pi n/\lambda_{1,2} \) where \( n \) is the refractive index of the medium and \( \lambda_{1,2} \) are the vacuum wavelengths. \( A_{1,2} \) are the complex envelopes of the pump and probe. The overall optical field is then:

\[ E(z, t) = E_1(z, t) + E_2(z, t) \quad \text{eq. 2.6} \]

The acoustic field is expressed in terms of the material density:

\[ \tilde{\rho}(z, t) = \rho_0 + [\rho(z, t)e^{i(q\cdot z-\Omega t)} + c.c] \quad \text{eq. 2.7} \]

where \( \rho_0 \) is the mean density of the medium and \( \rho \) is the amplitude of density change. The frequency of the acoustic field is noted as \( \Omega = \omega_1 - \omega_2 \). Its wave-number can be approximated as \( q = k_1 + k_2 \approx 2k_1 \), since the acoustic wave is the result of the beating of the two counter-propagating light waves and must conserve momentum.

The acoustic wave obeys the acoustic wave equation:

\[ \frac{\partial^2 \tilde{\rho}}{\partial t^2} - \Gamma \nabla^2 \frac{\partial \tilde{\rho}}{\partial t} - \nu^2 \nabla^2 \tilde{\rho} = \nabla \cdot \mathbf{f} \quad \text{eq. 2.8} \]

Here \( \nu \) is the velocity of sound in the medium, and \( \Gamma \) is the acoustic damping parameter which is a function of the thermal conductivity, shear viscosity and bulk viscosity of the medium\(^2\). \( \mathbf{f} \) is the force per unit volume which represents electrostriction: the effect of electromagnetic intensity on density changes. The force term

\(^2\)Shear viscosity is a measure of the resistance of the material of the medium to flow and bulk viscosity is a measure of the resistance to compression and expansion.
can be expressed as a gradient of a pressure difference: \( f = \nabla p_m \). The pressure difference, in turn, is proportional to the overall optical intensity, averaged over many periods of optical-frequency oscillations:

\[
p_m = -\gamma_e \langle E^2 \rangle / 8\pi
\]

The expression includes the electro-strictive parameter \( \gamma_e \) and the time averaged squared electric field. The driving term at the right-hand side of the acoustic wave equation therefore includes a beating component, which scales with the inner product of the two optical waves and oscillates at the difference between their frequencies:

\[
\nabla \cdot f = \frac{\gamma_e Q^2}{4\pi} \left[ A_1 A_2^* e^{i(\omega - \Omega t)} + c.c. \right]
\]

Using the slowly varying envelope approximation\(^3\), the acoustic wave equation can be simplified:

\[
-2i\Omega \frac{\partial \rho}{\partial t} + \left( \Omega_B^2 - \Omega^2 - i\Omega \Gamma_B \right) \rho - 2iQ\nu^2 \frac{\partial \rho}{\partial z} = \frac{\gamma_e Q^2}{4\pi} A_1 A_2^*
\]

Where \( \Gamma_B = Q^2 \Gamma \) is the Brillouin linewidth, and \( \Omega_B = |Q|\nu \) is the Brillouin frequency shift in the medium. In many cases the discussion is restricted to steady-state conditions, in which \( \frac{\partial \rho}{\partial t} \) vanishes. Finally, the last element in the left hand side may often be omitted since it relates to the propagation of the acoustic wave, which decays after tens of microns. This last approximation suggests that the

---

\(^3\) Where we assume that the second derivative is negligible in equation 2.8, see [18]
acoustic field at a given location is only affected by the optical fields at that point.

We therefore obtain:

\[
\rho(z,t) = \frac{i \gamma q^2 A_i A_i^*}{4\pi} \frac{\Delta \Omega_\rho}{\Omega_b^2 - \Omega^2 - i\Omega \Gamma_b}
\]

In several scenarios that are relevant to this work, we must consider stimulated acoustic fields that are not at the steady state. In these cases the temporal derivative of the magnitude of density fluctuations is retained:

\[
\frac{\partial \rho}{\partial t} + i \frac{\Omega_b^2 - \Omega^2 - i\Omega \Gamma_b}{2\Omega} \rho = i \frac{\gamma q^2}{8\Omega \pi} A_i A_i^*
\]

We now turn to the two nonlinear wave equations describing the evolution of the counter-propagating pump and probe light waves [18]:

\[
\frac{\partial^2 E_i}{\partial z^2} - \frac{1}{(c/n)^2} \frac{\partial^2 E_i}{\partial t^2} = \frac{4\pi}{c^2} \frac{\partial^2 P_i}{\partial t^2} \quad i = 1,2
\]

Here \( P_i \) denote nonlinear polarization terms which propagate with the frequencies \( \omega_{i,2} \) and wave-numbers \( k_{i,2} \) of the optical fields \( E_{i,2} \), respectively. The nonlinear polarization represents the additive electrical susceptibility that stems from density variations (photo-elastic effect). It can be expressed in the form\(^4\) [18]:

\[
P = \Delta \chi E = \frac{\Delta \varepsilon}{4\pi} E = \frac{1}{4\pi \rho_0} \gamma \rho E
\]

The above expression includes numerous terms, among which the term \( P_i \) defined above may be identified:

\[^4\] It is assumed that \( \Delta \varepsilon \), the dielectric constant fluctuations, scales linearly with the density change \( \rho \).
\[ P_1 = p_1 e^{i(kz - \omega_1 t)} + c.c \]  
\[ P_2 = p_2 e^{i(kz - \omega_2 t)} + c.c \]

The magnitudes of the two nonlinear polarization terms are identified as:

\[ p_1 = \frac{\gamma_e}{4 \pi \rho_0} \rho A_2 \quad \text{and} \quad p_2 = \frac{\gamma_e}{4 \pi \rho_0} \rho^* A_1. \]

Substituting the nonlinear polarization into the pair of nonlinear wave equations, and invoking the slowly varying envelope approximation yet again, we obtain two coupled equations for the complex envelopes of the pump and probe waves at the steady state:

\[ \frac{\partial A_z}{\partial z} = \frac{i \omega q^2 \gamma_e^2}{8 \pi n c \rho_0} \left| A_2 \right|^2 A_1 \]
\[ \frac{\partial A_z^*}{\partial z} = -\frac{i \omega q^2 \gamma_e^2}{8 \pi n c \rho_0} \left| A_1 \right|^2 A_2 \]

Where we have assumed that \( \omega_1 \approx \omega_2 = \omega \).

The two equations can be recast in terms of the evolution of intensities of the two waves:

\[ I_{1,2} = 2 n e_0 c \left| A_{1,2} \right|^2 : \]

\[ \frac{\partial I_1}{\partial z} = -g I_2 I_1 \]
\[ \frac{\partial I_2}{\partial z} = -g I_1 I_2 \]

\[ \frac{\partial I}{\partial z} \approx \frac{\partial (A A^*)}{\partial z} = A^* \frac{\partial A}{\partial z} + A \frac{\partial A^*}{\partial z} = AB + A^* B \]

---

\( ^5 \) The crossover is facilitated by the fact that if \( \frac{\partial A}{\partial z} = B \Rightarrow \frac{\partial A^*}{\partial z} = B^* \) then
In these equations we have condensed the various constants into $g$: the SBS 'gain coefficient'. Its spectral profile is well approximated by a Lorenzian fit:

$$
g = g_0 \left( \frac{\Gamma_B/2}{\Omega_B - \Omega} \right)^2 - \left( \frac{\Gamma_B/2}{\Omega_B - \Omega} \right)^2 \tag{eq. 2.22}$$

$$
g_0 = \frac{\gamma_c \omega^2}{nc^3 \rho_0 \Gamma_B} \tag{eq. 2.23}$$

Where $g_0$ is called the 'line center gain factor'. The spectral width of the gain is determined by the Brillouin linewidth $\Gamma_B$ (see equation 2.11). The linewidth, in turn, is determined by the relatively long phonon lifetime, and is therefore narrow: on the order of 30 MHz.

We are now in the position to make another assumption which further simplifies the solution. Since the pump is much stronger than the probe wave, we can usually assume that the transfer of power between the two waves would have a negligible effect on the pump magnitude. Under these conditions, which are referred to as the 'undepleted pump' regime, the intensity of the pump is regarded as constant and equation 2.20 is ignored. We are then left with equation 2.21 where $I_p$ is a parameter. The solution to 2.21 is now simple:

$$
I_z(L) = I_z(L) \exp \left( gI_z(L-z) \right) \tag{eq. 2.24}
$$

Using this equation it is relatively easy to determine the probe wave intensity throughout the interaction. For very short interaction lengths the gain experienced by the probe wave can be approximated as linear. However, for longer interaction lengths the gain becomes exponential.
Let us now return to the acoustic field equation that is not at steady state. For
brevity we will define $\Gamma_A = \frac{i \Omega^2_b - \Omega^2 - i \Omega \Gamma_b}{2 \Omega}$ and $g_1 = \frac{\gamma \gamma' q^2}{8 \Omega \pi}$. Here both pump and probe waves are regarded as undepleted. Integration over equation 2.11 yields$^\text{6}$ [31]:

$$\rho(z, t) = ig_1 \exp(-\Gamma_A t) \int \exp(\Gamma_A t') A_i \left( t' - \frac{z}{v_g} \right) A_i^* \left( t' - \frac{L-z}{v_g} \right) dt'$$

$$= ig_1 \int \exp[-\Gamma_A (t-t')] A_i \left( t - \frac{z}{v_g} \right) A_i^* \left( t - \frac{L-z}{v_g} \right) dt'$$

$$= ig_1 \int \exp[-\Gamma_A (t-t')] A_i \left( t - \frac{z}{v_g} \right) A_i^* \left( t - \frac{z}{v_g} + \theta(z) \right) dt'$$

Here $v_g$ is the group velocity of light in the fiber, and $\theta(z) = (2z-L)/v_g$ is a position-dependent temporal lag between the pump and probe waves at point $z$.

The amplitude of the acoustic wave is seen to be closely related to the cross
correlation of the pump and probe waves envelopes, weighted over an exponential
window [31]. This observation establishes the underlying principle of B-OCDA. I
will return to this result in the discussion of various B-OCDA configurations,
including the one that is the subject of this research. While in most B-OTDA
configurations the three waves might be considered at a steady state, there are a
number of B-OTDA techniques in which this is not the case, (i.e for extremely short
pulses). When solving the coupled equations for these techniques new solutions
must be found for the time dependent three-way interaction [32].

$^6$ The differential equation is solved using the Integrating Factor Method where the factor is chosen to be $\exp(\int \Gamma_A t dt)$. 

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To summarize, I list below the assumptions that have been made in reaching the above forms of solutions to the optical and acoustic waves subject to SBS interactions:

1) We have used the 'slowly varying approximation', where it is assumed that the change in the amplitude of the complex envelope of the light or sound wave is small in relation to the wavelength-scale oscillations, and therefore the second spatial derivatives of the complex envelope may be omitted.

2) We have related to the acoustic wave as non-propagating in the fiber medium, in contrast to the light waves, due to its fast dampening and its relatively slow propagation speed with respect to the speed of light. Under this assumption we were able to omit spatial derivatives of the acoustic wave.

3) Initially we assumed a steady state solution and eliminated all the temporal derivatives of the complex envelopes of the three waves accordingly. We later formulated a solution to the local magnitude of the acoustic field that is not at a steady state.

4) We neglected spontaneous Brillouin scattering, a reasonable assumption for short fibers.

5) The pump wave was considered to be undepleted, for both steady-state and non-steady-state solutions.

6) In the solution for the time-dependent local magnitude of the acoustic wave, the probe was considered to be undepleted as well. This is a valid assumption for relatively weak SBS interactions over short segments of fibers, such as the ones used in this research.
2.3 SBS LOCALIZATION:

2.3.1 SBS SENSITIVITY TO TEMPERATURE AND STRAIN:

As discussed earlier with respect to equations 2.2 and 2.3, both temperature and strain modify the value of the Brillouin frequency shift:

\[ \Delta v_B = C_T \Delta T + C_s \Delta \varepsilon \]  

\text{eq. 2.26}

Where \( C_T \) equals 1.26 MHz/°C and \( C_s \) equals 0.056 MHz/µε for a standard SMF fiber. A possible ambiguity between temperature and strain is apparent; however it can be overcome in a number of ways, and may even be taken advantage of by measuring both properties simultaneously [33]. In this research we will focus on temperature measurements under a constant strain regime.

By localizing the SBS interaction to a specific position along a fiber, it is possible to determine the above parameters at that location. SBS based distributed sensors work by resolving localized SBS along the entire length of a fiber. There are two main techniques used to localize SBS, and they will now be described.

2.3.2 BRILLOUIN OPTICAL TIME DOMAIN ANALYSIS (B-OTDA):

In this section I introduce the first and most widely employed SBS-based sensing technique [1, 34]. Horiguchi and coworkers first described B-OTDA 24 years ago [35], when they reported a system with 100 m resolution. Nowadays the industry standard is a spatial resolution on the order of 1 m, with 50 km range. Significantly better resolutions have been reported in research literature [1].
2.3.2.1 B-OTDA PRINCIPLE OF OPERATION:
In B-OTDA intense pump pulses are used to amplify a continuous-wave signal, and the power of the output signal wave is monitored as a function of time. SBS occurs only where and when the propagating pump pulse exists. By confining the SBS process to the pulse duration, the time dependent gain becomes a function of the SBS initiated by the pulse at different points along the fiber. Spatial distinction is achieved through temporal analysis.

![Image](image_url)

Figure 7: Illustration of the localization of SBS interactions in B-OTDA

2.3.2.2 RESOLUTION LIMITS:
In figure 8, it is indicated that the resolution of the fundamental B-OTDA scheme is restricted to an upper limit of about 1 meter, which corresponds to pulse duration on the order of the acoustic lifetime \( \tau = 1/\Gamma_B \approx 5 \text{ ns} \) [6]. Two main reasons have been given for this limitation. First, for shorter pulses the SBS gain becomes weaker and difficult to detect, since the acoustic wave does not have enough time to build up sufficiently to contribute to the SBS process. Second, the SBS gain
coefficient, $g_B(\nu)$, is determined by a convolution between the power spectral density of the pump pulses and the inherent 30 MHz-wide Brillouin line-shape [36,37]. When the pulse bandwidth is wide (= short pulse), the gain spreads over a broad spectrum, and the specific value of the Brillouin shift becomes more difficult to recover. The sensitivity of B-OTDA is therefore much degraded [35].

Figure 8: Effective Brillouin gain spectrum for different pulse lengths (from [36]). Below a 1 m-long interaction length, the spectrum is spread and the Brillouin shift is difficult to determine. Therefore changes in temperature and strain become harder to recognize.

2.3.2.3 STATE OF THE ART HIGH RESOLUTION B-OTDA

Advanced methods of B-OTDA using complex pulse schemes have managed to overcome the 1 meter limitation ([1] and references therein, [14]). One of these schemes relies on ‘pre-excitation’ [32]: by first pumping the medium with a long pulse or a continuous wave of relatively modest intensity, an acoustic wave is generated over a long segment of the fiber. When firing a subsequent, strong pulse
whose spatial extent is much shorter than a meter, there is no longer a problem of acoustic wave buildup time, and gain can be measured with higher resolutions.

Figure 9: Illustration of a complex pulse scheme with three sections alpha, beta and gamma. By manipulating their values gain and resolution can be optimized [from 32].

Bao and associates have reported a resolution of 2 cm over 2 km of fiber [14], using a technique called Differential Pulse-width Pair B-OTDA, or DPP-B-OTDA. In DPP-B-OTDA two pulses of different width are sent through a fiber, in two separate and successive experiments. The detected output signal from the pulses is then subtracted one from the other. The gain difference between the pulses is an indicator of the gain over a length that is equivalent to the pulse difference. For two pulses, one of 8 ns duration and the other of 8.2 ns duration, a resolution of 2 cm was achieved. The longer the overall length of the pulses the worse the signal-
to-noise ratio (SNR), but if the pulses are too short resolution is compromised like in a regular B-OTDA. Therefore a tradeoff exists between these two factors in the DPP technique.

![Image of time traces](Figure 11: Time traces of the Brillouin gain signal near the beginning of the fiber, in a differential pulse-width pair B-OTDA (from [14]))

2.3.3 BRILLOUIN OPTICAL CORRELATION DOMAIN ANALYSIS (B-OCDA):

Hotate and coworkers [38] first proposed the B-OCDA technique 15 years ago. It provides extremely high spatial resolution, of up to 1.6 mm [15]. Numerous variants of B-OCDA are reported in the literature, all sharing a common underlying principle which is described below (a review may be found in [39]). The technique reported in this work is a form of B-OCDA.

2.3.3.1 PRINCIPLE OF OPERATION:

At the end of section 2.2.1 we pointed out that the amplitude of the acoustic wave, at non-steady-state conditions, is related to the cross correlation between the complex envelopes of the pump and probe waves, integrated over an exponential
window. Using this property, B-OCDA effectively confines the SBS interaction to specific, narrow points of interest along the fiber by manipulating the correlation characteristics between the pump and probe. There are two basic approaches towards this objective.

2.3.3.2 PUMP-PROBE FREQUENCY/PHASE MODULATION METHOD:

Hotate [38] has developed a method where the pump and Brillouin shifted probe are frequency-modulated over a frequency range much larger than the Brillouin gain bandwidth. In this manner the pump and probe can only induce a substantial acoustic field at locations in the fiber where they are correlated, in the sense that the difference between their frequencies does not oscillate. At all other locations in the fiber, where the frequency shift between pump and probe varies on a time scale that is much faster than $\tau$, and SBS is largely inhibited. The resolution would be determined by the rate and span of frequency modulation [38]:

$$\Delta z = \frac{v_s \Gamma_B}{2\pi f_m \Delta f'}$$ \hspace{1cm} eq. 2.27

Where $\Delta z$ is the spatial resolution, $v_s$ is the group velocity of light in the medium, $\Gamma_B$ is the inherent, narrow Brillouin gain bandwidth, $f_m$ is the frequency modulation rate of the pump and probe frequencies, and $\Delta f'$ is the frequency modulation range. Another factor to be taken into account is the spatial periodicity of correlation peaks $d_m$ that will inevitably occur in this technique [38].

$$d_m = \frac{v_s}{2f_m}$$ \hspace{1cm} eq. 2.28
It is apparent that in order to get higher resolution, either \( f_m \) or \( \Delta f \) must be increased. However, by increasing \( f_m \) the correlation peaks recur at a higher periodicity and therefore the range of unambiguous measurements is reduced. Therefore, in order to achieve high resolution without compromising the measurement range, the amplitude of modulation \( \Delta f \) must be increased.

Frequency modulation may be accomplished by using external modulators at the output of laser diode sources, or by directly modulating the driving current of laser diodes. Direct modulation changes the lasing frequency through numerous chirp mechanisms. \( \Delta f \) values of tens of GHz were obtained. However, large current modulation introduces intensity variations that require proper compensation [40].

As mentioned above, by using this technique resolutions of 1.6 mm for short fiber segments were reported. By adding elaborate temporal gating schemes the range was increased to 1 km with 10000 resolution points of 7 cm each [41].

2.3.3.3 PHASE CODING METHOD

Zadok, Antman and coworkers [37] proposed a different principle of implementation of the B-OCDA method. By borrowing techniques from the world of Radar, they managed to increase the range of unambiguous measurements of previous B-OCDA schemes. The principle of operation of their technique is to encode the phase of the pump and probe by a joint binary sequence, which is designed to exhibit low correlation sidelobes.
Figure 12: By coding the phases of the pump and probe the acoustic field develops only where the phases of the two counter propagating sequences are correlated. The width of the SBS interaction region equals the spatial extent of a single bit. By using advanced sequences, noise due to correlation sidelobes can be minimized. (From [37]).

In this manner the resolution of the sensor is determined by the length of an individual bit in the coded sequence. The correlation length $\Delta z$ is on the order of [31,27]:

$$\Delta z = \frac{1}{2} v_s T$$  \hspace{1cm} \text{eq. 2.29}

Where $v_s$ is the group velocity of light in the fiber, and $T$ is the duration of an individual bit. For example, in using symbol duration of 200 ps, a resolution of 2 cm was achieved.

2.3.3.4 SWEEPING OF CORRELATION PEAK LOCATION WITH MODULATION FREQUENCY/BIT DURATION

The correlation point between the phase-modulated pump and probe is located at a specific position along the fiber. It can be moved, however, in a convenient
manner. The procedure for doing this is as follows: by using a periodic sequence of length \( N \) bits, multiple correlation peaks are introduced along the fiber. The zero-order correlation peak is located at an equal distance between the points of entry of the two waves. Multiple, additional correlation peaks appear with a periodic spacing of \( Z \equiv N \cdot \Delta z = \frac{1}{2} N \cdot v_g T \). The peak of order \( m \) appears \( m \cdot Z \) meters before or after the zero-order peak, with \( m \) a positive or negative integer. Therefore, small-scale changes to the symbol duration \( T \) effectively move the positions of all peaks, except for the zero-order one, along the fiber under test. Phase-coded B-OCDA setups include a deliberate delay imbalance between the paths that lead the SBS pump and probe into the fiber under test. The delay imbalance guarantees that high-order correlation peaks are in overlap with the measurement region. The sweeping method is illustrated in figure 13.

The decoupling of resolution and periodicity represents an important advantage over the frequency-modulation technique. The periodicity is determined only by the length of the entire phase sequence, whereas the resolution is determined by the duration of an individual bit. In frequency modulation B-OCDA, one metric is improved at the expense of the other. Phase-coding B-OCDA can introduce a single correlation peak along an arbitrarily long fiber under test.
Figure 13: Illustration of scanning the location of correlation peaks in phase-coded B-OCDA. The upper half of the figure shows the two counter-propagating pump and probe at a given point in time. They are made up of a repetitive 5 bit sequence of red, green and black with a silent bit in between each colored one. Eight correlation points are visible (points where the pump and probe are the same color green) in the bottom half are the same pump and probe whose base 5 bit sequence has been lengthened by increasing the individual bit duration slightly. All correlation points, other than the zero order one, are offset from their original positions.

2.3.3.5 HYBRID-B-OTDA/B-OCDA

In both B-OCDA techniques described above, unambiguous measurements require that a single correlation peak is established along the fiber under test. This can be accomplished with a very long phase code sequence, or by low frequency modulation rates and high frequency amplitude. In both cases, positional scanning is very time consuming, and becomes impractical when dealing with many thousands of measurement points.

In order to solve this problem, Elooz and coauthors [17] developed a new, hybrid B-OCDA-OTDA technique. As in phase-coded B-OCDA, both pump and probe are
jointly modulated by a high-rate phase sequence, which introduces narrow correlation peaks. The sequence is deliberately chosen to be short, so that hundreds of correlation peaks are established. In addition, the amplitude of the pump wave is also modulated by a single pulse whose duration is on the order of the phase code periodicity. The amplitude modulation guarantees that the different correlation peaks are formed at different times [17]. SBS amplifications which take place at individual peaks can be resolved by temporal analysis of the output signal, much like in a B-OTDA. Using this technique, Brillouin gain spectra were acquired over a 1600 meters-long, with 2 cm resolution [42].

2.4 SUMMARY:

I have shown in this chapter how from the physical phenomenon of Brillouin scattering, a distributed sensor system can be made. I have described the different techniques used to localize SBS, and elaborated on the state-of-the-art, high-resolution implementations. In the next section the new technique that was developed in this research will be introduced.
Optical amplifiers are based on the principle of stimulated emission in a gain medium with an energy bandgap that corresponds to a desired optical frequency $E_{\text{gap}} = \hbar \omega$ [43]. The electrons of the gain medium are excited to their higher energy states by either optical or electrical pumping. The optical signal that is to be amplified is then propagated through the gain medium. The interaction between an incident photon and an excited electron results in the stimulated emission of a second photon, of equal frequency and phase.

However, not all electrons experience stimulated emission and some decay in energy level spontaneously. Some of the spontaneous decay transitions are radiative, and lead to the emission of light over the entire spectral extent of gain in the medium. This so-called spontaneous emission is not related to the propagating signal in phase or frequency. The photons emitted through spontaneous emission are themselves amplified while traveling through the gain medium (in the same manner as the input signal). The resultant optical waveform at the output of the gain medium is therefore referred to as Amplified Spontaneous Emission, or ASE.

In various scenarios, ASE could be substantial enough to be utilized as a wideband source spanning the entire gain spectrum of the medium.

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7 For deeper understanding of this essentially quantum physical process see [43]
8 There are a number of other applications where ASE is utilized. In microwave photonics it can be used to generate RF noise [45], for interferometric applications (such as optical gyroscopes) it is used to achieve high sensitivities [46]. ASE can also be used for characterization of the frequency response of systems.
3.1 ASE AS A RANDOM PROCESS:

As explained above, ASE is the result of countless independent emitters within the gain medium, which are uncorrelated with one another. This description is analogous to that of thermal emission from the Sun or from incandescent light bulbs. It follows that ASE should be statistically categorized as a random process [44]. Both the phase and amplitude of ASE are real-valued random processes that are independent from each other.

Within the context of this work, we require the mathematical representation of a single polarization component of ASE. The analytical signal and complex envelope of a single emitter among the ensemble can be expressed as follows [44]:

\[
A_i(t) = A_i(t) \exp(i2\pi \tilde{v} t)
\]

\[
A_i(t) = \alpha_i(t) \exp(i\phi_i(t))
\]

Here \(A_i\) is the phasor of the \(i\)'th emitter. The amplitude \(\alpha_i\) and phase \(\phi_i\) are assumed to be statistically independent. \(\tilde{v}\) is the central frequency of the emission. ASE is represented by a sum over all emitters:

\[
A(t) = \sum_{\text{emitters}} A_i(t) \exp(i2\pi \tilde{v} t) \sum_{\text{emitters}} A_i(t)
\]

The right hand sum in the above equation is termed a Random Phasor Sum [44]. Due to the large number of emitters, the process obeys the central limit theorem: both the real and the imaginary part of the analytic signal may be separately described by Gaussian statistics [44]. In addition, the phases of all emitters are uniformly distributed over \([-\pi, \pi]\). The complex analytic signal therefore complies with the definition of a Circular Complex Random Gaussian Process [44]. In such
processes, the means of the real and imaginary parts both equal zero: \( \bar{r} = \bar{i} = 0 \), and their variances are identical: \( \bar{r}^2 = \bar{i}^2 = \sigma^2 \). It also follows that the real and imaginary parts are uncorrelated random processes. Based on these relations we will now present the amplitude, phase and intensity statistics of the ASE analytic signal. For further in depth analysis of such processes see the classic textbook on Statistical Optics by Goodman [44].

3.2 STATISTICS OF POLARIZED ASE:

3.3.1 STATISTICS OF AMPLITUDE:

In order to find the statistics of the amplitude we start with the joint density function of the phasor amplitude and the phase. Based on the aforementioned relations between the real and imaginary parts of the analytic signal, their jointly-Gaussian density function is:

\[
p_{r,i}(r,i) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{r^2 + i^2}{2\sigma^2} \right) \tag{eq. 3.3}
\]

We next introduce a change in variables, representing \( A(t) \) in terms of amplitude and phase: \( A(t) = a(t) e^{i\theta(t)} \). With the proper conversion to polar coordinates, we get the joint density function of the amplitude and Phase [44]:

\[
p_{a,\theta}(a,\theta) = \begin{cases} 
\frac{a}{2\pi\sigma^2} \exp \left( -\frac{a^2}{2\sigma^2} \right) & -\pi < \theta \leq \pi, \quad a > 0 \\
0 & \text{otherwise}.
\end{cases} \tag{eq. 3.4}
\]
From this we can then find next the marginal probability density functions of the amplitude $a$ and then of the phase $\theta$. By integrating the expression in eq 3.4 with respect to $\theta$, we end up with the marginal density function of the amplitude $a$ [44]:

$$p_a(a) = \begin{cases} 
\frac{a}{\sigma^2} \exp\left\{ -\frac{a^2}{2\sigma^2} \right\} & a > 0 \\
0 & \text{otherwise.} 
\end{cases} \quad \text{eq. 3.5}$$

This distribution function is known as Rayleigh Distribution [44]. The mean of this distribution is $\bar{a} = \sqrt{\pi/2\sigma}$ and the variance is $\sigma_a^2 = [2 - \pi/2] \sigma^2$. Figure 14 shows the marginal probability density function of the amplitude of a simulated ASE signal, calculated based on a signal realization of the random process over 1e6 time slots. The expected theoretical curve is shown as well.

![Figure 14: Probability density function of ASE amplitude.](image-url)
3.3.2 STATISTICS OF INTENSITY:

Detected photo-currents are proportional to the intensity of optical signals $I(t)^9$, which is in turn proportional to $|A(t)|^2$ (see eq. 2.14). Using the relation, we can express the marginal probability density function of the magnitude of the ASE signal in terms of intensity, $p_I(I) = p_A(a = \sqrt{I})|\frac{da}{dt}|$ [44]:

$$p_I(I) = \begin{cases} \frac{1}{2\sigma^2} \exp\left(-\frac{I}{2\sigma^2}\right) & I \geq 0 \\ 0 & \text{otherwise.} \end{cases} \quad \text{eq. 3.6}$$

The standard deviation and mean of this distribution keep the relation $\sigma_I = I^2 = 2\sigma^2$. The expression can be simplified into:

$$p_I(I) = \begin{cases} \frac{1}{I} \exp\left(-\frac{I}{I}\right) & I \geq 0 \\ 0 & \text{otherwise.} \end{cases} \quad \text{eq. 3.7}$$

Figure 15 shows the simulated probability density function of the intensity, as calculated for a specific realization (see above), alongside the theoretical curve.

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9 Goodman [44] stresses that this is instantaneous intensity as opposed to detected intensity which is inevitably averaged over the detection integration window. We will relate to this when SNR at detection is dealt with.
By integrating eq. 3.4 with respect to the amplitude $a$, we obtain the marginal probability density function of the phase. However, equation 3.4 represents a Rayleigh density with a coefficient of $1/2\pi$. The integration over the Rayleigh distribution returns unity, hence we are left with a uniform distribution [44]:

$$ p_{\phi}(\theta) = \begin{cases} \frac{1}{2\pi} & -\pi < \theta \leq \pi \\ 0 & \text{otherwise.} \end{cases} \quad \text{eq. 3.8} $$

The corresponding simulation can be seen in figure 16.
3.3 THE PHYSICAL SOURCE OF ASE - EDFA’S:

In this work I use the ASE of an erbium-doped fiber amplifier, or an EDFA. In an EDFA, the electrons of rare-earth Er$^{3+}$ ions that are embedded in a silica fiber are excited by a 980 nm pump wave. When these electrons relax, they can emit light in a range of wavelengths that is referred to as the optical C-Band (1525 nm - 1565 nm). Input signals at these wavelengths may be amplified through stimulated emission. We will use an EDFA without any input and utilize its wideband ASE. figure 17 shows a measurement of the optical power spectral density of ASE from an EDFA.
3.3.1 BANDWIDTH AND FILTERS:

As we will see below, resolution of B-OCDA systems is related with the bandwidth of pump and probe. The inherent bandwidth of ASE from an EDFA is about 4.5 THz, which is too wide for our purposes. In order reach a narrower bandwidth of ASE emission optical filters may be used. A simple form of suitable filters could be FBGs (see 1.2.2.3), that are fixed in central wavelength and in bandwidth. In the measurements I used FBGs of 7-9 GHz bandwidth. More advanced filters are based on adjustable bulk gratings and free-space optics. By changing the distance to a grating and the angle of incidence, both the central transmission wavelength and the bandwidth may be manipulated. The pass-band of such filters may be swept across the entire C-band, with a bandwidth that is adjustable between 5 to over a 100 GHz. Such tunable filters are used in the experiments as well.

3.3.2 CORRELATION TIME AND LENGTH:

The correlation time of the ASE signal is determined by its' FWHM bandwidth $\Delta \nu$ and its power spectral density profile [44]. The correlation time is on the order of
1/\Delta v. By multiplying the correlation time by the velocity of light in the medium we obtain the correlation length, which is closely related to spatial resolution in B-OCDA. Specific expressions for the correlation times of three common power spectral density profiles are given below [44]:

\[ \tau_c = \frac{0.664}{\Delta v} \quad \text{Gaussian spectral line} \quad \text{eq. 3.9} \]

\[ \tau_c = \frac{0.318}{\Delta v} \quad \text{Lorenztian spectral line} \quad \text{eq. 3.10} \]

\[ \tau_c = \frac{1}{\Delta v} \quad \text{Rectangular spectral line} \quad \text{eq. 3.11} \]

3.4 THE PROPOSITION OF ASE-BASED B-OCDA:

I now present the central contribution of this research: a B-OCDA system that is based on ASE. The uniqueness of the proposition is in the use of an optical noise source, rather than a modulated carrier, for the pump and probe. From a mathematical standpoint, the reason for the use of optical noise is simple. In equation 2.25 it was shown that the strength of the acoustic grating at a given location is related to the cross-correlation between pump and probe. Therefore, if both waves are driven from a low-coherence source, the acoustic grating would be confined to a very narrow correlation peak. This correlation length, as shown in the previous section, is a direct function of the bandwidth of the source.

On a more intuitive level, the wider the spectral bandwidth of a signal the faster its’ fluctuations are in time. With this understanding in mind, we may view the wideband optical noise as a rapidly changing random sequence, whose 'bit
duration’ is inversely proportional to its bandwidth. We can then apply a similar argument to the one invoked with respect to phase-coded B-OCDA [see figure 12]. At the point of correlation between pump and probe 'bits' are always equal and an acoustic wave is allowed to develop. At any other point in the fiber the inner product of offset 'bits' is rapidly changing, and is not consistent enough to allow for an acoustic wave to develop. However, in drawing this analogy a major difference between the two techniques becomes apparent as well: In ASE-based B-OCDA the fluctuations of the sequence are in phase as well as in amplitude. With the phase-coding technique care is taken to avoid the unwanted amplitude modulation. Amplitude fluctuations are inherent to ASE sources, and introduce noise at the detection of the output signal. This will be discussed in detail later.

Another issue introduced by the use of optical noise is the non-periodicity of the signal. In B-OCDA techniques that are based on the modulation of carriers, there is always the possibility of multiple points of correlation between the pump and probe, a direct result of the periodicity of modulation. Here there is only a single correlation peak between the pump and probe, at the point of equal paths. Even though this property is in some ways an advantage, since it removes ambiguity from the measurements, it does present a number of challenges. Firstly, the optical paths of the pump and probe must be carefully planned so that they are equal at the point of interest. Secondly, whereas in previous techniques the fiber could be swept by slight changes in the modulation frequency, here that is not an option. This issue will be addressed as well.

The advantages of using optical noise as the pump and probe outweigh the drawbacks in certain circumstances. One advantage is that wideband optical
sources remove the need for high-end modulators and arbitrary waveform generators. Another important advantage is that the resolution can be easily controlled by spectral filtering of the wideband sources to desired bandwidths. As a result resolution of much less than a millimeter is feasible, at least in principle, in optical media with sufficiently high nonlinearity. Several potential options for such media are introduced in subsequent subsections.

3.4.1 RESOLUTION:

The resolution of the system determined by the coherence length of the ASE, $L_c$:

$$L_c = v_g \tau_c = \frac{c}{n} \frac{1}{\Delta \nu}$$  \hspace{1cm} \text{eq. 3.9}

Where $v_g$ is the group velocity of light in the medium and $\tau_c$ is the coherence time set by the reciprocal of the ASE bandwidth $\Delta \nu$. The resulting spatial resolution is half of the coherence length:

$$\Delta z = \frac{1}{2} L_c$$  \hspace{1cm} \text{eq. 3.10}

The factor of 2 comes from the fact that the pump and probe waves are counter propagating. The expected resolution using a 25 GHz-wide ASE source is approximately 4 mm. Such resolution is possible with the phase-coded B-OCDA, however its implementation would require the generation of arbitrary bit patterns at 25 Gbit/s. Since such high frequency function generators, or even electro-optic modulators, are seldom available, ASE-based B-OCDA offers a good substitute. Note again that frequency-modulation B-OCDA had reached a resolution of 1.6 mm [15]. For ultra-high resolutions demanding more than 100GHz bandwidth, ASE sources offer the only viable solution.
ASE signals were simulated by an array of random complex numbers that were generated using the Matlab command \texttt{wgn(\sim,\sim, 'complex')}\). This array accurately represents a polarized ASE signal, such as those used in experiments. The simulated process was 100 ns long. While in reality the bandwidth of ASE is on the order of 4.5 THz, the initial bandwidth of the simulated process was chosen to be 250 GHz in order to relax the computational complexity. The signal was then passed through a tunable filter of varying bandwidth, on the order of 25 GHz. The probability density functions of the amplitude, intensity and phase of the filtered process remained in good agreement with the analytic expectations described earlier. The simulated distributions of amplitude and intensity are shown in figure 18.

The ASE signal generated was then used as an input for the pump and probe in a numerical simulation of a SBS interaction [31]. The resulting acoustic field can be described by the solution of the time dependent equation that has already been described in eq. 2.25.
\begin{equation}
q(z,t) = ig \int_0^t \exp \left[ -\Gamma_A (t-t') \right] A_1 \left( t' - \frac{z}{v_g} \right) A_2^* \left( t' - \frac{z}{v_g} + \theta(z) \right) dt'
\end{equation}

**eq. 3.11**

Here, however, due to the statistical nature of the ASE, the acoustic wave magnitude becomes a random process as well and must be described in terms of its local expectation value. In what follows, \( A_{p0} \) and \( A_{s0} \) are the average amplitudes of the pump and probe, respectively, and \( u(t) \) denotes the complex envelope of a polarized ASE source that is common to both waves. \( u(t) \) is of an average magnitude of unity, and it is characterized by a bandwidth \( \Delta \nu^m \) and coherence time \( \tau_c^m \approx 1/\Delta \nu^m \) [44].

The expectation value of the acoustic field magnitude at position \( z \), for \( t >> \tau \), is given by:

\[
\overline{q(z)} = jg A_{p0} A_{s0}^* \int_0^t \exp \left[ -\Gamma_A (t-t') \right] \overline{u \left( t' - \frac{z}{v_g} \right) u^* \left[ t' - \frac{z}{v_g} + \theta(z) \right] } dt'
\]

**eq. 3.12**

In Eq. 3.12, \( \gamma_c(\theta) \) denotes the auto-correlation of \( u(t) \), an overhanging bar sign represents the ensemble average, and it has been assumed that the ASE source can be described in terms of an ergodic random process\(^\text{10}\) [44]. We may therefore expect that the acoustic field would be confined to a single short segment, whose extent \( \Delta z \approx \frac{1}{2} v_g \tau_c^m \) is given by half the correlation length of the source, located at the center of the fiber where \( \theta(\frac{1}{2}L) = 0 \) [31,37]. A numerical calculation of the

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\(^\text{10}\) Ergodicity is the condition where the temporal statistics are equal to the ensemble statistics [44]. It follows that that the statistical average is not time dependent.
magnitude of the acoustic field as a function of time and position along a fiber under test is shown in **figure 19**. The simulation results support the analytic prediction. The acoustic field, and hence the SBS interaction, is effectively confined to a 4 mm-wide correlation peak, in agreement with $\Delta \nu^\circ$ of 25 GHz.

![Acoustic field amplitude - 25GHz ASE](image)

**Figure 19**: Simulated magnitude of the acoustic wave density fluctuations (in normalized units), as a function of position and time along a 8 cm-long fiber section. Both pump and probe waves are drawn from a polarized amplified spontaneous emission source, filtered to a bandwidth of 25 GHz. The acoustic field, and hence the SBS interaction between pump and probe, is confined to a single correlation peak, whose spatial extent of 4 mm corresponds to half the coherence length of the filtered source.
In most Brillouin analysis schemes, the difference between the central optical frequencies of pump and probe must be held stable, to within less than 1 MHz. Therefore, the two waves are typically drawn from a single source, and one of them is subsequently offset in frequency through electro-optic modulation by a RF tone. Standard electro-optic modulators generate two sidelobes, one of which is subsequently filtered out. Filtering is comparatively simple when the bandwidth of the common source is substantially narrower than the separation between sidelobes (which in turn is on the order of the Brillouin shift).

Figure 20: Typical setup for the generation of pump and probe in SBS analysis. An optical source is split into two arms where one is simply amplified and used as the pump, while the other is modulated to generate Stokes and anti-Stokes waves. For sufficiently narrow-band sources, it is relatively simple to filter out the anti-Stokes wave at any point before detection.
The bandwidth of a wideband ASE source, however, exceeds twice the modulation frequency: \( \Delta v_{ASE} > 2\Delta v_B \). This results in an overlap between the two modulation sidelobes, and poses a serious challenge for high resolution measurements, since the sidelobes cannot be simply separated. One sidelobe is downshifted in frequency (Stokes wave), and experiences gain. The complementary sidelobe is upshifted by the same frequency offset (anti-Stokes wave), and experiences attenuation. Measurement of the overall signal output would convey little information of the SBS interaction, since gain and attenuation would largely cancel out.

### 3.4.3.2 SOLUTION

There are two possible solutions to this problem. One solution is to use single sideband (SSB) modulation, and generate only the Stokes-wave component in the first place\(^\text{11}\). SSB modulators are specialty components, and one was not available to us. The solution we followed instead was to use a narrowband optical filter prior to the detection of the output probe wave. For any source bandwidth there would always be a range of spectral content, whose width is on the order of the Brillouin shift, which consists predominantly of the Stokes-wave component. The filter is therefore aligned to select only a fraction of the probe spectrum, towards its low-frequency extremity. Filtering can be easily implemented using an FBG with a passband that is a few GHz-wide. There are two down-sides to the use of an output filter. First, the signal power is reduced. Second and more importantly, the ratio of

\(^{\text{11}}\) SSB is based on the Hilbert transform. The optical carrier is modulated by a desired waveform (sine-wave in our case), and also by its Hilbert transform pair (a 90 degrees-shifted cosine wave in our case).
the signal power to noise due to the stochastic nature of ASE is degraded, as discussed in detail below. This particular noise mechanism is the limiting factor in the measurements SNR. Nevertheless, use of an output filter enabled an experimental demonstration of the proposed method, as discussed in chapter 4. **Figure 21** illustrates the power spectral density of the ASE pump wave, the double-sideband-modulated input probe wave, and the filtered output probe wave.

![Figure 21: Illustration of Stokes and anti-Stokes waves, each with a spectral full width at half maximum (FWHM) of 24 GHz displaying spectral overlap. The bandwidth of the signal is larger than twice the Brillouin shift of 8 GHz. By placing an optical filter in the spectral region where there is no overlap, SBS gain can be detected.](image)

The solution adopted may raise the question of the spatial resolution of the analysis. Is the detected gain an indication of the interaction with the original spatial resolution of the entire pump/probe bandwidth? Perhaps, because of the filtering, the detected gain is only the result of the SBS interaction of the spectral components actually detected, providing a much lower spatial resolution? I show below that the filtering of the output signal does not compromise the measurement resolution. The acoustic field is confined to the short correlation length between
the original pump and probe, prior to the filtering. Any filtering of the output signal, after the SBS interaction had already taken place, might affect the signal and noise levels of the measurements but can no longer affect resolution.

The question touches on a possible misconception of wideband SBS processes. In regular, narrow-band SBS interactions, it is customary to think of a single wavelength within the signal as interacting only with its 'sister' wavelength within the pump spectrum, that is shifted by the Brillouin frequency. While this is generally true, the situation is much different within the correlation length [47]. As explained in section 3.2.1, at the point of correlation the inner product of pump and probe is held steady, even though both are fluctuating within a broad spectrum. Consequently, the entire spectral content of the probe is effectively amplified by the entire spectral contents of the pump. In comparison, the gain contribution from the interaction with a specific 'sister wavelength' would be negligible, as individual spectral components carry little power.

In order to demonstrate this principle we simulated the SBS gain as a function of position and frequency offset between pump and probe in an ASE B-OCDA. The Brillouin shift of the simulated fiber was modified from its reference value by 40 MHz along a 4 mm-long segment only. The bandwidth of the ASE source was 25GHz, corresponding to an expected spatial resolution of 4 mm. The probe wave at the output end of the fiber was filtered to a narrower bandwidth of only 9 GHz, to retain only Stokes-wave components as discussed above. Nevertheless, figure 22 shows that the expected resolution of 4 mm was not degraded.
Figure 22: Simulated stimulated Brillouin scattering power amplification of a probe wave, as a function of the frequency offset between the central frequencies of the pump and probe waves and the position of their correlation peak along 20 millimeters of a fiber under test. The Brillouin shift of the fiber at room temperature is taken as zero frequency. The Brillouin shift within a 4 millimeter-long segment at the center of the fiber under test was raised by 40 MHz. Both pump and probe waves are drawn from a 25 GHz-wide polarized amplified spontaneous emission source. The probe wave at the output of the fiber under test was filtered to a bandwidth of 9 GHz prior to detection. The simulation indicates a spatial resolution of 4 mm, which corresponds to half the coherence length of the input, 25 GHz-wide signal.

3.4.4 SIGNAL TO NOISE RATIO CONSIDERATIONS:

As mentioned earlier ASE is inherently characterized by amplitude fluctuations. These fluctuations add a source of noise upon detection. Here we examine the limitations set by this source of noise on the measurement SNR. The observed quantity in ASE-based B-OCDA is the intensity of the filtered, output signal, integrated by the detector over a duration $T$:

$$W(t) = |A|^2 \int_{t-T}^{t} \left( t - \frac{L}{v_g} \right) d\tau$$  \hspace{1cm} eq. 3.13

The output of the detector, $W(t)$, is itself a random process. Its expectation value is $\bar{W} = |A|^2 T$ [44]. Since the process is assumed to be ergodic, the time dependence
in $\overline{W}$ is dropped. Assuming that $T$ is much longer than the coherence time of the filtered output probe wave $c_{e}^{out} \approx 1/\Delta v^{out}$, the standard deviation of the detector reading can be approximated as $\sigma_w \approx \overline{W} \sqrt{c_{e}^{out}}$ [44]. The expected increment in $\overline{W}$ due to SBS amplification, when the frequency offset between pump and probe matches the Brillouin shift, is given by:

$$\Delta W = \overline{W} \left[ \exp \left( g_0 |A_p|^2 \cdot \Delta \zeta \right) - 1 \right] \approx \overline{W} \cdot g_0 |A_p|^2 \cdot \Delta \zeta.$$  

Here $g_0$ (in units of $[W \cdot m]^{-1}$) is the SBS gain coefficient of the fiber under test. The SNR of the SBS amplification measurement can therefore be estimated as:

$$SNR \equiv \frac{\Delta W}{\sigma_w} \approx g_0 |A_p|^2 \cdot \Delta \zeta \frac{T}{c_{e}^{out}} \approx \frac{1}{2} g_0 \sqrt{v_s} |A_p|^2 \frac{\Delta v^{out}}{\Delta v^{in}} \frac{\Delta v^{out}}{B}$$  

eq. 3.14

Here $B \approx 1/T$ is the integration bandwidth of the detector, and the output signal power is assumed to be sufficiently high to overcome the detector thermal noise. It should be pointed out that the SNR scales with the power spectral density of the pump wave, and with the square root of the ratio between the output signal bandwidth and the detector bandwidth. $\Delta v^{in}$ is the bandwidth of the ASE source that builds up the acoustic wave, whereas $\Delta v^{out}$ is the bandwidth of the filtered output ASE signal to be detected. Ideally we would like the output signal bandwidth to be equal to the input signal bandwidth, so as to optimize the SNR. However, due to spectral overlap between Stokes and anti-Stokes sidelobes, this is not possible in our experiments.

Given the parameters of the experiments reported in the next chapter, the SNR of a single acquisition is expected to be very low, on the order of 0.05. An averaging
over a large number of repeating measurements at equal conditions is therefore necessary. Noise due to intensity fluctuations is an inherent drawback of ASE-based B-OCDA, when compared with other high-resolution Brillouin analysis techniques such as DPP-B-OTDA and frequency- or phase-modulated B-OCDA [48,31]. The intensity of the output signal in these methods is, at least in principle, deterministic, and the systems can be designed to be limited by the thermal noise of detectors.

3.4.5 HIGH BRILLOUIN GAIN MEDIA:

The Brillouin gain of the probe scales with the length of interaction with the intensity of the pump. Since the length of interaction in the technique proposed in this work is extremely short, the expected gain is very weak, further degrading the measurement SNR. A possible solution to this problem could be the use of highly-nonlinear wave-guiding media, rather than a standard silica fiber, in the Brillouin analysis. The Brillouin gain coefficient in such media can be orders of magnitude higher, potentially providing practical SNR levels even for coherence lengths that are well below a millimeter. Even though experiments were performed eventually using silica single-mode fibers, a few of the possible options for highly nonlinear media will be briefly introduced next. One of the options, that of Chalcogenide glass fibers, was employed in initial attempts for the implementation of ASE-B-OCDA. However, these attempts were unsuccessful due to the few-order-mode nature of the fiber available to us, and were eventually abandoned.
3.4.5.1 HIGH BRILLOUIN COEFFICIENT MATERIALS - CHALCOGENIDE GLASSES

The Brillouin gain in certain materials is two orders of magnitude higher than that found in the silica used in regular fibers. One such group of materials is Chalcogenide glasses. Chalcogenide glass is a compound that contains at least one of the three Chalcogen elements: sulfur, selenium or tellurium, alongside elements from the 14th or 15th group in the Periodic Table. Though amorphous, they nevertheless demonstrate bandgap behavior [49]. Chalcogenide glasses are transparent over a broad wavelength range, from the visible to the middle-infrared, and have found numerous applications in infrared beam delivery and imaging. Chalcogenide glasses are, however, brittle and must be handled with care.

Chalcogenide glasses are also characterized by pronounced third-order optical nonlinearities [26], including SBS. The Brillouin gain coefficient (see section 2) of $\text{As}_2\text{S}_3$ glass, for example, is a hundred times higher than that of silica [50]. Correspondingly, a fiber made from Chalcogenide $\text{As}_2\text{S}_3$ could provide a SNR that is a hundred times better than that of a standard fiber, for equal resolution and pump power level.

There is a disadvantage, however, in that the linear refractive index of $\text{As}_2\text{S}_3$ at 1550 nm is also significantly higher than that of silica, on the order of 2.4, and as a result fibers of this material have different dimensions than those of standard silica fibers. Another disadvantage is their cost: since Chalcogenide fibers are not widely used they are also very expensive. The following chart from [50] shows the properties of various Chalcogenide glasses in comparison to regular silica and another highly non-linear, bismuth-doped fiber:
Figure 23: Comparison of Brillouin gain properties for fibers of different materials with different geometries and lengths. The parameters which are of most interest are the gain factors $g_\text{th}$ or $G_\text{th}$, it is apparent that chalcogenide glasses have a gain factor two orders of magnitude larger than silica and bismuth oxide (HNL) fibers. From [50]

### 3.4.5.2 HIGH GAIN THROUGH FIBER STRUCTURE ENGINEERING

Another way to enhance the Brillouin gain is by engineering the structure of the fiber. The simplest way is to simply reduce the core diameter, since the Brillouin gain is directly related to the intensity, or power per unit area, of the pump wave. By reducing the core diameter by half, we may obtain a four-fold increase in the Brillouin gain.

A more advanced way to enhance gain is through the use of photonic crystal fibers, or PCF’s. PCF’s utilize periodic structural features – such as air holes, in order to increase confinement of the optical and acoustic modes to a very small cross-section [51]. This confinement can be described using the Bloch-wave function of the periodically structured material, in analogy to the states of electrons in semiconductors [52]. The Bloch wave functions prohibit the ‘escape’ of all modes at specific frequency ranges from within the central core area, and lead to their effective confinement. The resultant high intensity within the small solid core leads...
to high Brillouin gain. However, based on the acoustic waves supported by the structure there may be multiple frequency shifts that induce SBS [53]. By using PCF’s, Brillouin gain coefficients that are 6 times higher than that of regular fibers have been reported [54]. This effect can be enhanced by combining the qualities of the high confinement of PCF’s with those of highly non-linear materials.

![Figure 24: cross section of a PCF, from [51]](image)

There are several drawbacks to the use of specialty, highly nonlinear fibers. Their cost is prohibitive in long range sensing schemes, their quality could be uneven, and their integration with an interrogation system that is based on regular single-mode fibers could be challenging.

### 3.4.5.3 WAVEGUIDES

Ultra-high resolution SBS sensing may be attractive along on-chip, highly nonlinear waveguides. These may combine both qualities of highly nonlinear materials which have strong Brillouin gain, together with very small effective areas. Also, because the length of integrated-photonic waveguides is rarely in excess of a few cm, distributed sensing in waveguides is irrelevant unless sub-mm resolution could be achieved. The proposition of ASE-based B-OCDA is therefore particularly suitable.
for such a purpose. Already, B-OCDA has been used by Hotate [55] to characterize a 50 cm long silica Planar Lightwave Circuit (PLC). A resolution of about 6 mm was achieved and changes in the Brillouin Gain spectrum were observed along the waveguide, particularly at the entrance and exit points. SBS in Chalcogenide waveguides have been reported by Eggleton and colleagues [56], and later also by Levy and coworkers [57]. Distributed Brillouin analysis with sub-millimeter spatial resolution has yet to be reported.

3.4.6 THE SCANNING OF THE CORRELATION PEAK POSITION:

ASE sources do not introduce periodic correlation peaks in the medium. This poses yet another challenge to a B-OCDA system, since the scanning of high-order correlation peaks, as described earlier with respect to other B-OCDA setups, is inapplicable. An alternative way of moving the correlation point must be found. The most straightforward way of moving the correlation point is to use a manual or motorized variable optical delay line. In this case the sweep range will be limited by the length of the delay line. This mechanical aspect to the setup might become cumbersome and time-consuming.

Another, more elegant option would be to shift the correlation point by taking advantage of chromatic dispersion. Suppose that fibers of equal path lengths $L$ are added to the pump and signal branches. The fiber in one arm is chosen with zero dispersion, whereas the fiber in the other arm is characterized by a dispersion coefficient of $D \ [ps/(nm \cdot km)]$. The central wavelength of a filtered C-band ASE source can be tuned within a range $\Delta \lambda$ of 35 nm, effectively scanning the correlation peak over a range of $\frac{1}{2} \cdot LD \cdot \Delta \lambda_{g}$. The scanning range would be
approximately 6 cm per 1 km of standard SMF-28 fiber, and even longer with use of dispersion compensating fibers. However, a dispersion based technique would be difficult to implement since the optical filters would also need to be adjusted during the sweep. In addition every wavelength has its own Brillouin frequency, hence the post processing of data would become more complex.

Yet another option is to make copies of the ASE signal. This would be accomplished by forming a closed fiber loop with an ASE pulse as an input. The propagation delay in the loop must exceed the duration of the ASE pulse. A coupler would allow a small fraction of the power to leave the loop following each cycle, resulting in a periodic ASE signal.

3.5 SUMMARY:

In this section I presented a proposal for an ASE-based BOCDA technique. The technique is conceptually new, as it relies for the first time on broadband optical noise, rather than on the broadband modulation of carriers, to obtain high spatial resolution. Analysis and numerical simulations predict that the resolution obtained using this scheme should equal half the correlation length of the ASE source, which could be very short. For example, a 25 GHz-wide source should provide a spatial resolution of 4 mm. Compared with previous high-resolution B-OCDA schemes, the new technique has two potential advantages: its resolution is scalable to less than 1 mm in suitable highly nonlinear media, and it does not rely on high-rate pattern generators, modulators or microwave generators.

I also addressed the difficulties associated with the scheme: limited SNR due to the stochastic nature of ASE intensity; spectral overlap between Stokes and anti-
Stokes sidebands; and the positional scanning of a single correlation peak. Potential solutions to these problems were suggested as well. An experimental proof-of-concept is provided in the next chapter.
4 EXPERIMENTAL SETUP FOR ASE-B-OCDA

4.1 OPTICAL SETUP OVERVIEW:

Figure 25 shows the experimental setup that was used in high resolution B-OCDA measurements with an ASE source. The ASE emission from an EDFA, operating with its input disconnected, passed through a fiber-optic polarization beam splitter and an optical band-pass filter of adjustable bandwidth and central transmission wavelength. The filtered, polarized ASE source was split in two paths by a fiber-optic coupler. Light in the pump branch was amplitude-modulated by pulses of 25 ns duration and 2 \( \mu \)s period, amplified to an average power of 200 mW, and launched into one end of a 2 m-long fiber under test (FUT) via a circulator. The FUT was a silica single-mode fiber with a relatively small mode field diameter of 6.7 \( \mu \)m.

Light in the probe path was modulated in suppressed-carrier, double-sideband format in an electro-optic amplitude modulator, driven by a sine wave of radio frequency \( \sim 10 \text{GHz} \). The probe wave, consisting of Stokes and anti-Stokes sidebands, was transmitted through a manually-variable optical delay line, amplified to an average power of 10 mW, and launched into the opposite end of the FUT. The probe wave at the FUT output passed through the circulator and a 9 GHz-wide optical band-pass filter, which retained only part of the low-frequency spectral contents of the dual-sideband probe wave. Light at the filter output, therefore, comprised predominantly of Stokes sideband components. The filtered output probe was detected by a photo-receiver of 200 MHz bandwidth, and sampled by a real-time digitizing oscilloscope.
The experimental setup is divided into four units. The first unit is the generation of the ASE signal used as the source of both the pump and probe. The second unit is the generation of the pump and probe waves, consisting of their respective modulation schemes and delays lines. The third unit is the fiber under test where the SBS interaction takes place, and the fourth is the detection branch.
4.1.1 UNIT 1 - ASE SIGNAL GENERATION:

The wideband ASE signal was generated by an EDFA. The EDFA was pumped at 980 nm without any optical input, leading to ASE across the entire gain bandwidth of 4.5 THz. ASE did not have to compete with the amplification of any input narrowband signals. In order to reduce the source bandwidth to the GHz range with minimal noise, two stages of filtering were performed. The first stage narrowed the 4.5 THz bandwidth down to 150 GHz using a fixed-bandwidth tunable optical filter, with a comparatively gradual passband shape. This initial filtering reduced the power of the ASE significantly, hence another EDFA was required at the output of the filter. The second stage used a Yenista optical filter\textsuperscript{12} seen in figure 27. The adjustable bandwidth

\textsuperscript{12}This filter provides an excellent extinction ratio with an almost rectangular spectral output. The filters’ central frequency is tunable and its’ bandwidth can be tuned without loss from 120 GHZ down to under 6 GHz.
of the filter was set to 25 GHz. Since the EO modulators are polarization dependent, the ASE signal was passed through a Polarization Beam Splitter (PBS) in order to stabilize the setup. Only one of the polarized outputs was used as the common source for both pump and signal.

4.1.2 UNIT 2 - PUMP AND PROBE SIGNAL GENERATION:

Figure 28: Pump and probe arms of optical setup. Both arms are equal in their optical path length. The Polarization scrambler in the probe arm is only used in the calibration process, otherwise it is inactive.

After the ASE source was generated, a 1×2 coupler was used to spilt it into the pump and probe arms. One replica of the ASE source was used directly as a pump wave\textsuperscript{13}. The pump was modulated by an EO modulator and a function generator into 25 ns-long pulses, with a repetition rate of 500 KHz. The pulses were amplified with an EDFA to an average output power of 23 dBm, and peak power of 40 dBm.

\textsuperscript{13} A central wavelength of 1543.8 nm was used. It was determined by the central frequency of the none-tunable FBG optical filter used for pre-detection filtering.
The probe was generated from the second replica with an EO modulator and RF signal generator that modulated the ASE signal by a GHz-scale sinusoidal function. The sine wave frequency was varied within a 150 MHz-wide range, centered at the Brillouin shift of the FUT at room temperature. The range was sufficient to detect changes in the Brillouin shift due to temperature and strain changes. The probe arm also included a delay line. The delay line was essential for sweeping the measurement point along the fiber as discussed in the previous chapter. A manual delay line was used with a maximum delay of 10 cm, which translated into a 5 cm dynamic sensing range\textsuperscript{14}. Since the delay line was placed in the probe arm a longer delay meant that the pump could travel farther in the FUT before interacting with the probe, as a result the measurement point moved closer to the side of the probe input. A polarization scrambler was built into the setup, and used only during the calibration process as described below.

A circulator at the end of the pump's arm was used to allow the incoming pump wave to continue on to the fiber under test, and let the outgoing probe reach the detector. A polarization controller at the end of the probe arm was used to align the polarizations of pump and probe at their point of interaction, for maximum SBS gain [61]. States of polarizations were adjusted at the beginning of each experiment, and remained steady throughout its duration.

\textsuperscript{14} The dynamic sensing range is half the maximum delay due to the fact that the pump and probe are counter-propagating and the actual crossover time of the two signals is half of the optical delay time.
4.1.3 UNIT 3 - FIBER UNDER TEST (FUT):

In the final version of the setup, the FUT was a small-core fiber with a Mode Field Diameter (MFD) of 6.7 microns. It was 2 meters long and spliced at its ends to longer, standard single mode fibers (SMF’s). The Brillouin gain coefficient from the small core fiber was twice that of a regular SMF. As mentioned above the dynamic range of measurement was 5 cm due to the length of the delay line.

In order to demonstrate high resolution sensing, a heated metal plate was placed in contact with the FUT. The thermal conductivity between the heated metal plate and fiber was enhanced by applying highly conductive thermal paste. The length of the hotspot could be varied. A high-current, 10 Ohm resistor was used for heating the plate, and a thermocouple was used to verify a constant temperature for the duration of the experiment.

![Image](image.png)

**Figure 29:** Heating element. The 10 Ohm resistor heated the metal plate. Different lengths of the fiber could be heated by the different sized protrusions of the metal.

Initially, before the use of the small core silica fiber, a highly non-linear Chalcogenide fiber was used as the sensing fiber. This type of fiber would have a Brillouin gain over a 100 times stronger than that of ordinary silica fibers. Unfortunately, the fiber supported a number of modes at 1550 nm. Since the entire
setup was based on single mode components, light had to be coupled into and out of the fiber with single mode fibers without loss. This was accomplished by constructing a free space optical setup that could selectively excite only the fundamental mode of the Chalcogenide fiber. While we succeeded in coupling light in and out of the fiber with very low losses, the introduction of a hotspot gave rise to modal noise that inhibited stable measurements of the output probe power.

4.1.4 UNIT 4 – DETECTION:

At the output of the circulator, a FBG was used to select only Stokes wave components of the output probe that did not overlap with the anti-Stokes sideband, as explained in section 3.4.3. The FWHM of the FBG was 9 GHz. Following the FBG, one arm of a 1×2 splitting coupler was channeled to an optical spectrum analyzer (OSA), for monitoring possible thermal drifting of the FBG passband. The other arm was channeled to a 200 MHz-wide optical detector. The output of the Detector was sampled by a digitizing oscilloscope with an analog

Figure 30: Zoom in on Detection unit of setup. The fiber Bragg grating acts as a bandpass filter allowing only part of the Stokes wave to reach the detector. The OSA acts as a control for thermal drift and deterioration of the signal.
bandwidth of 6 GHz. Post-detection processing of data was carried out offline, over matlab.

4.2 STEP BY STEP CALIBRATION & OPTIMIZATION PROCEDURE:

After putting together the skeleton of the setup, the pump and probe branches needed to be equalized in length so as to ensure that the pump and probe met within the 2 m-long FUT. After that, the exact location of the meeting point had to be found to a precision of 5 cm, so that a hotspot could be applied within the scanning range of the setup.

4.2.1 PUMP & PROBE ARM LENGTH:

Figure 31 illustration of the method used to equalize the lengths of the pump and probe arms. The central section incorporates the entirety of unit 2. A pulsed laser is transmitted through both arms and detected after the recombination of the arms.

In order to measure the length of the pump and probe arms, an EO modulator was placed prior to the 1×2 coupler at the entrance of Unit 2, and at second 2×1 coupler joined the pump and probe arms together at the output of unit 2 and channeled them to a detector. By sending a short optical pulse simultaneously through both arms, the lengths difference between the two arms could be
observed in time domain analysis of the detector output, and matched by adding more optical path to the shorter arm. In this manner the propagation delays of the two arms were matched to within the pulse length of about 8 ns.

4.2.2 IDENTIFICATION OF THE PUMP/PROBE MEETING POINT IN THE FUT:

After this initial stage, the exact meeting point of the two waves had to be found within the FUT. This was accomplished by replacing Unit 1 with a phase coded source as described in sections 2.3.3 to 2.3.5. By using proven phase-coded B-OCDA techniques, we were able to find the zero order correlation peak with 2 cm precision. The zero order peak is readily identified since it does not move when the phase coding periodicity is modified\textsuperscript{15}. The physical location of the zero-order correlation peak within the FUT was found by setting the frequency offset between pump and probe to the Brillouin shift of the FUT at room temperature, and passing a heat source along the fiber while observing the strength of the peak. A decrease in the amplification peak indicated that the proper location of the pump and probe meeting point was correctly recognized. During this procedure the polarization scrambler was used in order to remove polarization dependent losses caused by the heat applied to the fiber.

4.3 SUMMARY:

In this section an optical setup implementing the ASE-B-OCDA technique has been presented. Each of the four main units of signal generation, pump/probe generation, FUT and detection have been described in depth. The calibration

\textsuperscript{15} For a more in depth explanation see section 2.3.5
procedures for the setup ensure the repeatability of the experiment. In the following section results of the measurements from this setup will be presented and discussed.
5 RESULTS

5.1 INTRODUCTION:

In the following sections the results of the ASE-B-OCDA experiments will be presented. First, the aspects of the setup used for control and monitoring are described. These include the spectra of the ASE at various stages, from generation to final pre-detection filtering. Next, the time domain signal observed at the photodetector output is discussed, and the methods of its post-detection analysis are explained.

The first actual results are Lorentzian Brillouin gain curves that were measured using narrow band ASE, with proper addressing of spectral overlap. Finally the results of two experiments, one with a 33 GHz wide ASE signal and a 1.5 cm hotspot and the other with a 25 GHz wide ASE signal and a 4 mm hotspot, will be presented.

5.2 SPECTRUM OF ASE SIGNAL:

The knowledge of the exact bandwidth of the ASE signal was essential in order to control the resolution of the measurement. The EDFA based ASE source that was used is characterized by the following output spectrum:
Figure 32: Spectrum of emission of EDFA pumped at 980 nm with no optical input. It spans tens of nm, or over 4.5 THz.

The overall optical power of this ASE emission was about 10 dBm. This initial spectrum was then filtered and amplified by the two stage optical filter as described earlier, generating an ASE signal with a reduced bandwidth as seen in the figure below:

Figure 33: example of a filtered 25 GHz ASE signal used as the source of both the pump and probe.

This filtered ASE signal was directly used as the pump wave. The probe wave was generated by suppressed carrier amplitude modulation, resulting in overlapping Stokes and anti-Stokes sidebands:
Figure 34: Example of a 25 GHz ASE signal modulated by 10.2 GHz. The Stokes and anti-Stokes sidebands are in spectral overlap.

The next figure shows the spectrum of the probe wave at the output of the FUT, following the selection of Stokes-wave components by the FBG:

Figure 35: Spectrum of output probe following filtering by an FBG, at the input of the detector.

The need for continuous spectral monitoring becomes apparent when the experimental spectra taken at various stages along the setup are plotted together. Since the Bragg wavelength of FBG drifts with temperature, the monitoring of its reflectivity spectrum allowed for the occasional compensation in form of adjusting the central wavelength of the Yenista tunable filter of unit 1 (see previous chapter).
In the experimental setup a pulsed pump was used. Pulsing with a low duty cycle was necessary to raise the instantaneous power level of the pump EDFA to well above its average value of 200 mW. Intense pump pulses are necessary for resolving SBS amplification over mm-long sections in the presence of noise as discussed earlier. The full width at half maximum duration of the pump pulses was 25 ns, and they were repeated at a rate of 500 KHz. The relatively short pulses also assisted and the recognition and rejection of multi-path reflections from the end of the FUT. Each temporal trace was averaged over 4096 repetitions (see earlier discussion of SNR in the acquisition of ASE probe waves). Examples of averaged, raw traces are given below:

---

**Figure 36**: Optical spectra of the ASE signal at various stages of the experimental setup. A reference trace of the Stokes and anti-Stokes sidebands was kept on screen, while the spectrum at the FBG output was continuously monitored.

**5.3 TIME DOMAIN DETECTED SIGNAL:**
Figure 37: Detected output probe wave as a function of time. The blue trace was taken for a frequency offset between pump and probe that matched the Brillouin frequency shift, whereas other traces were taken at different frequencies as detailed in the legend. The latter part of trace is more indicative of the Brillouin shift than the earlier part.

The pulsed pump imprints a pulsed amplification pattern on the output probe. While the integrated area of the observed pulse changes little with the frequency offset, its shape is modified. As seen in figure 37, the latter segments of the probe trace provide better indication of the Brillouin interaction strength. Figure 38 shows a map of the magnitude of the output probe, as a function of both time within the pulse and frequency offset. The trailing edge of the pulse pattern (at approximately 260 ns) exhibits the expected frequency dependence of Brillouin interaction, with a peak frequency offset of 10.2 GHz and a bandwidth of about 30 MHz. Other parts of the temporal pattern exhibit a much weaker spectral dependence.
Figure 38: Time dependent gain map of fiber, a result of multiple sweeps at different frequency shifts.

The Brillouin shift of 10.2 GHz is best observed towards the trailing edge of the output probe pulse.

The temporal shape seen in figure 37 is supported by numerical simulations of the output probe wave subject to a 25 ns-long pulsed pump. Figure 39 shows that the initial buildup of the output probe pulse has little dependence on the frequency offset between pump and signal, whereas the latter parts of the pulse exhibit more pronounced sensitivity: stronger amplification towards the end of the pulse is observed when the frequency offset matches the Brillouin shift. This temporal shape of the step response is inherent to second-order, damped resonance systems such as that described by the frequency dependence of the acoustic field [58] (see chapter 2).

Figure 39: Simulation of transient effects in the acoustic field build up for a 25 ns pulse
In subsequent data analysis, the strength of the SBS amplification was inferred from measurements of the output probe power towards the end of its pulse shape. The changes to the sampling instance with positional scanning of the correlation peak are negligible.

5.4 BRILLOUIN GAIN SPECTRUM:

In this subsection, a first experimental Brillouin gain spectrum obtained using ASE-based B-OCDA are reported. Figure 40 shows the Brillouin gain as a function of frequency offset, collected using an ASE source with a 4.3 GHz bandwidth and 25 ns pump pulse duration. This bandwidth corresponds to a spatial resolution of about 2 cm. Due to the relatively narrow bandwidth, the Stokes-wave sideband was not affected by output FBG filtering. The FWHM of the observed gain spectrum was about 35-40 MHz, in agreement with expectation. The FWHM value could represent slight broadening due to the comparatively short pulse duration (see section 2.3.2 for discussion). The duration of the pulses was restricted by parasitic reflections from the termini of the non-standard and relatively short FUT.
Figure 40: Brillouin gain of a 4.3 GHz-wide ASE signal, as function of frequency offset between pump and probe. A 25 ns-long pump pulse was used. Spectral dependence follows the expected width.

It would be possible to improve the sensitivity of the system if longer pulses were used, however, this would require eliminating the reflection at the end of the FUT or simply using a longer FUT.

5.5 EXPERIMENTAL RESULTS OF SENSOR:

A number of experiments were performed to test the ability of this technique to identify changes in temperature of the fiber at high spatial resolutions. Two set of results are presented below.

5.5.1 SENSING WITH 3.2 MM RESOLUTION OVER A 1.5 CM-LONG HOTSPOT:

Figure 41 shows an example of the recorded signal power as a function of time, with \( \nu \approx \nu_g = 10.2 \text{ GHz} \) and \( \Delta z \) chosen outside the hotspot. A peak of the output signal represents the SBS amplification at the meeting point of pump and probe.
The maximum height of the peak was noted for each $\nu$ and $\Delta z$. The optical power spectral densities of the pump wave, input probe wave, and filtered output probe wave are shown in the figure 42. The ASE source bandwidth $\Delta \nu$ was 33 GHz, corresponding to an estimated spatial resolution of 3.2 mm.

Figure 41: Time dependent gain of the probe wave, for a frequency offset between pump and probe of 10.2 GHz. The correlation peak between pump and probe was outside the hotspot. 4096 averages were used.

Figure 42: Spectra of ASE signals in B-OCDA experiments of 3.2 mm resolution. Pump (red), input probe (blue), and filtered output (black).
Figure 43 presents the relative measured amplification as a function of $\nu$ and $\Delta z$. Data was fitted to a Lorentzian shape. SBS gain centered at $\nu_s \sim 10.2$ GHz is observed, with a FWHM of approximately 30 MHz, in agreement with expectations. Figure 44 shows the fitted local $\nu_s$ as a function of $\Delta z$. A 1.5 cm-long hot spot is properly identified.

Figure 43: Map of measured SBS gain as a function of position of correlation peak, and of the frequency offset between pump and probe. Lorentzian fitting was applied to the measured spectrum at each position independently.

Figure 44: Measured Brillouin frequencies shifts along a 5 cm section of fiber. The spacing between each resolution point is 2.5 mm. Within the 1.5 cm long hotspot there are 5 points with higher Brillouin shifts, and at the edges of the raised section there are sharp drops in Brillouin shift. The results suggest a spatial resolution below 5 mm.
5.5.2 SENSING WITH 4 MM RESOLUTION OVER A 4 MM-LONG HOTSPOT:

In this experiment an ASE signal with a 25 GHz bandwidth, equivalent to 4 mm resolution, was used. A 4 mm-long section of the FUT was heated to 55 degrees. Figure 45 presents the relative measured amplification as a function of $\nu$ and position offset. A SBS gain line centered at $\nu_a \sim 10.2$ GHz is observed, with a full width at half maximum of approximately 30 MHz, in agreement with expectations. The hotspot at the center of the scanned region is clearly recognized. For comparison, a similar map with the hotspot removed is shown in figure 46.

The use of the term 'resolution' in the fiber sensors literature is often inconsistent with its 'proper' definition, in microscopy or radar systems, for instance. In microscopy the term relates to the ability to distinguish between two adjacent disturbances, whereas in many of the fiber sensors works the term refers to the smallest disturbance that can be detected. Here, the 2.5 mm step size suggests that only a 5 mm 'real' resolution can be claimed, according to the Nyquist criterion. In future experiments, the step size can be reduced to achieve 4 mm resolution. The terminology used throughout this work follows the conventions of the fiber sensors community with respect to resolution. Indeed, the experiment demonstrates the detection of a 4 mm-wide disturbance.
Figure 45: Map of measured SBS gain as a function of position of correlation peak, and of the frequency offset between pump and probe. A 4 mm-long hotspot is clearly recognized.

Figure 46: Map of measured SBS gain as a function of position of correlation peak, and of the frequency offset between pump and probe, along the same section of fiber as in figure 45 above. The hotspot was removed.

Figure 47 shows the fitted local $v_B$ as a function of $\Delta z$. One trace corresponds to the FUT with the hotspot in place, and the other two represent the same section with the hotspot removed. The 4 mm-long hotspot is clearly recognized. The variations in the reconstructed Brillouin shift within unheated segments is estimated as $\pm 1.5$ MHz.
Figure 47: Measured Brillouin frequency shifts along a 5 cm section of fiber. The spacing between each resolution point is 2.5 mm. The red trace is for the fiber with the hotspot in place. The blue trace was taken with the hotspot removed. The magenta trace was collected with the room cooled down to a lower temperature.

5.7 SIGNAL TO NOISE RATIO (SNR):

In section 3.4.4 we estimated the SNR of the system as:

\[
SNR \equiv \frac{\Delta W}{\sigma_w} \approx g_0 |A_p|^2 \cdot \Delta z \sqrt{\frac{T}{t_{\text{out}}} \cdot \frac{1}{2} g_0 v_s \frac{|A_p|^2}{\Delta v_{\text{out}}} \sqrt{\frac{\Delta v_{\text{out}}}{B}}}
\]  

**eq. 5.1**

Here \( B \) is the integration bandwidth of the photo-detector, and the output signal power is assumed to be sufficiently high to overcome the detector thermal noise. The SNR scales with the power spectral density of the pump wave, and with the square root of the ratio between the output signal bandwidth and the detector bandwidth. In the above experiment \( \Delta v_{\text{in}} \) is approximately 25 GHz, \( \Delta v_{\text{out}} \) is about 9 GHz, \( B \) equals 200 MHz, \( |A_p|^2 \) is on the order of 10 W, and \( g_0 \) is estimated as 0.2 [W·m\(^{-1}\)]. The estimated SNR of a single acquisition is therefore very low, on the order of 0.05. The estimated SNR compares well with the experimental results which were on the order of 0.1. The experimental SNR was calculated by
comparing the relative gain that was obtained after 4,096 averages, against the
temporal standard deviation of a single, unamplified trace without SBS
amplification.

5.8 SUMMARY:

We have shown in this section that Amplified Spontaneous Emission can be used to
initiate localized Stimulated Brillouin Scattering. The localization of the SBS
process is determined by the spectral bandwidth and shape of the ASE signal. It
has been experimentally shown that the Brillouin gain spectrum behaves as
expected and is not broadened.

Brillouin amplification was inferred from the trailing edge of the pulse-amplified
output probe wave. The trailing edge of the amplification event was shown to be
more sensitive to the specific frequency offset between pump and probe, in both
modelling and measurement. Careful timing of the output probe wave helps
analyze the very weak amplification that takes place over mm-long fiber segments.

Experimentally it was shown that the ASE-BOCDA technique is tunable for
different bandwidths of ASE, between 4.3 and 33 GHz. The experimental results
showed that the ASE-BOCDA technique is capable of identifying hotspots in the
fiber under test that are only 4 mm wide. The SNR of the measurements agrees
well with the theoretical calculations. SNR remains the primary factor that restricts
the further scaling of resolution. It may be improved in proper highly nonlinear
media, or with the use of single-sideband modulators to circumvent the need for
output filtering of the probe wave.
In short, we have shown the ASE-BOCDA method to be a viable high resolution distributed sensing technique. It is relatively simple to implement, and may scale towards ultra-high resolution sensing due to the very wide bandwidth of ASE.
In this research a new technique for distributed fiber sensing was presented. This technique introduced the concept of taking Amplified Spontaneous Emission, usually considered a detractor in most optical systems, and utilizing its wideband properties to enable localization of the SBS process in fibers – thus giving a new twist to the already well known B-OCDA technique. A theoretical explanation was provided describing the localized SBS process and what ramifications the statistical nature of ASE has on this process. Subsequent simulations that backed up the theory, in relations to both resolution and SNR, were also presented. The technique was implemented in a laboratory setup and experiments were successful in proving its viability. The resolution reached in the experiments was between 3-4 mm where an actual hotspot of 4 mm was identified in the fiber under test.

6.1 FUTURE WORK:

Future work on this scheme would follow two directions. First, attempts will be made to overcome the practical limitations of the current experiments, in terms of pre-detection filtering of the output probe wave and the manual scanning of the correlation peak position. Second, the employment of the method to distributed sensing within waveguides and with sub-mm resolution will be attempted. In what follows, I elaborate on possible improvements to the experimental setup.
6.1.1 SINGLE SIDEBAND MODULATION:

The need to filter the optical signal before detection was due to the overlap between the Stokes and anti-Stokes sidebands that were generated by regular double sideband modulation (DSB) of the probe wave. The result of this pre-detection filtering was that while there is always lower gain when raising the resolution (due to the localized SBS in a smaller and smaller section of the fiber), this reduction in gain was exaggerated by the fact that only a small portion of the probe spectrum reached the detector. In addition, as discussed at length in chapter 3, the reduction of the optical bandwidth of the detected ASE waveform elevates the noise power that is associated with its stochastic nature. Both mechanisms make the SNR that is associated with higher resolution measurements prohibitively low.

Alternatively, if a Single Sideband (SSB) modulation scheme is used instead, no filtering of the output probe wave prior to detection would be necessary. Figure 48 shows the ratio between the SNRs that are expected in using DSB and SSB modulation. SSB provides an added value for source bandwidth that exceeds the Brillouin shift. The benefit increases according to the square root of the source bandwidth (and resolution). For example, a spatial resolution of 1 mm in standard would require a 100 GHz-wide ASE source. At such broad bandwidth, use of an SSB modulator would improve the SNR by a factor of 3, and reduce the necessary number of averages by an order of magnitude.
Figure 48: Ratio between the SNR in the measurement of a SSB modulated probe without pre-detection filtering, and that of a DSB modulated probe filtered by an output FBG, as a function of bandwidth.

6.1.2 ADVANCED PUMP PULSING SCHEMES:

Another way to improve SNR and reduce the number of averages from 4096 is to use a new pump pulsing scheme that is currently being developed by our group [59]. In this scheme, the pump is modulated by a long binary sequence of pulses, rather than by a single pulse. Brillouin interaction at the correlation peak imprints a replica of the pump sequence on the intensity of the output probe [60]. The probe pattern can be compressed into a narrow and intense virtual peak, using digital post-processing protocols of matched or mismatched filtering [61]. The technique could improve the SNR by a factor of $\sqrt{N}$ where $N$ is the number of 'on' bits in the amplitude modulation sequence, and as result less averaging might be necessary. On the other hand, the peak power of pulses within the extended sequence would necessarily weaker than that of isolated pulses, so that the benefit in SNR would be partially compromised.
The method for variable optical delay may also be improved. Motorized delay lines providing longer scanning ranges than the manual one used in the current experiment are readily available. The correlation peak can also be scanned optically, as discussed already in section 3.4.6. The number of resolution points could reach several hundreds, using optical and/or mechanical scanning means.

It is also possible to generate multiple ASE based correlation peaks along the fiber under test. Figure 49 illustrates a setup where a repetitive ASE signal can be produced. By launching an ASE pulse, whose length is comparable to the length of the loop between the couplers, the output of the loop will transmit a repetitive signal with a number of pulse replicas that is determined by the Q factor of the loop. If this signal is used as the source for the pump and probe, then multiple correlation peaks will be built up in the fiber at distances determined by the length of the loop.
Figure 49: Optical loop for generating a repetitive pulsed ASE signal. The arm of the 99% arm of the second coupler is channeled back into the loop and only the 1% arm is channeled to the output. In every cycle 3dB is lost on the entrance coupler, this would be compensated by the SOA. The reason an SOA is used within the loop (as opposed to an EDFA) is so as not to lengthen the optical path.

6.2 POSSIBLE APPLICATIONS:

One possible application of this technique is in a tunable resolution sensor, where a long section of fiber may be interrogated first at low resolution. When an anomaly occurs, the system would be able to zoom in at high resolution to the point of the anomaly, thereby enabling quick identification of the point of occurrence. A dual-resolution Brillouin sensor could be superior to Rayleigh based methods in terms of range and capability for reference-free, absolute readings. In many cases, Rayleigh-based systems gather and analyze more high-resolution data than is necessary. Another potential advantage of a high-resolution B-OCDA sensor is the measurement of an absolute frequency, which is less susceptible to losses along the fiber under test.
Finally, ASE-based B-OCDA could allow for distributed analysis along photonic-integrated waveguides and circuits with sub-mm resolution. Such measurements could reveal not only temperature and strain variations, but also local variations in geometry and modal structure.

6.3 CONCLUDING REMARKS:

This research has yet again proven the truth in the saying 'One's man's noise is another man's signal'\(^{16}\). By using optical noise we were able to find a new, relatively simple, method to reach ultra-high resolutions for in distributed sensing.

During the course of the research a number of interesting issues arose that ended up not being integrated into this thesis. One such issue that needs to be mentioned, if only due to the amount of time that was dedicated to it, was the initial use of a Chalcogenide fiber as the sensing fiber. Much time was spent in the fine tuning of an elaborate free space fiber coupling setup that allowed selective mode excitation in the highly non-linear fiber. Even though this did not find its' place in the thesis, it was an interesting challenge and one that was solved through the integration of free space optics solutions with fiber based optics and utilized a number of different control platforms. In the end this approach was abandoned due to a fundamental problem of modal noise in the fiber.

The combination of time domain analysis with correlation domain analysis proved to be essential for this technique. Without it many difficult aspects of this experiment would have been almost impossible to overcome. The time domain

\(^{16}\) Attributed to Prof. Moshe Tur of Tel Aviv University.
analysis allowed us to focus the detection at the specific instance in which the gain is most sensitive to the Brillouin shift. Also, without the time domain analysis it would have been extremely difficult to locate the actual point of correlation within the fiber.

Finally, we return to the most important aspect of this research. ASE as a non-coherent light source has been used in a number of applications, primarily for interferometric systems. Perhaps counterintuitively, it was shown in this thesis that ASE can act as a source of stimulated Brillouin scattering and sensing as well.
REFERENCES


58. S. Engelberg, A Mathematical Introduction to Control Theory, (Imperial College Pres, 2005).


תקציר

חיישנים מבוזרים המבוססים על סיבים אופטים מספקים מענה ייחודי לבעיות חישה רבות.他们当今在建筑控制领域处于领先地位，也被用于许多商业安全系统的许多方面。

有几种不同的方法可以实施基于光波导的传感器，每一种都有其独特的特征。其中一种主要方法是基于布拉格光栅，其中非线性互动发生在两个光场之间，它们对外部温度的任何变化以及沿光导的弯曲都很敏感。

这种方法有许多优于其他方法的优点，例如，它可以测量几百公里的范围，具有毫米量级的分辨率，对单个部分的弯曲敏感度高达百万分之一或更低，以及相对低的光损沿光导，以及相对简单的数据处理。商业应用中的这种方法技术正在不断发展，特别是在能源、石油和天然气的远距离测量领域。

两种技术被开发用于基于光栅的传感器：基于空间频率的布拉格光栅光谱分析（B-OCDA）和基于相关空间分析的布拉格光栅时间分析（B-OTDA）。

在最近的几年中，这些技术的空间分辨率显著提高。目前报道的最高空间分辨率是1.6毫米，对于长度为数厘米的短段，B-OTDA方法的分辨率是2厘米，对于2公里的范围。

所有这些传感器技术和装置都依赖于激光相干和窄带，其中各种调制和相位和频率控制需要有光子学和混合电路的复杂解决方案。例如，为了达到4毫米的分辨率，需要一个宽带宽的22吉赫兹。所需的设备在技术上是前沿的，成本高昂，有时难以实现。

yster
This research presents a new method of using a highly resolved sensor based on the Bragg effect. The main difference between the proposed technique and previous techniques is the use of an amplified spontaneous emission (ASE), as a common source for the two optical signals involved. By using ASE, there is no longer a need to increase the optical bandwidth of the light to improve resolution. Instead, it is necessary to narrow the source width. The result of this paradigm shift is that the resolution limit is no longer determined by the equipment bandwidth. Sensors based on ASE can provide sub-millimeter resolution in appropriate non-linear media. In addition, the research introduces new application possibilities, such as sensing defects in optical fibers made of planar waveguides.

The presentation and measurement capabilities of the method are demonstrated within the framework of this research through theoretical discussions, numerical simulations and experiments. The signal-to-noise ratio, detection range and complexity of the measurement system are discussed in detail. Experimental results demonstrate a spatial resolution of 3-4 mm on the surface of a 2 cm rod. A warm spot of 4 mm is clearly identified in the measurement results. The experimental error in the measurement of the Bragg angle is ±1.5°, and for measurement of mechanical displacement ±30 μs is ±1.5°C, ±30 s ±1 mm.

The potential extensions of this research are discussed in the concluding remarks.
עבודת זו נועשת בהדרכת של פרופ’ אבי צדוק

מון הפקלוטה להנדסה של אוניברסיטת בר-Јילן
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