# 1 Introduction

The field of optics and photonics has a long history, starting with the development of lenses by the ancient Egyptians and Mesopotamians, followed by theories on light and vision developed by ancient Greek philosophers. During the centuries perennial new phenomena were found and described, leading to the mathematical law of refraction, now known as Snell's law, in 1621. The investigation of the interaction of light and matter continued over centuries. In 1854, John Tyndall demonstrated to the Royal Society that light could be conducted through a curved stream of water, proving that a light signal could be bent. In 1880, Alexander Graham Bell invented his 'Photophone', which transmitted a voice signal on a beam of light. At the end of the 19th century the guidance of light through bent glass rods has been shown for the purpose of lighting in houses or as surgical lamp, as well as, for guiding light images in an attempt of early television. Although uncladded glass fibers were fabricated in the 1920s the field of fiber optics was not born until the 1950s when the use of a cladding layer led to considerable improvement in the fiber characteristics. These early fibers inhabit an extreme loss of more than 1000 dB/km. Continuous engineering in purity of the glass and the fiber properties finally led to a loss of only 0.2 dB/km in the 1550 nm wavelength region. The availability of low-loss silica fibers in combination with the evolution of of laser devices, led not only to a revolution in the field of optical fiber communications but also to the advent of the new field of nonlinear fiber optics.

Light is an electromagnetic wave phenomenon described by the same theoretical principles that govern all forms of electromagnetic radiation. The Maxwell equations for a light wave propagating in a dielectric medium without free electronic charges or currents are well known [1, 2]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1.1}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \tag{1.2}$$

$$\nabla \cdot \mathbf{D} = 0 \tag{1.3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{1.4}$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field vectors and $\mathbf{D}$ and $\mathbf{B}$ are the corresponding electric and magnetic flux densities. $\nabla\times$ and $\nabla\cdot$ represent the curl and divergence vector operators. The relationship between the electric flux $\mathbf{D}$ and the electric field $\mathbf{E}$ depends on the electrical properties of the medium, described by the dielectric polarization $\mathbf{P}$. Within a dielectric medium the dielectric polarization is the macroscopic sum of of all electric dipole moments induced by the electric field. Correspondingly the relationship between magnetic flux density $\mathbf{B}$ and the magnetic field strength $\mathbf{H}$ depends on the magnetic properties of the material described by the magnetization $\mathbf{M}$, which is defined analogously to the dielectric polarization. The relations between the flux densities and the field strengths are given by [1, 2]:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \tag{1.5}$$

$$\mathbf{B} = \mu_0 \left(\mathbf{H} + \mathbf{M}\right) \tag{1.6}$$

where $\varepsilon_0$ is the vacuum permittivity, $\mu_0$ is the vacuum permeability. For a nonmagnetic medium, such as an optical fiber, $\mathbf{M} = 0$. In a linear, non-dispersive, homogeneous and isotropic medium the vectors $\mathbf{P}$ and $\mathbf{E}$ are parallel and proportional to each other, leading to [2]:

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E} \tag{1.7}$$

where the scalar constant $\chi$ is called dielectric susceptibility. The substitution of Eqn. 1.7 in Eqn. 1.5 shows that also $\mathbf{D}$ and $\mathbf{E}$ are parallel and proportional:

$$\mathbf{D} = \varepsilon \mathbf{E} \tag{1.8}$$

where the scalar variable

$$\varepsilon = \varepsilon_0 \left(1 + \chi\right) \tag{1.9}$$

is the permittivity of the medium. The relative permittivity $\varepsilon/\varepsilon_0 = 1 + \chi$ is also referred to as the dielectric constant of the medium. In order to find the wave equation for the propagation

of light in a medium Maxwell's equations can be used. Taking the curl of Eqn. 1.1 and using Eqns. 1.2, 1.5 and 1.6, $\mathbf{B}$ and $\mathbf{D}$ can be eliminated in the favor of $\mathbf{E}$ and $\mathbf{P}$, leading to [1]:

$$\nabla \times \nabla \times \mathbf{E} = -\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2} \tag{1.10}$$

where $c$ is the speed of light in vacuum and the relation $\mu_0 \varepsilon_0 = 1/c^2$ was used. Now it is convenient to represent this equation in the frequency domain [1]:

$$\nabla \times \nabla \times \tilde{\mathbf{E}} = \varepsilon(\omega)\frac{\omega^2}{c^2}\tilde{\mathbf{E}} \tag{1.11}$$

where $\tilde{\mathbf{E}} = \int_{-\infty}^{\infty} \mathbf{E} \exp(\mathrm{j}\omega t)\,\mathrm{d}t$ is the Fourier transform of $\mathbf{E}$ and $\varepsilon(\omega) = 1 + \tilde{\chi}$ is the frequency-dependent relative dielectric constant. As $\tilde{\chi}(\omega)$ is in general complex, so is $\varepsilon(\omega)$. Its real and imaginary parts can be linked to the refractive index $n(\omega)$ and the absorption coefficient $\alpha(\omega)$ by using the definition [1]:

$$\varepsilon = (n + \mathrm{j}\alpha c/2\omega)^2 . \tag{1.12}$$

The refractive index and attenuation of the fiber are related to the susceptibility by the relations [1]:

$$n(\omega) = 1 + \frac{1}{2}\mathrm{Re}[\tilde{\chi}(\omega)] \tag{1.13}$$

$$\alpha(\omega) = \frac{\omega}{nc}\mathrm{Im}[\tilde{\chi}(\omega)] \tag{1.14}$$

where *Re* and *Im* stands for the real and imaginary part, respectively. Further simplifications to Eqn. 1.11 can be made due to the low optical losses in an optical in the wavelength region of interest. Therefore, the imaginary part of $\varepsilon(\omega)$ is small in comparison to the real part and $\varepsilon(\omega)$ can be replaced by $n^2(\omega)$. Additionally the vector identity $\nabla \times \nabla \times \mathbf{E} \equiv \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = -\nabla^2 \mathbf{E}$ can be utilized, leading to the following expression in form of the Helmholtz equation [1]:

$$\nabla^2 \tilde{\mathbf{E}} + n^2(\omega)\frac{\omega^2}{c^2}\tilde{\mathbf{E}} = 0. \tag{1.15}$$

The nonlinear effects in optical fibers occur either due to intensity dependence of the refractive index of the medium or due to scattering phenomena. Fiber nonlinearities are important in optical communications, both as useful attributes and as characteristics to be

avoided. For intense electromagnetic fields, a homogeneous material behaves like a nonlinear medium. Therefore, the material polarization $\mathbf{P}$ is no longer proportional to the electric field $\mathbf{E}$ and can be decomposed by a Taylor series [3]:

$$\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E} + \varepsilon_0 \chi^{(2)} \mathbf{E}^2 + \varepsilon_0 \chi^{(3)} \mathbf{E}^3 + \ldots = \mathbf{P}^L + \mathbf{P}^{NL} \tag{1.16}$$

where $\varepsilon_0$ is the permittivity of vacuum and $\chi^{(k)}$ is the $k$-th order susceptibility. The dominant contribution to $\mathbf{P}$ is the linear susceptibility $\chi^{(1)}$, as described previously. The second order susceptibility $\chi^{(2)}$ is responsible for second-harmonic as well as sum-frequency generation. A medium, which lacks inversion symmetry at the molecular level, has non-zero second order susceptibility. However, for a symmetric molecule, like silica, $\chi^{(2)}$ vanishes. Therefore, optical fibers do not exhibit second order nonlinear refractive effects. Obviously the third order susceptibility $\chi^{(3)}$ is responsible for lowest order nonlinear effects in fibers [1]. The refractive index in the presence of this type of nonlinearity can be represented as [4]:

$$n = n_0 + n_2 I \tag{1.17}$$

with $I = \frac{1}{2} c \varepsilon_0 n_0 E_0^2$ and $n_0$ as the linear or low-intensity refractive index. The optical constant $n_2$, that characterizes the strength of the optical nonlinearity, can be expressed by [4]:

$$n_2 = \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_0} \tag{1.18}$$

The power dependence of the refractive index is responsible for the Kerr-effect. Depending on the type of input signal, the Kerr-nonlinearity manifests itself in different effects, including:

- self-phase modulation (SPM): implies that the nonlinear phase modulation is self-induced. In principle, the higher intensity portions of an optical pulse encounter a higher refractive index of the fiber compared with the lower intensity portions while it travels through the fiber. Since the intensity of the signal is time varying it generates a time varying refractive index in the medium. The leading edge will experience a positive and trailing edge a negative refractive index gradient. This temporally varying index change results in a temporally varying phase change, leading to different phase shift of the different parts of the pulse. The final result is frequency chirping, where the rising edge of the pulse is frequency shifted in the upper side, whereas the trailing edge experiences a shift in lower side. Hence, the primary effect of SPM is to broaden the spectrum of the pulse and simultaneously keeping the temporal shape unaltered. With an sufficiently high amount of dispersion the pulse will be temporal broadened, but with

equally distributed portions of SPM and dispersion, a soliton is formed which is neither dispersed in the temporal domain nor in the frequency domain. The SPM effects are more pronounced in systems with high-transmitted power because the chirping effect is proportional to transmitted signal power.

- cross-phase modulation (XPM): is a similar effect to SPM, but involves two or more optical pulses, for instance at different wavelengths, that can interact with each other via the alteration of the intensity dependent refractive index. XPM is always accompanied by SPM and occurs because the nonlinear refractive index seen by an optical wave depends not only on the intensity of that wave but also on the intensity of the other co-propagating waves. Therefore, XPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels. This effect can lead to asymmetric spectral broadening and distortion of the pulse shape, manifesting in degradation of system performance in optical communications.

- four wave mixing (FWM): The interaction of two or more light waves can lead to a second kind of $\chi^{(3)}$ nonlinearities, which involve an energy transfer between waves and not simply a modulation of the refractive index. If three optical fields with carrier frequencies $\omega_1, \omega_2, \omega_3$ co-propagate inside the fiber simultaneously, $\chi^{(3)}$ generates a fourth field with frequency $\omega_4$, which is related to other frequencies by a relation, $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$. Clearly there can be a large variety of such process, depending on the particular product of the four fields. SPM and XPM are significant mainly for high bit rate systems, but the FWM effect is independent of the bit rate and is critically dependent on the channel spacing and fiber dispersion. Decreasing the channel spacing increases the four-wave mixing effect and so does decreasing the dispersion.

In the global communications systems largely conventional silica fibers (type Corning SMF-28) used for data transmission. Since glass is a solidified liquid, there are small variations in material density and material composition. The size of the variations is in the range of the wavelength or less, which leads to minor changes in the refractive index. Such fluctuations in density, like impurities or thermal movement of particles in the material, are responsible for various kinds of scattering of the light in all directions of the space in an inhomogeneous material. There are basically two kinds of scattering:

- Elastic scattering, where the frequency of the scattered wave is identical to the incident wave,

- Inelastic scattering, where the scattered wave undergoes a frequency change with respect to the incident light wave.

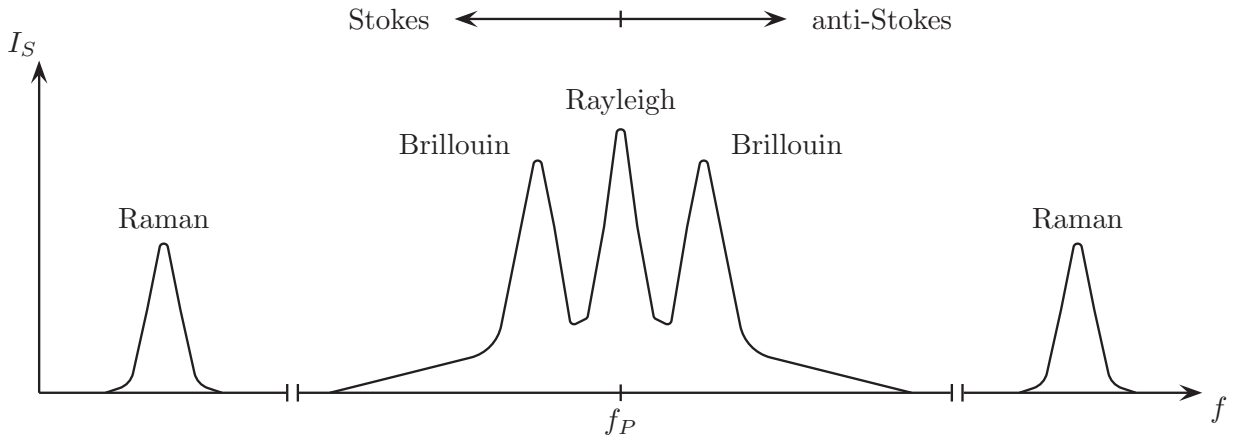


Figure 1.1.: Schematic representation of a typical spectrum of the scattering of light [4].

Under the most general circumstances, an incident light wave at the frequency $f_P$ that is coupled in a scattering medium generates a typical spectrum as shown in Fig. 1.1. By definition, those components of the scattered light which are shifted to lower frequencies are called Stokes components. Additionally, energy is transferred from the pump wave to the stokes wave, which means energy loss for the pump wave. Contrary, components that are shifted to higher frequencies are referred to as anti-Stokes components. Here the pump wave is accompanied by an energy gain. In general, the spectrum of the scattered light consists of the following components [4, 5]:

- Rayleigh scattering, caused by structural variations in the density of the medium. It is known as quasi-elastic scattering, because no frequency shift is caused. The scattering from the sides of the Rayleigh scattering is the result of fluctuations in positioning of the anisotropic molecules. Due to the very rapid molecular reorientation these components are spectral very broad.

- Raman scattering, which is formed by the interaction of light with the vibrational states of the molecules of the medium. Equivalently, Raman scattering can be described as the scattering of light by optical phonons. Thereby, the scattered light is spectral shifted by several tens of THz and a spectral width with a magnitude in the THz range.

- Brillouin scattering, the scattering of light by sound waves, which have their origin in density variations of the material. Brillouin scattering can also be considered as the scattering of light by acoustic phonons. Thereby, the frequency shift at telecommunications wavelengths is in the range of 10–15 GHz and spectral width is in the range of 10–30 MHz.

In principle, all scattering processes occur at arbitrary frequencies $f_P$ of the incident light wave, and are therefore not bound to narrow frequency ranges. All mentioned scattering processes can occur as [5]:

- Spontaneous scattering, which dominates at low power densities of the pump light wavelength. The scattered light is non-directional and the intensity is proportional to the pump wave. All spontaneous scattering processes have in common that the intensity of the scattering is proportional to the frequency $f_P^4$ or the wavelength $\lambda_P^{-4}$ of the pump wave.

- Stimulated scattering, where the power of a wave is amplified at the scattering frequency by the power of the pump wave. The emission of the scattered light occur, depending on the direction of propagation of the pump wave, in a preferred direction. The intensity of the scattered light is strongly non-linearly dependent from that of the pump light. The intensities of the stimulated scattering processes are, in contrast to the spontaneous scattering processes, only proportional to $f_P$ or $\lambda_P^{-1}$ of the pump wave.

In the red and near infrared spectral range of 600 nm to 1550 nm, the Rayleigh scattering forms the theoretical limit of attenuation. After the previous classification Rayleigh scattering is a spontaneous scattering process. If additional refractive index fluctuations are induced by spatially variable thermal effects due to light absorption in the medium, then the Rayleigh scattering will be increased. This process may be referred to as stimulated Rayleigh scattering and can play a role in high-power fiber lasers [6, 7].

Raman scattering is exploited in many applications [8]. One classical application is the fiber based Raman laser [9], which can be also realized on silicon waveguides [10, 11]. Additional, Raman scattering is utilized as amplifier in optical fibers. The Raman amplification may occur at any wavelength as long as an appropriate pump laser is available. Raman amplification may be realized as a continuous amplification along the fiber which let the signal never become too low. A Raman amplifier is bidirectional in nature and more stable. It has been shown, that Raman amplifiers have several advantages compared to Erbium doped fiber amplifiers, particularly when the transmission fiber itself is used as a Raman amplifier [12]. Especially the advantages of self phase matching and broad gain-bandwidth lead to advantages in wavelength division multiplexed systems [13]. However, a more detailed description about Raman scattering including the physical process, gain, spectral shape and threshold can be found in [4, 5, 14].

The effect of Brillouin scattering, including applications, will be explained more detailed in the following chapter. Therefore, chapter 2 starts with the physical process of spontaneous and stimulated Brillouin scattering, followed by the main parameters. Further a detailed

analysis of the polarization dependence is given. The remainder of the chapter focuses on possible applications of Brillouin scattering. As will be shown, most of the applications would benefit from a narrowed Brillouin gain bandwidth.

Accordingly, several methods for the Brillouin gain bandwidth reduction are introduced in chapter 3, accompanied with experimental evidence. First, an investigation of environmental influences and fiber properties on the bandwidth will be given. Afterward the bandwidth reduction by a multi stage system, the superposition of a Brillouin gain with two losses and the utilization of a frequency domain aperture will be introduced and explained in detail. The rest of the thesis will continue with selected applications in optical communication.

Chapter 4 will first give an introduction to classical optical spectrum analysis, followed by the utilization of polarization pulling assisted Brillouin scattering accompanied by a significant increase of the resolution through gain bandwidth narrowing. Furthermore, the Brillouin based optical spectrum analyzer will be connected with the technique of heterodyne detection to achieve unprecedented resolution.

Chapter 5 will introduce the delay and storage of light in general and subsequently focus on a new method called Quasi-Light-Storage, where the nonlinear effect of stimulated Brillouin scattering is exploited for the multiplication of a frequency comb with the power spectral density of a signal, leading to multiple time delayed copies of the signal. Through the utilization of the bandwidth narrowing methods the maximum storage time can be enhanced significantly. The basic theory, as well as possibilities and limits will be given.

The 6-th chapter utilizes Brillouin scattering as an narrow band optical filter for the processing of an optical frequency comb. Depending on the number of extracted lines, two main applications will be described. First the generation of high quality mm- and THz-waves including wireless transmission, and second, the generation of almost ideal sinc-shaped Nyquist pulse sequences. The last chapter will summarize the thesis and give an outlook for further enhancements and future applications.

# 2 Brillouin Scattering

Brillouin light scattering is generally referred to as inelastic scattering of an incident optical wave field by thermally excited elastic waves in a sample. The theoretical prediction of spontaneous light scattering on thermally excited acoustic waves was carried out in 1922 by namesake Léon Brillouin [15]. Leonid Mandelstam is believed to have recognized the possibility of such scattering as early as 1918, but he published his idea only in 1926 [16]. The experimental confirmation of spontaneous Brillouin scattering in liquids and crystals was performed in 1930 by Gross using a lamp as the light source [17]. After invention of the laser the effect of stimulated Brillouin scattering was first observed in 1964 by Chiao et al. [18]. In addition, the development of low-loss glass fibers was pushed by Corning and the Bell Laboratories in the 1970s [19], resulting in increased research towards optical-fiber transmission systems [20]. However, Brillouin scattering in optical fiber and especially the threshold of the stimulated process is well known since the early 1970s [21, 22]. The significance of stimulated Brillouin scattering (SBS) in fibers for optical communication systems was first described in detail by D. Cotter in 1983 [23]. Since then, the development of fibers and systems stride on and new insights were obtained [24].

Since its discovery, the SBS has affected optical systems in different ways. On the one hand it drastically limits the maximum transmittable power in standard single mode fibers [25]. Therefore, over the past decades several approaches for avoiding the detrimental effects of SBS or increasing the threshold were investigated, including the artificial broadening of the pump laser spectrum [26, 27], theoretically the utilizing of a single narrow band fiber Bragg grating along the fiber [28], isolators in the transmission system [29], changing the effective mode area and the doping of the fiber [30] as well as using fibers with different Brillouin shifts in the systems [31].

But on the other hand, stimulated Brillouin scattering offers a variety of applications in different fields. Besides the high resolution spectrum analysis, optical delay and quasi-light

storage as well as general signal generation and processing, as will be discussed in the forthcoming chapters, stimulated Brillouin scattering in fibers can be utilized for thermal and strain sensing [32–34] and ultra-narrow linewidth light sources [35, 36]. Applications from other fields of science include the analysis of bulk viscosity of liquids [37], the measurement of temperature of water and even the ocean [38], microscopic imaging [39] and even characterization of elastic properties of materials in geoscience [40].

This chapter will give a detailed overview about the fundamentals and the physical process of spontaneous and stimulated Brillouin scattering. Subsequently, the coupled energy equations and key parameters including gain, bandwidth, threshold and shift are discussed. Additionally, the chapter will show the polarization attributes of stimulated Brillouin scattering and give an introduction to the polarization pulling effect. Finally, different applications of stimulated Brillouin scattering are discussed.

## 2.1. Spontaneous Brillouin Scattering

The scattering of light is caused by inhomogeneities of refractive index in the media. In real inhomogeneous propagation medium static fluctuations of the local dielectric permittivity lead to elastic scattering of light in all directions. In optical fibers, thermally reasoned lattice vibrations (phonons) produce already density fluctuations in the medium that spread with velocity of sound. The spontaneous Brillouin scattering refers to the scattering of a light wave with the frequency $f_P$ on these thermally excited acoustic waves in a medium, as can be seen in Fig. 2.1 [5].

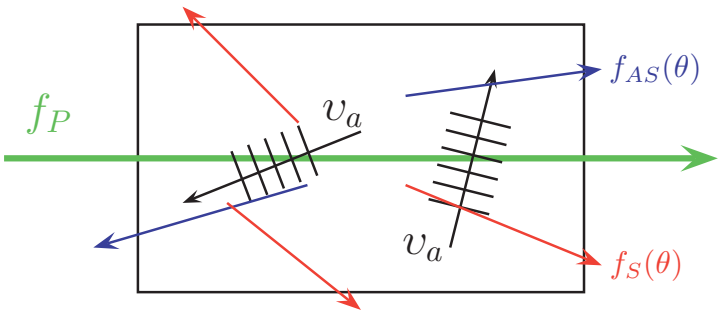


Figure 2.1.: Scattering process of spontaneous Brillouin scattering.

The sound waves propagate in the medium with the velocity $\upsilon_a$ and produce a periodic modulation of the refractive index of a medium due to the photoelastic effect. The diffraction and reflection of light waves on stationary periodic refractive index gratings is known in wave theory as Bragg reflection [2].

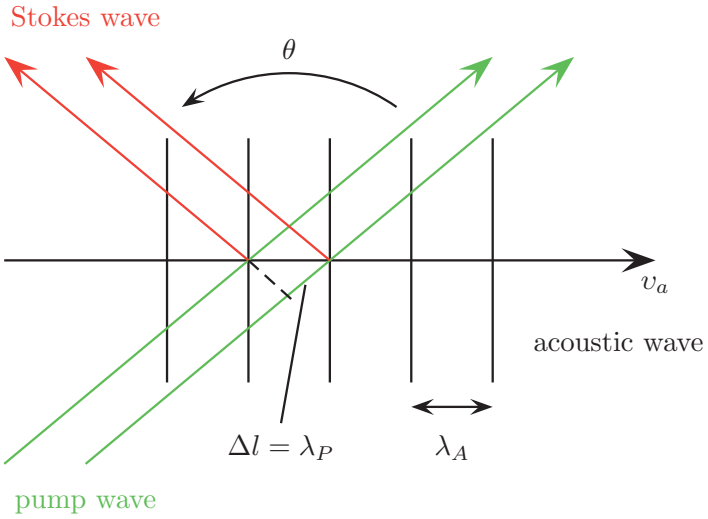


Figure 2.2.: Reflection of a light wave on a sound wave, which is represented by their phase fronts with the same density or refractive index gradient. Partial reflections of the pump light wave at the same refractive index gradient with the distance $\lambda_A$ of the sound wave will superimpose constructively to a scattered Stokes wave when the entire path difference is $\Delta l = \lambda_P$.

The wavelength of the sound wave $\lambda_A$ determines the spatial period of the refractive index modulation. At such a periodic refractive index a pump wave with the vacuum-wavelength $\lambda_P$ is reflected when the Bragg condition is satisfied:

$$\lambda_P = 2 n_P \lambda_A \sin \frac{\theta}{2} \tag{2.1}$$

where $n_P$ is the optical refractive index of the medium of the incident pump wave, and $\theta$ the angle between the propagation direction of the incident and the reflected beam, as can be seen in Fig. 2.2. The propagation direction of the sound wave in isotropic media is always perpendicular to the bisecting line of $\theta$. The scattered light wave experiences through reflection on the acoustic wave, which propagates with the speed of sound $v_a$, a frequency shift due to the Doppler effect:

$$f_S = f_P \left(1 - 2n \frac{v_a}{c_0} \sin \frac{\theta}{2}\right) = f_P - f_B(\theta) \tag{2.2}$$

$$f_{AS} = f_P \left(1 + 2n \frac{v_a}{c_0} \sin \frac{\theta}{2}\right) = f_P + f_B(\theta) \tag{2.3}$$

wherein at the same scattering angle $\theta$ a Stokes wave of smaller frequency $f_S$ is generated

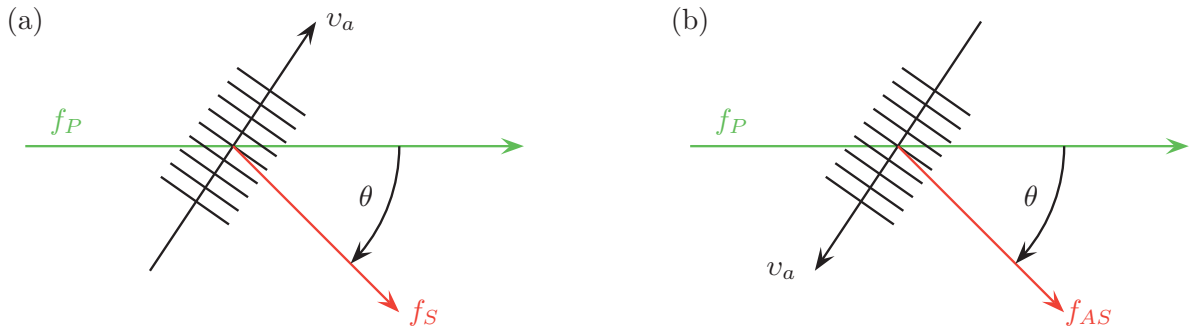


Figure 2.3.: Depending on the propagation direction of the sound wave $v_a$ with respect to the pump light wave with the frequency $f_P$, Brillouin scattering generates at a scattering angle $\theta$ a Stokes wave (a) with a smaller frequency $f_S$ or an anti-Stokes wave (b) with a higher frequency $f_{AS}$ with respect to $f_P$.

when the acoustic wave moves away from the pump wave, and an anti-Stokes wave with greater frequency $f_{AS}$ is generated when the sound wave moves towards the pump light wave, as can be seen in Fig. 2.3 [5].

The maximum frequency offset occurs during scattering in the reverse direction with $\theta = \pi$, and is referred to as material-specific Brillouin frequency shift $f_B$ or shortly Brillouin frequency with the angular frequency $\Omega_B$:

$$f_B = 2n\frac{v_a}{c_0}f_P, \qquad \Omega_B = 2\pi f_B \tag{2.4}$$

A comparison with Eqn. 2.1 shows that for $\theta = \pi$ the Brillouin frequency shift $f_B$ is equal to the acoustic frequency $f_A$ of the sound wave. The Brillouin shift in fused silica with a refractive index of $n = 1.445$ and a velocity of sound of $v_a = 5960\,\mathrm{m/s}$ at a pump wavelength of $\lambda_P = 1550\,\mathrm{nm}$, or $f_P = 193.4\,\mathrm{THz}$, is calculated to be $f_B = 11.1\,\mathrm{GHz}$. Which is caused by an acoustic wave with the frequency $f_A = f_B$. The Brillouin frequency shift $f_B$ is typically three orders of magnitude smaller than the frequency offset of Raman scattering. While the Raman frequency shift is independent of the pump frequency and a material constant, the Brillouin frequency shift is directly proportional to the pump frequency $f_P$.

Spontaneous Brillouin scattering on thermally excited sound waves also takes place in optical fibers. Due to the waveguide properties and the propagation of light in the z-direction, only the forward scattering in the same direction and back scattering in the opposite direction with respect to the pump wave that is guided in the core are relevant. A lateral scattering with large angle with respect to the fiber axis is not guided in the core, but radiated into the jacket and into the environment. The most important process is the back scattering (scattering angle $\theta = \pi$) of a pump light wave on a longitudinal sound wave propagating in