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Measurement of the Brillouin Gain/Phase Characteristics in Optical Fibers Using a Double-Modulation Technique of a Single Light Source

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Abstract

We propose a simple measurement method of the Brillouin gain/phase characteristics in optical fibers based on the pump and probe technique using a doubly-modulated single light source. Our method is based on the phenomena that an intensity modulated optical waveform having the same order of the Brillouin bandwidth is distorted by the Brillouin phase and gain spectra. The availability of the method is studied analytically and experimentally.

Introduction

Stimulated Brillouin scattering (SBS) in optical fibers is one of dominant nonlinearities caused by an interaction between optical field and acoustic wave. While the SBS limits the optical power that can be transmitted in fiber-optic systems, it also can provide optical amplification with high efficiency [1]. Although the SBS has a high optical gain with a relatively low pump power, it is not suitable for signal amplification in optical communication system because of its very narrow gain bandwidth of several tens of MHz.

Recently, the large phase change accompanying with the narrow and high gain spectra of the SBS has been remarked from a viewpoint of all-optical signal processing. This large phase change causes the higher group index in optical fibers, and then it let incoming optical pulses transmit more slowly than its original speed [2]. This phenomenon is called “slow light” and is considered to apply for a light-controlled optical delay line or an optical buffer that may be indispensable for future all-optical packet routers. Accordingly, the precise measurements not only for the Brillouin gain spectra (BGS) but also for its phase spectra (BPS) are very important so as to fully understand the slow light.

In this paper, we present a simple method to estimate the Brillouin phase characteristics as well as the SBS gain profile in optical fibers. Our method utilizes the phenomena that the waveform of the intensity-modulated (IM) probe light at the modulation frequency comparable to the Brillouin bandwidth is distorted when it is amplified by the Brillouin gain with the large phase characteristics. The availability of the proposed method is analytically and experimentally investigated.

Principle of the Brillouin gain/phase measurement

Figure 1 shows the measurement setup of the Brillouin gain/phase characteristics. A single frequency CW light from an external cavity laser (ECL) is divided into two streams by an optical coupler and the one is used as the SBS pump after amplified by an Er-doped fiber amplifier (EDFA). The other is phase-modulated at frequency f_{PM} by a $LiNbO_3$ phase modulator. The modulation frequency f_{PM} is adjusted to about 10-11 GHz corresponding to the Storks shift of the test fiber, and the lower first sideband of the PM light is used as a probe light. This setup enables precise frequency scanning of the probe light with high stability since the frequency difference can be controlled only by the RF signal regardless of the pump wavelength. In order to measure the gain/phase characteristics, the probe light is successively intensity modulated at f_{IM} by a $LiNbO_3$ intensity modulator and then input into the test fiber from the opposite port to the pump light.

Figure 2 shows the principle of the Brillouin gain/phase measurement. The Brillouin gain spectrum in optical fibers is assumed to have an ideal Lorenzian shape function and its phase spectrum is described by its derivative as shown in the Fig. 2. When the modulation frequency of the probe light f_{IM} is the same order of the Brillouin bandwidth, each spectrum component of the IM probe light experiences different gain and large phase shift as well, according to the probe frequency location relative to the BGS. This situation changes the intensity and phase relationship between each IM spectrum

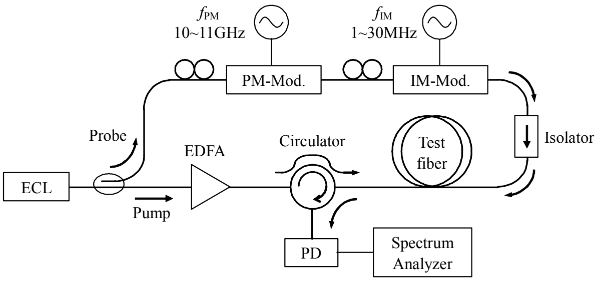

Fig.1 Measurement setup of the Brillouin gain/phase characteristics using a double-modulation technique.

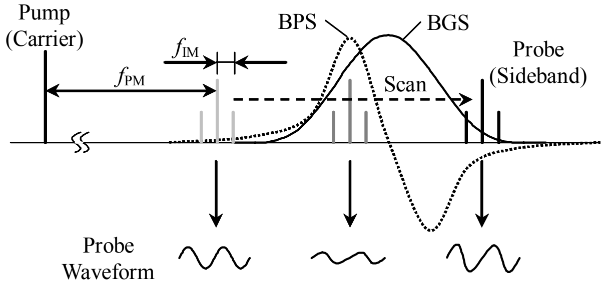

Fig.2 Principle of the Brillouin gain/phase measurement using an intensity-modulated probe light.

component and gives rise to modification (distortion) of the output probe IM waveform. Since this waveform modification strongly reflects the phase characteristics of the SBS, we can estimate the phase characteristics by analyzing the output probe waveform. The gain characteristics can also be estimated in the same manner when the lower frequency IM modulation is applied.

To simply evaluate the waveform modification, we utilize the f_{IM} component of the output probe waveform because it can be easily measured with an RF spectrum analyzer after O-E conversion. We have analyzed and measured the f_{IM} component of the output probe waveform depending on the frequency difference between pump and probe by scanning f_{PM}, taking into account the Brillouin gain/phase characteristics.

Numerical simulation results

Figure 3 (a) shows the assumed BGS and BPS used in the simulation that is calculated from the Lorenzian function. The gain bandwidth Δf_G is set to 20 MHz. The β shows the maximum phase shift of the BPS and Δf_P is the frequency width between the extremal points of the BPS. Fig. 3 (b) and (c) show simulated results of the f_{IM} component power after the gain and phase of IM probe light are changed by SBS, assuming f_{IM}=1 MHz and 30 MHz, respectively. The horizontal axis shows the relative probe frequency location to the Storks shift. Each simulated curve shows the case when the β is assumed to 0, 0.8, 1.0, 1.2, 1.4 rad, respectively. The BGS can be obtained from the f_{IM} component power profile of f_{IM}=1 MHz regardless of the maximum phase shift β. When the f_{IM}= 30 MHz, we can see the extremal points of the BPS causes the dip in the f_{IM} component power profile and its depth has the correlation with the magnitude of the β. Therefore, if we measured the frequency location and depth of the dip, we can obtain the values of β and Δf_P.

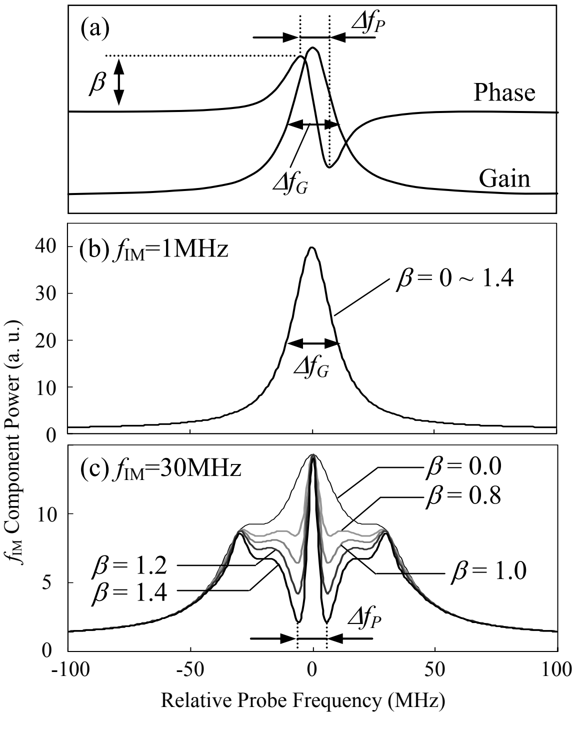

Fig.3 (a) Assumed Brillouin gain/phase spectra. (b)(c) Simulated f_{IM} spectrum power profile.

Experimental results

Figure 4 shows the measured f_{IM} component power as a function of f_{PM}, that corresponds to the frequency difference between the pump and probe lights, when we measured a conventional single mode fiber with the length of 1.3 km. The pump power is 40 mW and the f_{IM} is (a) 1 MHz and (b) 30 MHz. The similar f_{IM} spectrum distribution is observed as compared with the simulation results. From the results of f_{IM}=1 MHz, the Δf_{G}=12 MHz is obtained. From the results of f_{IM}=30 MHz, we can clearly see two dips of the f_{IM} component power in both sides of its peak at 10.802 GHz, which corresponds to the Storks shift. The measured Δf_P from these dips is about 9 MHz. From the comparison to the simulation results, the maximum phase shift β of the sample SMF is estimated to 1.4 rad. In the measured result, however, the asymmetric characteristic is observed. This might be due to the slightly asymmetric BGS caused by the inhomogeneity along the fiber length.

Conclusion

We have presented a new measurement method of the SBS gain and phase characteristics in optical fibers using the doubly-modulated single light source utilizing the SBS-induced waveform distortion of the IM probe light with peculiar frequency. We successfully demonstrated that the frequency width Δf_P of the Brillouin phase spectra can be measured from the dips of the f_{IM} component power profile and the maximum phase shift β can be estimated by comparing with the simulation.

References
[1] N. A. Olsson *et al.*, Appl. Phys. Lett., **48**, pp.1329, 1986.
[2] K. Y. Song *et al.*, *Opt. Lett.*, **30**, pp.1782, 2005.

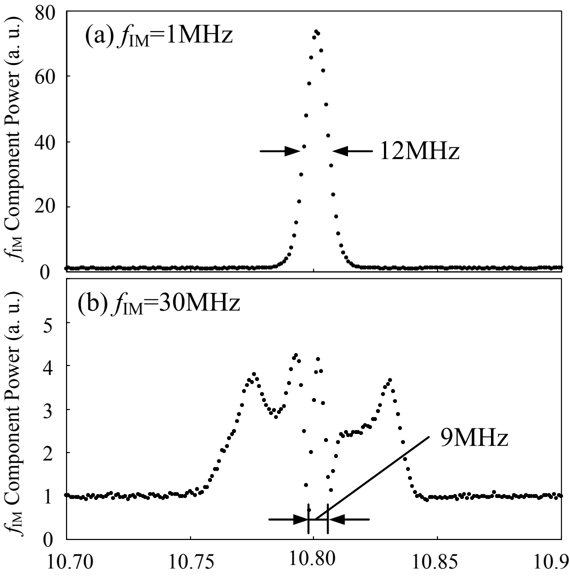

Fig.4 Measured f_{IM} component power as a function of the relative probe frequency f_{PM}.