Characterization of SBS Gain and Loss Spectra Using Fresnel Reflections and Interaction of Two Sidebands

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Abstract: A compact single-ended setup for stimulated Brillouin scattering (SBS) spectra characterization is proposed based on microwave modulated optical sidebands and Fresnel reflection in optical fibers. The measured spectra agree well with the theoretical lorentzian profile.

OCIS codes: (060.2270) Fiber characterization; (290.5900) Scattering, stimulated Brillouin.

1. Introduction

Stimulated Brillouin scattering (SBS) effect in optical fibers has found tremendous beneficial applications, such as optical amplification, photonic microwave signal processing, and fiber-optic sensors [1-3], due to its narrow-band spectra and low threshold. For these applications, both the amplification and depletion process of SBS effect have been utilized. Therefore, it is highly desired to characterize the spectra of SBS gain and loss accurately. Especially, a single-ended configuration for measurement of SBS spectra and Brillouin frequency shift is highly desired [4]. Until now, a number of techniques have been proposed to measure SBS spectral characteristics [5-8]. The most commonly used setup for SBS spectral characterization is mainly based on two separated lasers to generate pump and probe light, which suffers from the wavelength fluctuation of the two lasers [5]. A possible solution to this problem is presented by using a single laser source together with an external modulator to generate the interacting lightwaves, but this method is not suitable for the measurement of the depletion-induced SBS loss spectra [6]. A. Loayssa et al have proposed two techniques to overcome these limitations based on Brillouin fiber laser and optical single-sideband modulation, respectively [7,8]. However, their experimental setups seem complex and a single-ended configuration is unavailable.

In this letter, we present a single-ended configuration for SBS spectral characterization using optical carrier suppression (OCS) modulation and Fresnel reflection in optical fibers. The first-order sidebands generated by OCS technique are used as the pump signal, and introduced to the fiber under test (FUT). The backward Fresnel reflections at the cleaved end of the FUT act as the probe signal, and experience the amplification and the depletion caused by the upper and lower-frequency sideband of the pump signal, respectively. By sweeping the microwave frequency around half Brillouin frequency shift and monitoring the power of each sideband, SBS gain and loss spectra can be obtained simultaneously without additional pump laser source and broadband photodetector.

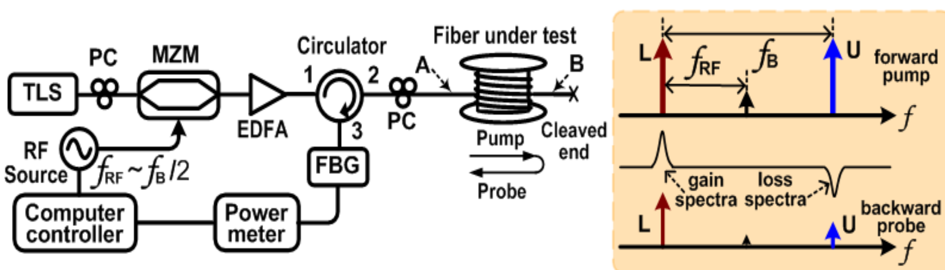

Fig.1. Experimental setup and operation principle. TLS, tunable laser source; PC, polarization controller; MZM, Mach-Zehnder modulator; EDFA, Erbium-doped fiber amplifier; FBG, fiber Bragg grating; U: upper sideband; L: lower sideband.

2. Operation Principle and Experimental Setup

The schematic of the proposed scheme is shown in Fig. 1. A continuous wave (CW) light from a tunable laser source (TLS) with a linewidth of less than 300 kHz (Yokogawa AQ2201) is launched to a Mach-Zehnder modulator (MZM) (Avanex PowerBit F-10), which is driven by a microwave signal from a microwave signal generator (Anritsu 68347C). The MZM is properly biased at the transmission null point to generate OCS signal. Then the generated first-order sidebands are amplified by an Erbium-doped fiber amplifier (EDFA), and introduced to the subsequent FUT, where they interact with the probe signal generated by the Fresnel reflection. The two sidebands of pump signal stimulate the SBS effect in the FUT, and the interaction between the pump and probe signal is described schematically in Fig. 1. Finally, the back-reflected probe sidebands appear at the port 3 of the circulator, and one of them is detected by a power meter after passing a fiber Bragg grating (FBG) with central wavelength of 1558.78 nm and 3 dB bandwidth of 0.06 nm. By setting the wavelength of the TLS at 1552.71 nm or 1552.84 nm, the upper and lower-frequency sideband is detected by the power meter, respectively. Both the microwave signal generator and the power meter are controlled and synchronized by a computer. Therefore the results of the power meter are recorded by the computer, while the microwave frequency is swept with a step of 1 MHz. It is noted that, the power variation is monitored using a low-frequency detection scheme instead of a broadband photodetector.

The gain and loss spectra of the SBS in optical fibers are supposed to have a Lorentzian profile in the linear amplification region and a Gaussian shape in the saturated amplification region [9]. Generally, most of the SBS spectra characterization schemes are based on the un-depleted pump approximation [4-7]. And our objective is to provide precise SBS gain and loss spectra simultaneously in the un-depleted pump regime. The Brillouin gain and loss spectra can be measured by sweeping the modulation frequency f_{RF} in the vicinity of the half Brillouin frequency shift $f_B/2$. After OCS modulation, the optical field at the output of the MZM is given by

$$E_{Pump} = A_{-1}\exp j\left[2\pi(v_0 - f_{RF})t\right] + A_{+1}\exp j\left[2\pi(v_0 + f_{RF})t\right] \quad (1)$$

where A_{-1} and A_{+1} are the complex amplitudes of the lower and upper sideband, respectively. The two first-order sidebands with frequency spacing of $2f_{RF}$ propagate through the FUT acting as the pump signal, and generate the Fresnel back-reflected probe signal accordingly. When f_{RF} is close to $f_B/2$, the lower probe sideband will be amplified by the incident upper pump sideband, and the upper probe sideband will be depleted by the incident lower pump sideband through SBS process. Therefore at the output port 3 of the circulator, due to the amplification and depletion process arising in SBS effect, the intensity of two probe sidebands before the FBG are given by [6]

$$\begin{aligned} I_{-1} &= I_{-1}^{B}\exp\left\{g_{gain}(v)I_{+1}^{A}L_{eff} - \alpha L\right\} \\ I_{+1} &= I_{+1}^{B}\exp\left\{g_{loss}(v)I_{-1}^{A}L_{eff} - \alpha L\right\} \end{aligned} \quad (2)$$

where I_{-1}^{A} and I_{+1}^{A} are the pump intensity of lower and upper sideband at the near end A of the FUT; I_{-1}^{B} and I_{+1}^{B} are the probe intensity of lower and upper sideband at the far open end B of the FUT, respectively; L_{eff} represents the usual effective interaction length for nonlinear effects; α is the fiber loss coefficient, and L is the total fiber length. Since only 4% power of input signal is reflected back from the air–silica interface due to the Fresnel reflection, the power of the incident pump sidebands is around 14 dB larger than that of the reflected probe ones. Therefore, the amplification of the lower pump sideband caused by upper probe sideband is very weak. Nevertheless, the depletion of the upper pump sideband by lower probe one can not be neglected, and this may result in the variation of I_{+1}^{B}, which can be represented as

$$I_{+1}^{B} = R\cdot\left(I_{+1}^{A} - \Delta I_{+1}^{A}\right) \quad (3)$$

where R is the Fresnel reflection index and ΔI_{+1}^{A} is the depletion power of the upper pump signal. According to (3), some amending can be made for the measurement results, Furthermore, due to the small R, the impact of the pump depletion can be greatly reduced.

3. Experimental Results and Discussion

The spectra of the FBG, the first-order sidebands before and after the FBG are measured when a 5.4-GHz microwave signal is introduced to the MZM. In Fig. 2(a), the TLS is set at 1552.84 nm, the lower sideband (frequency domain) is detected and the SBS gain spectra can be obtained by sweeping the microwave frequency. Similarly, the SBS loss spectra can be measured by adjusting the wavelength of TLS at 1552.71 nm. In order to demonstrate the interaction of the pump and probe sidebands due to the SBS effect, we set the wavelength of the TLS at 1552.84 nm. By setting the microwave frequency at three values close to half Brillouin frequency shift, we get the spectra of the probe signal before the FBG, as shown in Fig. 2(b). There is no obvious interaction between the pump and probe signals when microwave frequency is set at 4.423 GHz or 6.423 GHz. However, when the microwave frequency becomes 5.423 GHz, the upper sideband is depleted and the lower sideband is amplified due to the SBS effect. We also observed that the second-order lower sideband at frequency $v_0 - 2f_{RF}$ is amplified by the suppressed optical carrier at v_0 because of their frequency spacing falling within the Brillouin gain spectra. However such interference to our measurement can be neglected due to the large carrier suppressed ratio of more than 20 dB.

We use our proposed approach for characterizing different fibers including a 20-km standard single mode fiber (SSMF) and a 2.7-km highly nonlinear fiber (HNLF). As shown in Fig. 2(c), the SBS gain spectra of 20-km SSMF and 2.7-km HNLF is measured at several pump power levels, when the wavelength of the TLS is set at 1552.84 nm.

It can be observed that, the measured gain spectra agree well with the theoretical lorentzian profile. Apart from the detailed characterization of the gain spectral profile, the measurements also provide precise information on the Brillouin frequency shift, which is 10.846 GHz for the 20-km SSMF and 9.262 GHz for the 2.7-km HNLF at room temperature. Furthermore, the 3 dB Brillouin linewidth of the SSMF and HNLF are found to be 36 MHz and 44 MHz, respectively. When the wavelength of the TLS is adjusted at 1552.71 nm, the SBS loss spectra can be obtained. Fig. 2(d) presents a characterization of SBS loss spectra for the same SSMF and HNLF with different pump powers. Those experimental results verify that the proposed measurement approach can be used to characterize both the SBS gain and loss spectra with the same single-ended configuration simultaneously. The above measurements are carried out by sweeping the microwave signal generator with a step of 1 MHz. The resolution of SBS spectral can be further improved in order to obtain more detailed measurement results. In the experiment, the depletion of the pump power and the amplified spontaneous emission (ASE) power has an impact on the measurement. The SBS spectra value at the edge of the profile is over-estimated due to the ASE power.

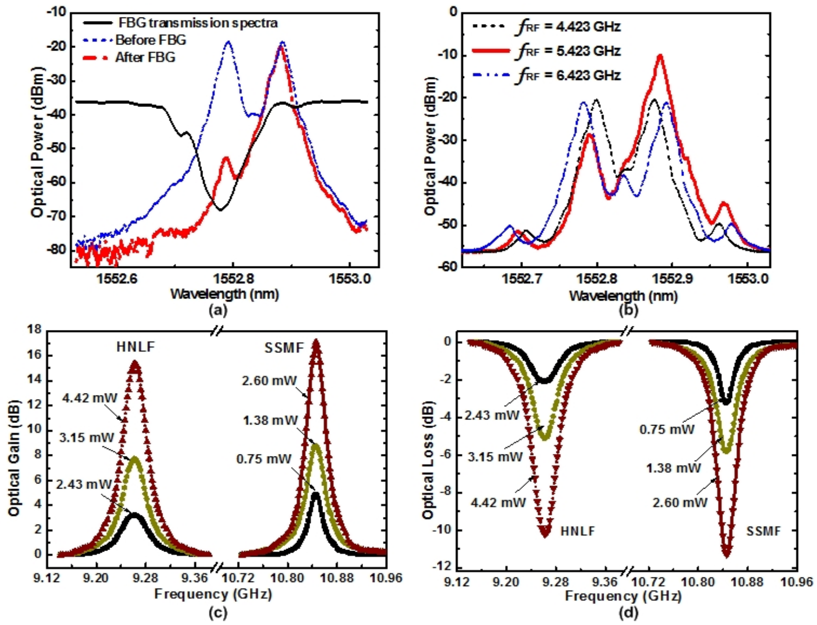

Fig.2. Optical spectra of (a) the FBG and (b) the backward reflected sidebands before FBG; SBS (c) gain and (d) loss spectra in a 20-km SMF and a 2.7-km HNLF with respect to the pump power.

4. Conclusions

We have proposed and experimentally demonstrated a simple and stable technique for SBS spectral characterization based on the OCS modulation and Fresnel reflection. The single-ended measurement configuration has been proved to provide precise measurement of SBS gain and loss spectral simultaneously. The measurement implemented with a single-ended configuration has shown many advantages such as immunity of the laser frequency fluctuation and compact setup without additional pump laser source and broadband photodetector.

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