

Measurement of Nonlinear Parameter of an Optical Fiber by Characterizing of Self-phase Modulation based on BOTDA

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Abstract. We propose a novel method to measure the nonlinear parameter of an optical fiber by characterizing the evolution of self-phase modulation (SPM) based on Brillouin optical time-domain analysis (BOTDA). The nonlinear parameter of an optical fiber is measured to be 2.03 W-1km-1, which agrees well with previously reported result.

1. Introduction

Due to the long interaction length and the confinement of light in the small core over the entire fiber, the efficiency of the nonlinear processes can be tremendously enhanced in a single-mode fiber, which makes an optical fiber a suitable nonlinear medium to observe a wide variety of nonlinear effects at relative low power levels [1]. The growing applications of the nonlinear effects especially in optical communication drive the interest in the measurement of nonlinear parameter of an optical fiber. Several different nonlinear effects have been proposed to measure the nonlinear parameter, including SPM, XPM, FWM and modulation instability. Among these methods, the SPM was widely used due to its simple structure, where the optical spectrum of a pulse at the fiber output exhibits peaks at multiples because of the SPM-induced phase modulation and the ratio of the peak heights depends only on the nonlinear phase shift and can be used to deduce the nonlinear parameter. However, ps-order or fs-order pulses from a mode-locked Ti:sapphire laser are usually used as the light source and a grating-based optical spectrum analyzer is used to record the SPM-induced broadened spectrum, which makes the measurement system complicated and expensive.

Stimulated Brillouin scattering in optical fibers has been extensively studied and found applications in many fields, such as light storage, slow light, all-optical signal processing, microwave photonics, and optical fiber sensing. The dependence of the Brillouin frequency shift on temperature and strain shows a linear relationship, which has been utilized to develop a distributed optical fiber sensor [2]. BOTDA scheme is widely used for distributed temperature and strain sensing, where the Brillouin spectra over the sensing fiber can be obtained by sweeping the frequency offset between a pump pulse and a CW probe (Stokes wave). The SPM-induced spectral broadening of the pump pulse has a considerably detrimental effect in the measurement for a long-range sensing in a BOTDA system [3], so that the pump pulse power should be carefully controlled to avoid the SPM. In this paper, we propose a method to use an ns-order pulse for measuring the nonlinear parameter of an optical fiber by characterizing the evolution of SPM based on BOTDA, where the Brillouin spectrum is the convolution of the intrinsic Brillouin gain spectrum and the pulse spectrum, subsequently reflecting



the pulse spectrum broadening induced by the SPM. This method features a simple setup by using an ns-order pulse instead of ps-order or fs-order pulses from a complicated mode-locked Ti:sapphire laser.

2. Experimental setup

BOTDA system consist of a pump pulse and a CW probe, where the Brillouin spectra over the fiber can be obtained by the scanning the frequency offset between the pump and probe waves in the vicinity of the Brillouin frequency shift. The experimental setup is shown in Fig. 1. A narrow linewidth (3 kHz) fiber laser operating at 1550 nm is used to provide the light source and its output is divided into two parts to provide the pump and probe waves. A microwave source is applied on a Mach-Zehnder electro-optic modulator performing a carrier-suppressed two sidebands modulation, where the frequency difference between the carrier and sidebands equals to the microwave frequency. A narrow-band FBG with a 3-dB bandwidth of 0.03 nm is used to extract the first-order lower sideband working as the probe wave. The frequency offset between the pump and probe waves can be scanned by changing the microwave frequency. The other part of the laser is launched into a high extinction-ratio (ER) electro-optic modulator (EOM) to create a pump pulse with the ER higher than 45 dB. Before launched into the fiber under test, the pump pulse is amplified by an erbium-doped fiber amplifier (EDFA). A polarization scrambler is used to continuously change the polarization state of the probe wave to reduce the polarization-dependent fluctuation on the signal by averaging a large number of signals, where an averaging number of 2000 is used in our experiment.

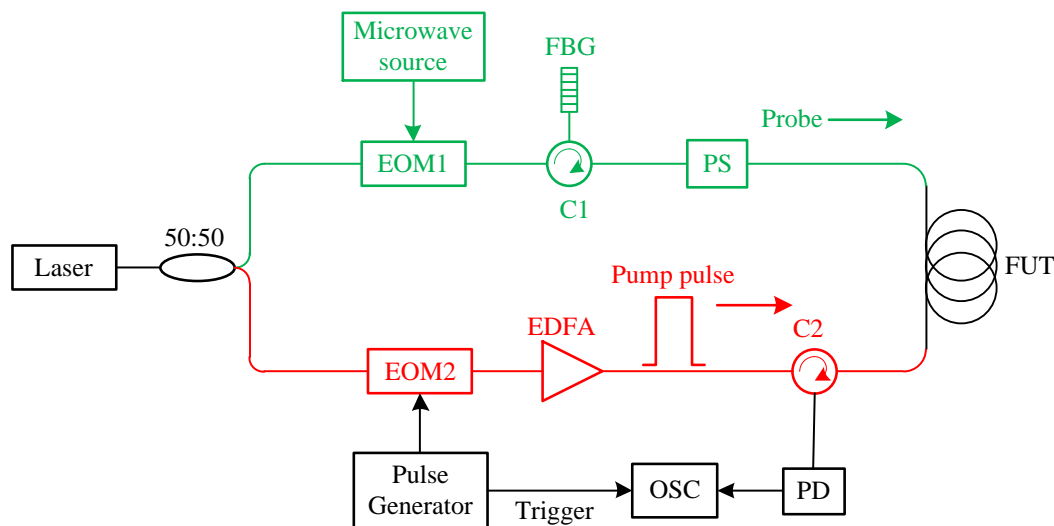


Figure 1. Experimental setup. EOM: electro-optic modulator, FBG: fiber Bragg grating, PS: polarization scrambler, C: circulator, PD: photo-detector, FUT: fiber under test, EDFA: Erbium-doped optical fiber amplifier, OSC: oscilloscope.

3. Results and discussions

A 9.72-ns Gaussian pulse with a peak power of 2.28 W was used as the pump pulse. A 2-km standard single-mode fiber was used as the fiber under test and the frequency offset between the pump and probe was scanned from 10.45 to 11.16 GHz and the measured 3-D Brillouin spectra over the entire fiber is plotted in Fig. 2. The evolution of the Brillouin spectra over the distance clearly shows the SPM-induced pulse spectrum broadening and the generation of multi-peak spectra.

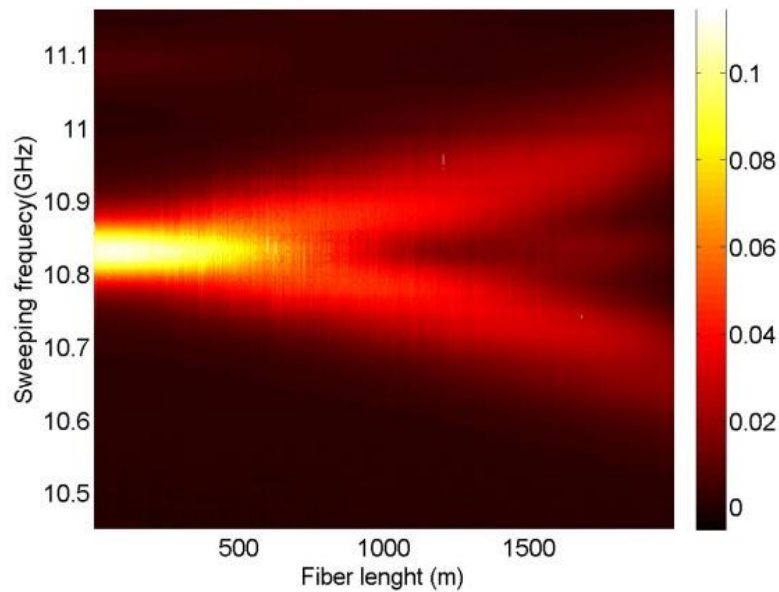


Figure 2. The evolution of Brillouin spectra over 2-km fiber with the SPM.

The simulated Brillouin spectrum under SPM with the nonlinear phase shift of 1.5π is plotted in Fig. 3, where the measured 9.72-ns pulse shape is chosen as the pump pulse in the simulation. The simulated Brillouin spectra exhibit asymmetric, which is caused by the slightly rising edges deviation from the ideal Gauss curves. Through comparison, it is found that the measured Brillouin spectrum at the position of 1056.8 m in Fig. 2 matched very well with the simulations for the case of 1.5π . Using a fiber loss of $\alpha=0.2\text{dB/km}$ and ignoring the Brillouin loss, the effective length is calculated to be 1031.5 m. Considering the peak power of 2.28 W and according to $\phi_{\max} = \gamma P_0 L_{\text{eff}}$, the nonlinear parameter is calculated to be $2.03 \text{ W}^{-1}\text{km}^{-1}$, which agrees very well with previous reported results[4].

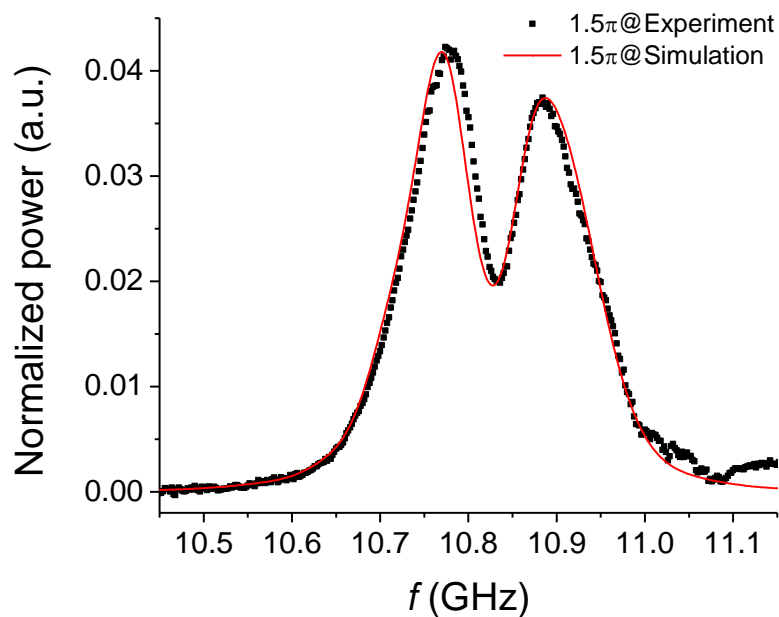


Figure 3. Comparison of measured and simulated Brillouin spectra the nonlinear phase shift of 1.5π .

4. Conclusions

To summarize, we propose to use BOTDA to characterize the evolution of SPM of an ns-order Gaussian pulse in an optical fiber, where the nonlinear parameter of the fiber can be measured by comparing the Brillouin spectra at a specific phase shift. In experiment, a 2-km standard single-mode fiber was used as the test fiber, and a 9.72-ns Gaussian pump pulse with a peak power of 2.28 W was used as the pump pulse; the nonlinear parameter is measured to be 2.03 W-1km-1 through comparing the Brillouin spectra.

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