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Research on frequency response effect of microwave photonic filter based on Brillouin effect

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Abstract. Stimulated Brillouin Scattering (SBS) effect is a typical third-order optical nonlinearity that can be generated in various media through the excitation by intense light. Due to the excellent characteristics of the SBS laser, such as low threshold, wide ultra-narrow line width, and counter-propagating scattering light of adjacent orders, it has been widely applied in fields like high-resolution spectrometry, optical sensing, and quantum computing. This paper utilizes the OptiSystem software for simulation and explores the integration of microwave filters with the SBS effect. Experimental results demonstrate the feasibility of adjusting the pump branch laser frequency to achieve tunable filter passband characteristics.

Keywords: Stimulated Brillouin Scattering, Brillouin Gain Spectrum, Microwave Photonic Filter.

1. Introduction

In today's rapidly advancing technological age, the demand for speed and accuracy in information transmission is increasing. Therefore, fiber optics naturally becomes the medium of choice for optimal transmission when modern communication networks need to convey information. Although the history of using fiber optics in communication is not long, the development of fiber optics has evolved over more than 100 years, both theoretically and experimentally. The Stimulated Brillouin Scattering (SBS) effect is a common and significant nonlinear optical effect in the field of optics, first experimentally verified in 1964. Scholars like Chiao and Townes observed it by irradiating quartz and sapphire with electromagnetic waves emitted by a microwave laser (Maser). The backward SBS effect induced by low-power lasers was first observed in optical fibers by researchers such as Ippen in 1972 [1]. The SBS effect is widely applied in optical fiber sensing, slow and fast light generation, and fiber optic gyroscopes, benefiting from its extremely low threshold, narrow linewidth, high coherence, and fixed wavelength spacing. In 2018, Wei Wei and others from Shanghai Jiao Tong University proposed an ultra-high resolution software-defined optical filter that incorporates the stimulated Brillouin scattering effect [2]. They introduced a high-resolution method for digital design. This method utilizes a digital-to-analog converter, allowing for greater controllability and the production of high-precision electromagnetic waveforms. Experimental results have shown the successful development of high-precision rectangular filters with a frequency range from 50MHz to 3GHz and a filtering suppression ratio of over 40dBm.

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2. Stimulated Brillouin Scattering

2.1. Nonlinear Effects in Optical Fibers

When a dielectric is placed in a high-intensity electromagnetic field, its optical response becomes nonlinear, and the same happens in optical fibers. The field applied to the medium changes the anharmonic oscillations of the bound electrons, causing the medium to produce a nonlinear response, thereby making the induced polarization strength P and the electric field E exhibit a nonlinear relationship (non-linear relations), yet still conforming to the following formula:

$$P = \varepsilon 0(\chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} \vdots EEE + \ldots)$$

In this equation, j represents the permittivity of free space, while (j)(j = 1,2,) denotes the jth-order electric susceptibility of the medium (jth-order polarization). The key contribution of P is reflected by its linear polarization and polarizabilities that have significant effects on the material's refractive index and attenuation coefficient. The second-order polarizability cannot produce nonlinear effects, such as second harmonic generation, in mediums where molecular structure has inversion symmetry, and its value is zero. Nonlinear effects in optical fibers are mainly determined by phenomena like third-harmonic generation, four-wave mixing, and nonlinear refraction, for example, third-order polarization. Self-phase modulation (SPM) and cross-phase modulation (XPM) are currently among the most extensively researched modulation techniques, which are nonlinear effects caused by nonlinear refraction.

2.2. Basic Principles of Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) refers to the process where pump light in a medium causes nonlinear interaction between the pump light and Stokes light through the electrostriction effect, generating sound waves. The acoustic phonons mentioned in the context of SBS actually refer to the propagation of ultrasound in optical fibers. Therefore, by exploring the acousto-optic properties in optical fibers, we can gain a deeper understanding of the SBS effect.

2.2.1. Forward Stimulated Brillouin Scattering

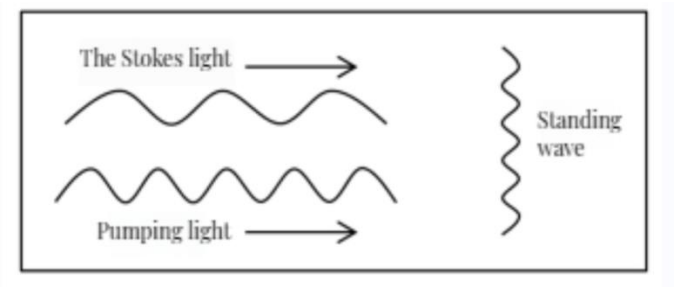


Figure 1. Forward Stimulated Brillouin Scattering

In optical fibers, if the sound waves generated by SBS are perpendicular to the propagation direction of the pump light, then the resulting Stokes light will propagate in the direction of the pump light. This phenomenon is known as forward SBS. Since the new frequency light generated by stimulated Brillouin scattering propagates in the same direction as the pump light, it results in a reduced signal-to-noise ratio for the required optical signal. As shown in Figure 1, with a pump wave frequency of ωP, it excites a transverse acoustic wave of frequency ΩA, which after interaction with the medium produces Stokes light of frequency ωS. Energy conservation requires that the frequencies of the pump wave, Stokes wave, and sound wave must satisfy the following equation:

$$\omega p = \omega s + \Omega A$$

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Meanwhile, momentum conservation requires that the wave vectors of the pump light and Stokes light meet the condition:

$$kp = ks$$

For forward-moving SBS, the frequency shift relative to the light frequency is very small, so the frequency difference between the pump light and Stokes light is minimal, leading to:

$$kp \approx ks$$

Thus, the phase matching condition can be approximately considered valid. Since optical fibers possess both optical and acoustical guiding properties, the phenomenon of forward SBS can be observed within the fibers.

2.2.2. Backward Stimulated Brillouin Scattering

In optical fibers, backward Stimulated Brillouin Scattering (SBS) generally occurs more easily than other nonlinear effects, primarily because its threshold power is very low, usually 2-3 orders of magnitude lower than that of Raman scattering. Generally, a narrower linewidth of the pump light is preferred, which might lead to a larger excitation energy level gap. Continuous wave or quasi-continuous wave pumping is often used to achieve higher SBS efficiency. Therefore, pump light sources with narrower pulse widths are selected to suppress SBS in fibers. The mechanism behind backward Brillouin effect is the inelastic scattering caused by the downward frequency shift of the Stokes wave, which in turn induces the transfer of sound waves. The difference between forward and backward scattering (SBS) mainly lies in the form of sound waves participating in the scattering process. The sound waves reaching SBS from the back differ from those from the front, with the former being predominantly longitudinal waves, aligning with the propagation direction of the pump light in the fibers. Therefore, to meet the phase matching condition, the Stokes light can only propagate backward as shown in Figure 2.

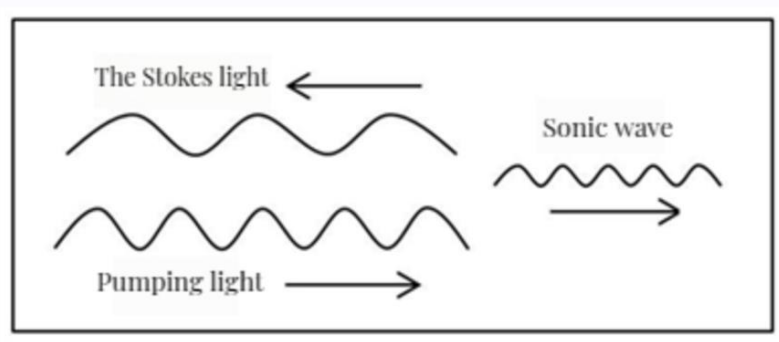


Figure 2. Backward Stimulated Brillouin Scattering

The optical field modes for both forward and backward SBS are obtained by solving the Maxwell equations. Due to the very small frequency differences among the multimode patterns of backward SBS, each Stokes wave's frequency difference is minimal. Therefore, if the frequency of this Stokes wave is still within the linewidth of the laser, the scattering peak does not seem significantly different from a single peak structure. The intensity of backward SBS can be calculated through the acousto-optic overlap integral, affected similarly by the interaction between the sound field and the optical field:

$$Ii = \frac{(\int |E|^2 uidxdy)^2}{\int |E|^4 dxdy \int |ui|^2 dxdy}$$

By calculating the overlap integral, the SBS gain spectrum can be obtained. Assuming a Lorenzian profile for the BG spectrum, the calculation formula for the BG spectrum is:

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$$SB(f) = \sum \frac{\frac{\Delta fB^2}{2}}{(f - fB,i)^2 + \frac{\Delta fB^2}{2}} Ii \frac{4\Pi n^8 p12^2}{\lambda^3 pcfB,i\Delta fB}$$

This estimation is generally feasible. From this, it is concluded that the pump wavelength is almost unrelated to the BG spectrum. Light tends to leak more towards the cladding, changing the overlap integral of the sound field and optical field, ultimately leading to a change in the BG peak value.

2.3. Summary of This Chapter

This chapter provides a comprehensive introduction to several common nonlinear effects principles in optical fibers. It focuses on the physical mechanisms behind backward SBS effects occurring within optical fibers. For SBS, only longitudinal waves play a role; hence, in calculations, it's sufficient to consider only the propagation modes of longitudinal waves.

3. Microwave Photonic Filters Based on Stimulated Brillouin Scattering

Microwave photonic filters are developed leveraging the scattering effect of Stimulated Brillouin Scattering (SBS). These filters typically incorporate a design that combines Phase Modulation (PM) with SBS [3-5], utilizing the SBS effect for their construction. Initially, light carriers are emitted from a laser source to a modulator, phase-modulated by the radio frequency (RF) signal. With the aid of an optical haloformer in the fiber, the signal light and pump light are transmitted in opposite directions, triggering the SBS effect (SoundBridgeBurrynDistribution, SBS). This causes phase modulation to be converted into intensity modulation, preventing the mutual cancellation of the two mixed signals, which are the upper and lower sidebands and the carrier beat afterward. Finally, the required RF signal is obtained through frequency beating by a photodetector.

3.1. Generation of the Pump Signal

The focus on microwave filters involves controlling the optical frequency comb as the pump signal, aiming for the reconfigurability of the passband. Considering the need for precise control over the frequency spacing and amplitude of each frequency component of the pump optical frequency comb via external modulator modulation, an optical frequency comb is generated, and a few RF signals are simply coupled to produce a Brienton pump structure diagram as shown in Figure 3. Initially, the light signal output from the laser diode (LD) enters a dual-parallel Mach-Zehnder modulator (DPMZM) driven by the RF signal to generate a single-sideband modulation signal. After amplification to a sufficiently high power by an Erbium-Doped Fiber Amplifier (EDFA), the modulated signal can serve as the Brillouin pump (PUMP) signal, with carrier suppression achieved. Here, the function of the Polarization Controller (PC) is to control the polarization state of the pump light, maximizing the Bridge gain.

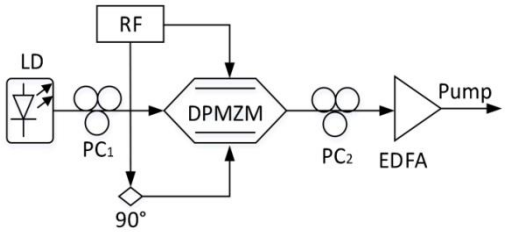


Figure 3. Brienton Pump Structure Diagram

3.2. Structural Design of Microwave Photonic Filters Based on the Stimulated Brillouin Scattering Effect

The schematic diagram of the microwave photonic filter system, as shown in Figure 4, is designed based on the Stimulated Brillouin Scattering effect and divided into two main parts. In the upstream branch,

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light emitted from the laser diode (LD1) is introduced into the Phase Modulator (PM), driven by an external RF signal (RF1) to produce a modulated signal. After processing through an optical isolator (ISO), optical attenuator (OA), etc., the modulated signal is then outputted. It enters the Single Mode Fiber (SMF) in the forward direction. In the branch, light from the laser diode (LD2) is inputted into the Dual Parallel Mach-Zehnder Modulator (DPMZM), modulated by an additional RF signal (RF2). After parameter adjustment, a carrier-suppressed single-sideband signal is obtained, then amplified to generate strong pump light for wavelength conversion. The optical signal is inputted in reverse into the single-mode fiber, passing through an optical circulator (OC). When the signal light intersects with the pump light in the single-mode fiber, the Bridge scattering effect is triggered. Eventually, the two light signals converge after the optical circulator (PD) and are inputted into a photodetector (Photodetector), generating the required signal through photoelectric conversion.

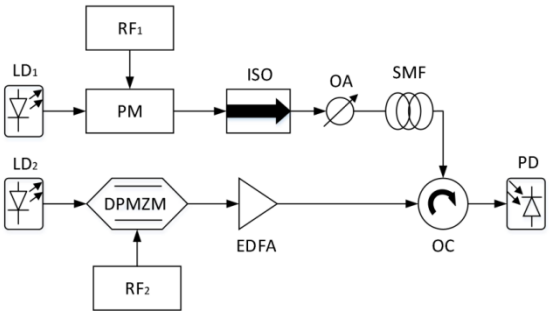


Figure 4. Schematic Diagram of the Microwave Photonic Filter System

4. Frequency Response Characteristics of Microwave Photonic Filters Based on Stimulated Brillouin Scattering

Initially, we analyze the principles depicted in the diagram based on theoretical calculations: In this scenario, the frequencies of both lasers are set to 1550nm, approximately 193.41448 THz. In the upper branch, a 3GHz sinusoidal signal is used for the RF signal input in project management. The frequencies of the first order above and below the phase-modulated signal output by the PM are 193.41748 THz and 193.41148 THz, respectively. Both have comparable amplitudes but are complementary in positioning. In the branch, three sinusoidal signals spaced 20MHz apart are chosen as the input for the RF signal, with a central frequency of 14GHz. The DPMZM's parameters are set to output the first-order sideband signal with carrier suppression at 193.42848 THz. The frequency interval of the three sinusoidal signals is set to 20 MHz, and then the mixed signal is amplified through an amplifier to a sufficiently high power to serve as the pump light source. Each sinusoidal signal, upon encountering the branch signal in the fiber, causes the SBS effect, leading to the overlay of gain spectra and further widening its bandwidth. Theoretically, the center frequency of the generated Brillouin gain spectrum should be 193.41748 THz, as the Brillouin frequency shift is set to 11GHz. The upper-order band signal produced in the upper branch falls precisely within this gain region, thus achieving amplification of this band signal. Eventually, the signals from these two paths enter the photodetector through the optical haloformer, thereby generating the required filtering signal. Below, the simulation software OptiSystem is used to verify the above theory. First, the system diagram listed above is constructed using OptiSystem, and the mentioned parameters are set. The frequency response diagram of the filter and the simulation-derived partial zoom-in as shown in Figure 5.

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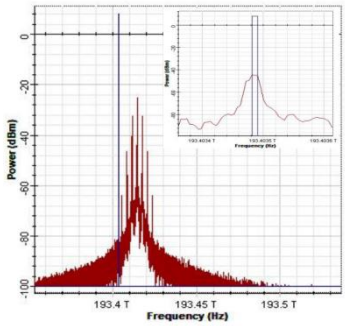


Figure 5. Filter Frequency Response Diagram

Subsequently, we altered the frequency of the pump branch laser and observed the center frequency of the Brillouin gain spectrum, as shown in the experimental results of Figure 6 (a) (b) (c).

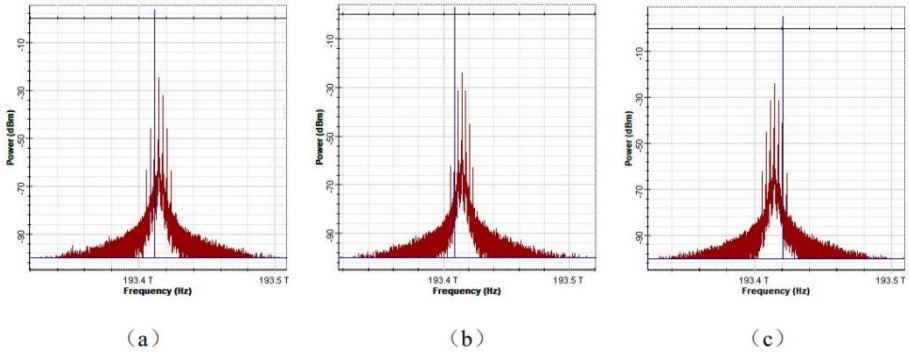


Figure 6. Center Frequency of the Brillouin Gain Spectrum
(a) f=193.41148 THz; (b) f=193.40848 THz; (c) f=193.42048 THz

It is known from the observation of the diagrams that the center frequency of the Brillouin gain spectrum varies. Conclusion: By adjusting the frequency of the pump branch laser, the center frequency of the filter can be tuned, hence the tunability of the filter's passband center frequency is achieved, thus the center frequency of the Brillouin gain spectrum can be changed.

5. Pump Power Influence on Filter Output Power

Figure 7 shows the relationship between the sinusoidal signal input in the pump branch, as well as the pump light power and different filter output powers with different input laser powers of the filter at various frequency intervals. From the graph, it is observed that when the frequency intervals of the sinusoidal signal input into the pump branch are 30MHz (triangular line), 20MHz (dotted line), and 15MHz (square line), respectively, corresponding to N = 3, N = 5, N = 7, both the pump signal power and the filter output power increase as the input power of the pump branch laser increases. When the input power is the same, the output power of both the pump signal and the filter also increases as the frequency interval of the sinusoidal signal input into the pump branch decreases.

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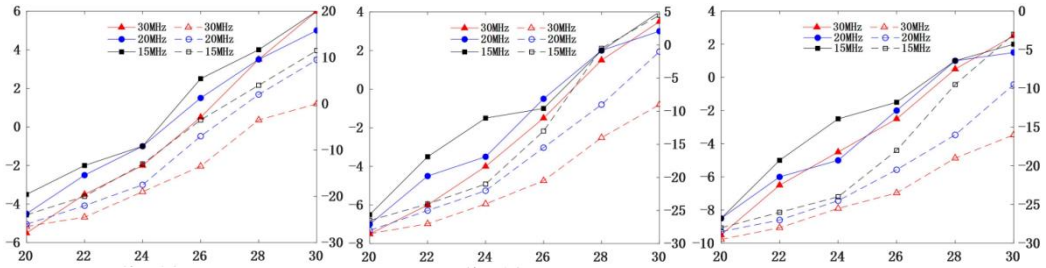


Figure 7. Variation Diagram of Pump Signal and Filter Output Power

6. Summary

The article initially introduces a design combining the SBS effect with microwave photonic filters, elaborating on the composition structure and working principle of the filter, as well as the system's composition structure and working principles, thereby generating the pump signal. The next step draws conclusions through simulation: The adjustability of the microwave photonic filter can be achieved by adjusting the frequency of the input laser in the pump branch. Finally, the simulation and analysis of the key factors affecting the filter output power are presented, which are the power of the pump and the length of the fiber.

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