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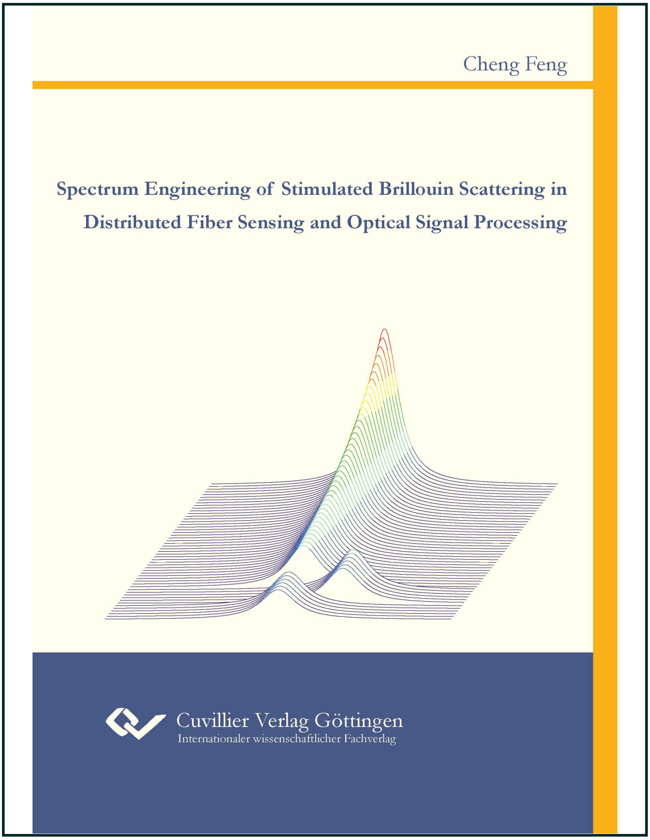
Spectrum Engineering of Stimulated Brillouin Scattering in Distributed Fiber Sensing and Optical Signal Processing



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1 Introduction

The field of optics and photonics has a long history. It starts with the development of lenses by the ancient Egyptians and Mesopotamians, followed by theories on light and vision developed by ancient Greek philosophers, and the development of geometrical optics in the Greco-Roman world. In between, the ancient Greek mathematician Euclid described the law of reflection at about 300 B.C., the Roman astronomer Ptolemy tried to experimentally derive the law of refraction in the 2nd century and the Persian mathematician and physicist Ibn Sahl discovered the full law of refraction in 984 B.C., which is later well-known as the Snell's law. Based on these behaviors, light is first treated as discrete particles which travel in a straight line with a finite velocity in Newton's corpuscular theory of light. Until Thomas Young and Augustin Fresnel demonstrated the interference and diffraction of light in 1801 and 1818, respectively, the wave theory of light proposed by the Dutch physicist Christiaan Huygens in 1678 has been accepted. Later on in 1865, the Scottish scientist James Clerk Maxwell deduced further that light is an electromagnetic wave, and can be well described by electromagnetic wave theory.

1.1. Basics of Electromagnetic Wave Theory

Like all forms of electromagnetic radiations, the optical wave also follows Maxwell's equations. Its well known mathematical expressions are as follows: [1, 2]

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1.1.1a}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{1.1.1b}$$

$$\nabla \cdot \mathbf{D} = \rho_f \tag{1.1.1c}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{1.1.1d}$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field vectors, respectively, with $\mathbf{D}$ and $\mathbf{B}$ as the corresponding electric and magnetic flux densities. The current density $\mathbf{J}$ and the carrier density ρ_f symbolize the sources of the electromagnetic field. For a light wave propagation in a dielectric medium without free electronic charges or currents, we have $\mathbf{J} = 0$ and $\rho_f = 0$. $\nabla\times$ and $\nabla\cdot$ represent the curl and divergence vector operators, respectively.

The relationship between the electric flux density $\mathbf{D}$ and the electric field $\mathbf{E}$ depends on the electrical properties of the medium, described by the dielectric polarization $\mathbf{P}$. The dielectric polarization is the electric dipole moment per unit volume of the dielectric material induced by an external electric field. In analog to this, 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 similarly to the dielectric polarization. The relations between the flux densities and the field strengths are given by: [1]

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \tag{1.1.2a}$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \tag{1.1.2b}$$

where ε_0 and μ_0 are the permittivity and permeability of vacuum. For a non-magnetic medium, such as optical fibers, $\mathbf{M} = 0$. In a homogeneous, linear, non-dispersive and isotropic dielectric medium, the polarization $\mathbf{P}$ is aligned to and proportional to the electric field $\mathbf{E}$, that is:

$$\mathbf{P} = \chi \varepsilon_0 \mathbf{E} \tag{1.1.3}$$

where the constant χ is the dielectric susceptibility. The substitution of Eq. (1.1.3) in Eq. (1.1.2a) yields:

$$\mathbf{D} = \varepsilon_0 (1 + \chi) \mathbf{E} = \varepsilon \mathbf{E} \tag{1.1.4}$$

showing that, $\mathbf{D}$ and $\mathbf{E}$ are also parallel and proportional. Here $\varepsilon/\varepsilon_0 = 1 + \chi$ is the relative permittivity of the medium.

The wave equation for the optical wave propagation can be derive with the elimination of $\mathbf{B}$ and $\mathbf{D}$ by taking the curl of Eq. (1.1.1a) and using Eqs. (1.1.1b), (1.1.2a) and (1.1.2b), leading to: [1]

$$\nabla \times \nabla \times \mathbf{E} = -\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2} \tag{1.1.5}$$

where $c = 1/\sqrt{\mu_0 \varepsilon_0}$ is the speed of light in vacuum. By applying a Fourier transform, we can get the wave equation in the frequency domain as: [1]

$$\nabla \times \nabla \times \tilde{\mathbf{E}} = \tilde{\varepsilon}\left(\omega\right) \frac{\omega^2}{c^2} \tilde{\mathbf{E}} \tag{1.1.6}$$

where $\tilde{\mathbf{E}}$ is the Fourier transform of $\mathbf{E}$, defined as

$$\tilde{\mathbf{E}} = \int_{-\infty}^{\infty} \mathbf{E} \exp(j\omega t) \mathrm{d}t \tag{1.1.7}$$

and $\tilde{\varepsilon}(\omega) = 1 + \tilde{\chi}(\omega)$ is the frequency-dependent relative dielectric constant, where $\tilde{\chi}(\omega)$ is the Fourier transform of χ. As $\tilde{\chi}(\omega)$ is in general complex, so is $\tilde{\varepsilon}(\omega)$. Its real and imaginary part represent the refractive index $n(\omega)$ and the absorption coefficient $\alpha(\omega)$ with the following definition: [1]

$$\varepsilon = (n + j\alpha c/2\omega)^2 . \tag{1.1.8}$$

Based on this definition, the refractive index and fiber attenuation can be derived as: [1]

$$n(\omega) = 1 + \frac{1}{2}\mathrm{Re}\left[\tilde{\chi}(\omega)\right] \tag{1.1.9a}$$

$$\alpha(\omega) = \frac{\omega}{nc}\mathrm{Im}\left[\tilde{\chi}(\omega)\right] \tag{1.1.9b}$$

where Re and Im denote the real and imaginary part, respectively.

If we assume the loss of the medium is low in the wavelength range of interest, the imaginary part of $\tilde{\varepsilon}(\omega)$ is small in comparison to the real part. Therefore, $n^2(\omega)$ can be used to replace $\tilde{\varepsilon}(\omega)$ for further simplifications to Eq. (1.1.6). Additionally, provided that the refractive index $n(\omega)$ is independent of the spatial coordinate, the vector identity $\nabla \times \nabla \times \mathbf{E} \equiv \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = -\nabla^2 \mathbf{E}$ with $\nabla \cdot \mathbf{D} = \varepsilon(\nabla \cdot \mathbf{E}) = 0$ can be utilized, leading to the following expression in form of the Helmholtz equation: [1]

$$\nabla^2 \tilde{\mathbf{E}} + n^2(\omega) \frac{\omega^2}{c^2} \tilde{\mathbf{E}} = 0. \tag{1.1.10}$$

1.2. Basics of Nonlinear Optics

If the external electric field to an atom is not too high, the shift of the internal carrier acts as a field-induced dipole moment that is parallel and proportional to the external field, as indicated by Eq. (1.1.3). However, with a strong external field strength, the electrons of the dipole move in nonlinear oscillations in the Coulomb potential, whose nonlinearity can no longer be neglected [2]. The invention of the laser in 1960 enables such a high intensity and thus discovers the variety of optical nonlinear effects.

The optical nonlinear effects can be both useful attributes and characteristics to be avoided. For electromagnetic fields with high intensities, the material polarization $\mathbf{P}$ of a homogeneous material is no longer proportional to the electric field $\mathbf{E}$ and can be extended by a Taylor series as: [2, 3]

$$\mathbf{P} = \varepsilon_0\chi^{(1)}\mathbf{E} + \varepsilon_0\chi^{(2)}\mathbf{EE} + \varepsilon_0\chi^{(3)}\mathbf{EEE} + \ldots = \mathbf{P_L} + \mathbf{P_{NL}} \tag{1.2.1}$$

where $\chi^{(k)}$ is the k-th order susceptibility. The dominant contribution to $\mathbf{P}$ is the linear susceptibility $\chi^{(1)}$, as described in Sec. 1.1. The second order susceptibility $\chi^{(2)}$ is responsible for the second order harmonic and sum-frequency generation. Another important effect related to $\chi^{(2)}$ is:

- Pockels effect: this linear electro-optic effect induces a refractive index change that linearly depends on the strength of the applied electric field [3]. It occurs in a medium (or crystal), whose molecule lacks inversion symmetry, such as lithium niobate ($LiNbO_3$) as the main material for electro-optic modulators [4]. Based on this principle, the modulator shifts the optical phase linearly by the external bias voltage (see Appendix B.1 for details).

For a medium with symmetric molecule, like silica as in the optical fiber, $\chi^{(2)}$ is degraded to zero. Therefore, optical fibers do not exhibit second order nonlinear effects, and the third order susceptibility $\chi^{(3)}$ is responsible for the third (also the lowest) order nonlinear effects in fibers [1]. The refractive index with the absence of the second order nonlinearity can be represented as [3]:

$$n = n_0 + n_2 I \tag{1.2.2}$$

where I is the intensity of the optical wave, defined as,

$$I = \frac{1}{2}c\varepsilon_0 n_0 |E_0|^2 \tag{1.2.3}$$

and n_0 is the linear (or low-intensity) refractive index. The nonlinear Kerr constant n_2 characterizes the strength of the nonlinear effects and can be expressed as: [3]

$$n_2 = \frac{3}{2}\frac{\chi^{(3)}}{c\varepsilon_0 n_0} \tag{1.2.4}$$

The power dependence of the refractive index leads to the Kerr effect, which includes:

- Self-phase modulation (SPM): indicates that the phase modulation can be self-induced. It occurs particularly when the intensity of the optical wave is not equally distributed in the time domain, such as a pulse. The higher intensity period of the optical wave faces a higher refractive index, while the lower intensity part encounters a lower one. Specifically for a pulse, the rising edge experiences a positive, and the falling edge a negative refractive index gradient. This time varying refractive index leads to a phase change of different parts of the pulse, also called frequency chirping. In frequency domain, this results in the rising edge shifting towards the higher frequency while the falling edge to the lower one. Whereas, the spectrum broadening will not change the original shape of the pulse in time domain.

- Cross-phase modulation (XPM): is a similar effect to SPM, but involves two or more optical waves, for instance in different frequencies, with time varying intensities. These waves interact with each other via changing the intensity dependent refractive index. Therefore, XPM is always accompanied with SPM and corporately results in a temporal phase shift that not only depends on the intensity of the optical wave itself, but also on the intensities of optical waves in other co-propagating channels. Specifically for a pulse signal, XPM will lead to an asymmetric spectrum broadening for the rising and falling edge, and a distortion on the pulse shape.

- Four wave mixing (FWM): generates a new light wave with frequency $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$ when three light waves with frequencies ω_1, ω_2, ω_3 are simultaneously co-propagating inside the nonlinear medium. In principle, all frequencies corresponding to different plus and minus sign combinations are possible. However, most of these combinations do not practically build up because of a phase-matching requirement [5]. A narrow channel spacing, a close-to-zero dispersion and other contributions to the phase matching [6, 7] will help to fulfill the requirement and thus significantly increase the FWM efficiency.

1.3. Scattering Effects in Optical Fibers

At the end of the 19th century, the first guidance of light through bent glass rods came into life. Although uncladded glass fibers were fabricated in the 1920s, the field of fiber optics was not born until the 1950s, due to the significant benefit of using the cladding layer brought to the fiber characteristics. These early fibers suffered an extreme loss of over 1000 dB/km. After intensive and continuous engineering in purity of the glass and the fiber properties, the fiber loss was finally dropped to only 0.2 dB/km in the 1550 nm wavelength region in 1979 [8]. The residual loss comes mainly from the phenomenon of Rayleigh scattering due to the inevitable impurity of the fiber.

The nonlinear effects in optical fibers result not only from the intensity dependence of the refractive index of the medium, as discussed in Sec. 1.2 , but also due to scattering phenomena. The scattering effects occur when the light is interacting with the medium due to thermal vibrations, impurity, etc. According to the scattered wave frequency, they can be categorized into elastic and inelastic scatterings. The scattered wave frequency in an elastic scattering is identical to that of the incident wave, while an inelastic scattering shifts the scattered wave frequency, due to an interaction with the medium usually with an energy and momentum conversion. Considering the most general scenario when an incident pump wave with the frequency ν_p is coupled into a standard single mode fiber (SMF), the scattered wave would form a spectrum as depicted in Fig. 1.3.1 [3]. Based on the definition, the frequency down- and up-shifted scattered waves are called Stokes and anti-Stokes waves, respectively. According to the energy conservation, the energy flows from the pump to the Stokes wave, while the anti-Stokes wave transfer energy to compensate the depletion of the pump.

The common types of scatterings are listed as follows according to their threshold in SMF:

- Rayleigh scattering: is the scattering of light due to the steady density fluctuations. It occurs when there is impurity in solid medium, and in liquid and gas even it is a pure media. It is known as the quasi-elastic scattering owing to the zero frequency shift. Since the medium molecular re-orientation process is very rapid, the Rayleigh spectrum is usually very broad, called Rayleigh-wing [3]. Rayleigh scattering is not directional and therefore can be observed almost in every direction. Rayleigh scattering determines the limit of the optical fiber loss. Due to the high sensitivity of the phase of the Rayleigh back scattering on the external strain and temperature, phase sensitive and coherent optical time-domain reflectometry (Φ-OTDR and COTDR) are widely used for distributed fiber sensing [9].

- Brillouin scattering: is the scattering of light from sound wave, *i.e.*, propagating density (or pressure) waves. From a quantum point of view, Brillouin scattering can also be

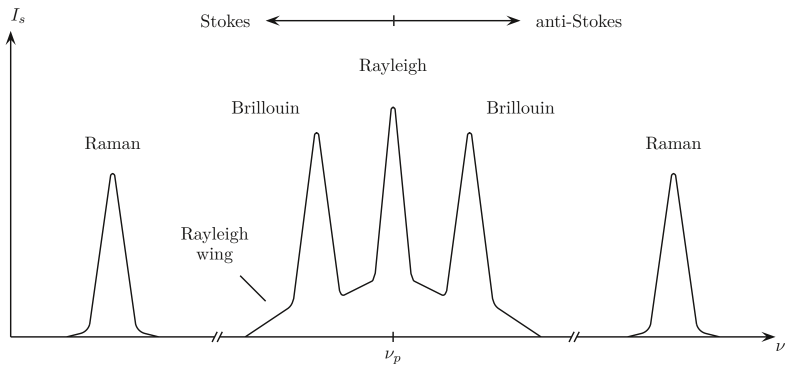

Figure 1.3.1.: Schematic of a typical spectrum of the scattering effects [3].

considered as a scattering of light by acoustic phonons. In the telecommunication wavelength range, the Brillouin scattering causes a frequency shift of around 11 GHz and has a linewidth of around 30 MHz. Its wide range of applications in the field of photonics will be introduced in the rest of this thesis.

- Raman scattering: results from the interaction of light with the vibrational modes of the medium molecules. It can also be equivalently described as a scattering of light by optical phonons. Since the vibrational modes of a molecule and their Raman spectral shifts are unique, the Raman scattering are widely used for spectroscopy. For optical fibers with the incident wave in the telecommunication wavelength range, the Raman scattering shifts the scattered wave frequency by tens of THz from the incidence wave frequency and has a linewidth of tens of THz. Due to the gain mechanism on the scattered waves, Raman amplifiers are widely used in the filed of laser physics and telecommunications [10]. The Raman gain dependence on the temperature enables the Raman scattering based OTDR and optical frequency-domain reflectometry (OFDR) technique to be one of the most popular options for distributed temperature sensing [11, 12].

1.4. Structure of the Thesis

After a general introduction of the fundamental knowledge in fiber optics, the specifications about Brillouin scattering and its applications will be explained in the following chapters of this dissertation. The following content is divided into 8 chapters:

In chapter 2, a detailed theory of Brillouin scattering specifically in optical fibers will be introduced. It starts with the process from spontaneous (SpBS) to stimulated Brillouin scattering (SBS), and lies an emphasis on its theoretical model and the gain spectrum characteristics. As will also be described in the following chapters, an engineered gain spectrum would benefit a variety of applications based on SBS.

Chapter 3 is devoted to one of the popular applications of SBS, namely the distributed fiber sensing. After the introduction of common configurations of distributed Brillouin sensors, we will mainly focus on the most consolidated technique, Brillouin optical time-domain analysis (BOTDA). An improved theoretical model based on the fundamental model of SBS in chapter 2 is proposed to this technique with a generalized solution. An overview on the updates and limitations of the technique is also provided.

In chapter 4 and chapter 5, the basic idea of gain spectrum engineering by exploiting the superposition of gain and loss(es) is applied on the static and dynamic BOTDA, respectively. In the proposed static technique, the gain spectrum is engineered to have sharper shape with higher contrast than the conventional one. In this way, the peak of the spectrum is more accurate to be estimated and more robust to the inevitable noise. In the proposed dynamic technique, the proposed gain spectrum is engineered so that the linear range of the spectrum is extended. This will benefit to slope-assisted sensing for a more accurate dynamic measurement with higher strain amplitude.

In chapter 6, a general picture of another popular application of SBS, namely the microwave photonic filter (MPF) is presented. The advantages and limitations of a conventional Brillouin based MPF regarding the key performances are reviewed. In chapter 7 and chapter 8, instead of the conventional Brillouin gain interaction, novel techniques based on Brillouin loss will be proposed for optical filtering and microwave photonic notch filtering (MPNF), respectively. The proposed optical filter blocks the undesired signal with Brillouin losses and leaves the passband signal transparent. The technique has successfully circumvented the Brillouin noise and proposes a solution to this bottleneck problem of the conventional Brillouin gain based filter. The investigation on the Brillouin loss based MPNF focuses on the impairments induced by the fiber dispersion on the filter performances. It is demonstrated that, any dispersion misalignment will drastically degrade the filter performance in terms of an undesired notch frequency shift and significant lower rejection.

In chapter 9, the summary of the works in the previous chapters is presented. As a perspective and future work, an idea to apply the out-of-phase signal cancellation on the BOTDA setup is proposed. According to the theoretical investigation, the proposed method would significantly improved the signal-to-noise ratio of the gain spectrum, bringing attractive benefits for slope-assisted dynamic measurements.

2 Brillouin Scattering

Brillouin scattering is named after the French physicist Léon Brillouin, who theoretically predicted the light scattering by a thermally excited acoustic wave in 1922 [13]. However, Soviet physicist Leonid Mandelstam is believed to have recognized the possibility of such scattering as early as 1918, but he published his idea only in 1926 [14]. In order to credit Mandelstam, the effect is also called Brillouin-Mandelstam scattering. The first experimental validation of this phenomenon was carried out in 1930 by Gross in crystals and liquids [15]. Limited by the available maximum optical intensity, only spontaneous process was observed at that time. Thanks to the invention of the laser, the process of stimulated Brillouin scattering (SBS) was first observed in 1964 [16]. As a popular telecommunication and nonlinear waveguide, the SBS effect in optical fibers has also been intensively studied. Its first successful experimental demonstration could date back to 1972 [17]. In the same year, the ultra-low threshold of SBS in the optical fibers was quantitatively determined [18], which makes it one of the most prominent nonlinear effects in optical fibers [19].

The investigations on the SBS in optical fibers have been split into different directions since its discovery. On one hand, the easy occurrence of SBS drastically limits the maximum incidence power and becomes a bottleneck of optical fiber communication. Several approaches have been proposed to overcome this detrimental effect, such as artificially broadening the pump spectrum [20]. On the other hand, besides microwave photonics filter and distributed sensing, which will be discussed in details in the following chapters, SBS can also be utilized in numerous applications in the filed of optics and photonics, such as fast/slow light [21–23], spectroscopy [24] and laser physics [25].

In this chapter, an overview of the physical procedures of SBS will be presented. From a simplified theoretical model and its steady-state solution, a general picture of the SBS will be provided and key issues, such as threshold and polarization dependence, will be discussed. Finally, different ways to engineer the spectral property of the Brillouin gain will be presented.

2.1. Bragg Scattering of Optical Waves by Sound Waves

The Brillouin scattering is the result of the deviation of an optical wave in a density modulated material. It can be well modeled by the interaction in a Bragg scattering cell schematically shown in Fig. 2.1.1 [3]. Provided that a traveling acoustic wave of frequency ν_A is established in a scattering medium and propagates with the velocity of v_A, its wavelength can be derived as $\Lambda = v_A/\nu_A$. The density modulation of the material leads to the periodical variation of the refractive index, and thus the incident optical wave is scattered as specified by Fig. 2.1.1. Due to the phase mismatch, the scattered wave intensity is usually weak. However, the total scattered field may become strong with the help of a constructive interference when the phase match condition given by,

$$\lambda_E = 2\Lambda \sin\theta \tag{2.1.1}$$

is satisfied, where λ_E is the wavelength of the incident light and θ is the incidence angle. This condition is also known as the Bragg condition and determines the maximum wavelength that can form a constructive interference in a specific structure.

We first consider the situation when the acoustic wave is propagating in the direction of the solid arrow of v_A in Fig. 2.1.1. Taking the conservation of energy and momentum, and the wave vector diagram into consideration, we may have,

$$\nu_S = \nu_E - \nu_A \tag{2.1.2a}$$

$$\boldsymbol{k_S} = \boldsymbol{k_E} - \boldsymbol{k_A} \tag{2.1.2b}$$

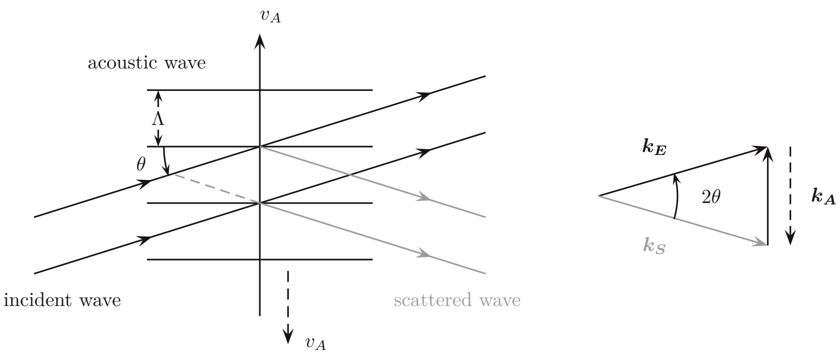

Figure 2.1.1.: Schematic of the Bragg scattering of an optical wave by an acoustic wave (left) and its wave vector diagram (right). The constructive interference will be formed when the optical path length difference between the scattered and incidence wave (dashed gray line) equals to the incidence wavelength.