Optical time-domain measurement of Brillouin dynamic grating spectrum in a polarization-maintaining fiber

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We demonstrate the distributed measurement of Brillouin dynamic grating spectra in a polarization-maintaining fiber based on time-domain analysis. Local reflection spectra of the Brillouin dynamic grating are acquired by synchronized propagation of the pump and the probe pulses based on the map of the Brillouin frequency distribution. Large temperature sensitivity as high as −50.9 MHz/°C is observed with 2 m spatial resolution in 100 m range. © 2009 Optical Society of America
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Brillouin scattering in optical fibers has been widely studied in photonic societies for communicational or sensor applications [1]. While the theoretical explanation of the Brillouin scattering is given by three-wave interaction between one acoustic and two optical waves, it has been recently reported that the generation of the acoustic wave can be separated from the optical scattering process, leading to a novel concept of Brillouin dynamic grating (BDG) [2]. When the BDG is generated in a birefringent medium such as a polarization-maintaining fiber (PMF), the reflection spectrum highly depends on the change in the local birefringence, which can provide a useful sensing mechanism for temperature or strain variation [3,4]. It has been also reported that the BDG can be used as a basis of acousto-optic data storage in a PMF [5]. In our former work [3], a correlation-based technique for the distributed measurement of the BDG spectrum (BDGS) has been presented applying a synchronized and sophisticated control to the frequency modulations of two lasers. Although the correlation-based method is featured by several advantages such as high speed, high resolution, and random accessibility of the sensing position, the complicated frequency modulation scheme could be a drawback in practical applications. In this Letter we demonstrate for the first time, to the best of our knowledge, an optical time-domain technique as another approach to measure the local BDGS, applying the pulse-based interaction among the optical and the acoustic waves.

The measurement principle is depicted in Fig. 1, where Brillouin pump1 (pulse ν) and pump2 (cw) are counterpropagated through the x-polarization axis (slow axis) of a PMF. Acoustic waves are generated by the stimulated Brillouin scattering when the frequency difference of the pump waves is equal to the local Brillouin frequency (ν_B) of the PMF. The generated acoustic wave can play the role of a dynamic reflection grating for the orthogonally polarized (y-pol.) waves at different optical frequencies ($\nu+\Delta\nu$), satisfying a phase-matching condition as follows [2]:

$$\nu_B = \frac{2n_x \nu V_a}{c} = \frac{2n_y(\nu+\Delta\nu)V_a}{c}, \quad (1)$$

where $n_x(n_y)$ and V_a are the refractive index of $x(y)$ polarization and the velocity of acoustic wave, respectively. The frequency offset ($\Delta\nu$), i.e., the optical frequency difference between pump1 and probe, is linearly dependent on the local birefringence ($\Delta n \equiv n_x - n_y$), given by the following equation [2]:

$$\Delta\nu = \frac{\Delta\nu_B}{\nu_B}\nu = \frac{\Delta n}{n}\nu, \quad (2)$$

where $\Delta\nu_B$ is the ν_B difference between x and y polarizations. Therefore, the variation in the peak frequency of the BDGS contains the information of the local birefringence change. In a recent study, it has also been demonstrated that the combined information of ν_B and $\Delta\nu$ enables the discriminative measurement of temperature and strain with high accuracy [4].

Our experimental setup for the distributed BDGS measurement is shown in Fig. 2. A 102 m PANDA

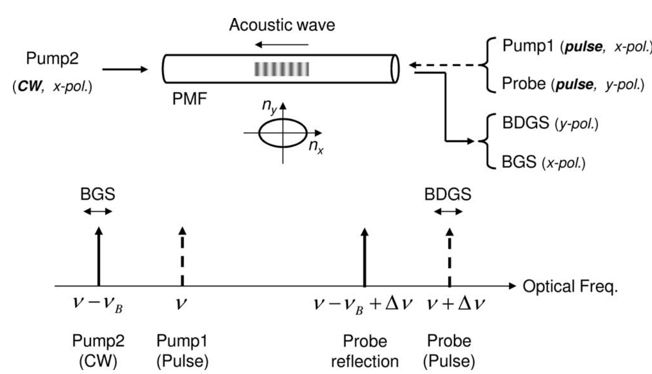

Fig. 1. Schematic view of the time-domain measurement of Brillouin dynamic grating spectrum (BDGS). Note that the Brillouin gain spectrum (BGS) and the BDGS are measured by sweeping the optical frequencies of pump2 and probe, respectively.

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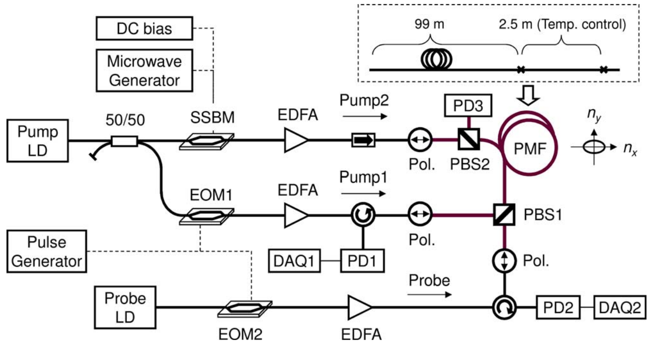

Fig. 2. (Color online) Experimental setup: LD, laser diode; SSBM, single-sideband modulator; EDFA, Er-doped fiber amplifier; PBS, polarization beam splitter; Pol., polarizer; EOM, electro-optic modulator. The inset shows the structure of the fiber under test.

PMF (manufactured by Nufern) with a mode-field diameter of 10.5 μm and a nominal $\Delta n \sim 3.1 \times 10^{-4}$ at a wavelength of 1550 nm was used as a fiber under test (FUT) and a 2.5 m section near the end of the fiber was temperature controlled (inset). ν_B of the fiber was ~10.845 GHz with the Brillouin gain bandwidth (FWHM) of 46 MHz. A 1550 nm distributed-feedback (DFB) laser diode (pump LD) was used as a light source for the pump waves and the output was divided by a 50/50 coupler. For pump1 a Gaussian pulse with a FWHM of 20 ns was generated in one of the coupler arms by an electro-optic modulator (EOM1) and a pulse generator and then launched to the FUT through the slow axis (x-pol.) via a polarization beam splitter (PBS1). In the other arm, pump2 (cw) was generated by a sideband-generation method using a single-sideband modulator (SSBM) and a microwave generator so that the optical frequency was downshifted from the carrier by around ν_B of the FUT. The output from the SSBM was launched to the fiber in the opposite direction to pump1 through the slow axis via another PBS (PBS2). We first carried out the distributed measurement of the BGS by sweeping the SSBM modulation frequency and the BGS signal of pump2 was received by a photodiode (PD1) and a data acquisition card (DAQ1) via PBS1 and an x polarizer. When the BGS through the fast axis (y-pol.) of the FUT was measured, the other ports of the PBSs were used. Figure 3(a) shows the measurement result of the BGS distribution, where almost uniform difference (~2.6 MHz) of ν_B's was observed with a small fluctuation (±1 MHz) of ν_B near 10.845 GHz along the FUT. From this result, the spectral location of the BDG could be estimated to be ~46.3 GHz higher than the pump by Eq. (2).

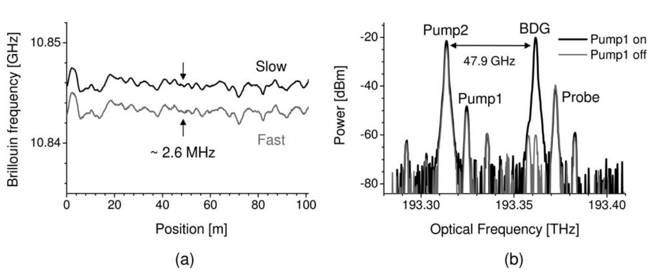

Fig. 3. (a) Measured distribution maps of the Brillouin frequency (ν_B) along the slow and the fast axes of the FUT. (b) Optical spectrum showing the reflection by the BDG measured at the position of PD2 in the setup. Note that the BDG disappears when pump1 is off.

To measure the BDGS distribution, another DFB LD (probe LD) with a high-accuracy current controller was used as a light source. A Gaussian probe pulse with a FWHM of 20 ns was prepared by another electro-optic modulator (EOM2) and the pulse generator. The output from EOM2 was propagated in the same direction as pump1 through the fast axis (y-pol.) via PBS1. The time delay between the pump1 and the probe pulses was controlled to ~5 ns (the probe lags) by monitoring PD3 at the end of the fiber, so as to maximize the reflection efficiency of the BDG considering the excitation time (~5 ns) of the generated acoustic phonons. For setting a proper frequency-sweep region for the probe, we roughly measured the spectral location of the BDG by sweeping the optical frequency of the probe and monitoring the back reflection with an optical spectrum analyzer. The result is depicted in Fig. 3(b), where $\Delta\nu$ was measured to be ~47.9 GHz, slightly higher than our estimation. The distributed measurement of the BDGS was performed by sweeping $\Delta\nu$ with a step of 4 MHz through the LD current control, while the SSBM modulation frequency was fixed to 10.845 GHz, the center of the ν_B distribution of the FUT. The reflected probe signal was received by PD2 and DAQ2 via PBS1 and a y polarizer, and signal averaging of 128 times was applied for noise reduction. The frequency-sweep range of the probe was 1.2 GHz around $\Delta\nu = 47.9$ GHz, and the pulse repetition rate was 600 kHz. The overall elapsed time of the measurement was about 7 min.

Figure 4(a) shows some examples of the raw data received by PD2 at different $\Delta\nu$'s (47.60, 48.06, and 48.22 GHz) in the BDGS measurement, where the reflection amplitude is plotted as a function of position (converted from time) along the FUT. One can see large fluctuations in the reflection amplitudes depending on both $\Delta\nu$ and the position. Figure 4(b) depicts a few selected BDGS at different positions (21.3, 51.5, 79.6, and 100.9 m) constructed by arranging the trace data of Fig. 4(a). It is clearly seen that reflection peaks appear at different $\Delta\nu$'s for different posi-

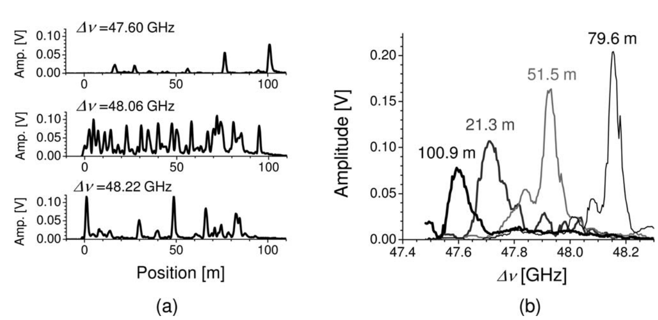

Fig. 4. (a) Selected traces (raw data) of the BDGS measurement representing the local reflection amplitude of the BDG along the position at different $\Delta\nu$. (b) Selected BDGS representing the reflection amplitude with respect to $\Delta\nu$ at different positions. Note that this plot is composed by arranging the traces in Fig. 4(a).

tions, where $\Delta\nu$ value at each peak ($\Delta\nu_P$) corresponds to the local $\Delta\nu$ in Eq. (2). The variation in the bandwidth and the peak reflectance at different positions reflect the nonuniformity of $\Delta\nu$ in the FUT within the spatial resolution (2 m) of the measurement.

The distributed measurement of the BGS and the BDGS was carried out three times with setting different temperatures (25.5°C, 28.5°C, and 32.5°C) on the 2.5 m test section of the FUT. The measured maps of the $\Delta\nu_P$ distribution are shown in Fig. 5(a). A large fluctuation of about ±200 MHz is seen along the FUT that is thought to originate from an uneven axial strain in the winding process around the spool as also explained by the ν_B fluctuation in Fig. 3(a). Additionally, the frequency shift by the temperature difference is clearly observed in the test section at the end of the FUT (dashed box). As depicted in Fig. 5(b), the temperature sensitivity is measured to be −50.92 MHz/°C, which is about 50 times larger than that of conventional Brillouin sensors (~1 MHz/°C) in magnitude with an opposite sign. This large negative slope matches well with the former result [4].

Figure 6 shows the BDGS distribution in three dimensions (3D) near the end of the FUT (top) and the relative power of the probe reflection (bottom) from the test section at (a) 25.5°C and (b) 32.5°C, respectively, where one can verify the large deviation of $\Delta\nu_P$ (dashed circle) by the temperature change. It is also noticeable that the relative power of the probe reflection [i.e., the area under the BDGS plotted in Fig. 4(b)] is decently maintained through the FUT, although the peak reflectance and the bandwidth are fluctuated as shown in the 3D plots owing to the nonuniformity of the fiber. This is attributed to the fact that the fluctuation (±2 MHz) of ν_B along the FUT is well within the Brillouin gain bandwidth (~46 MHz) regardless of large fluctuations in $\Delta\nu_P$.

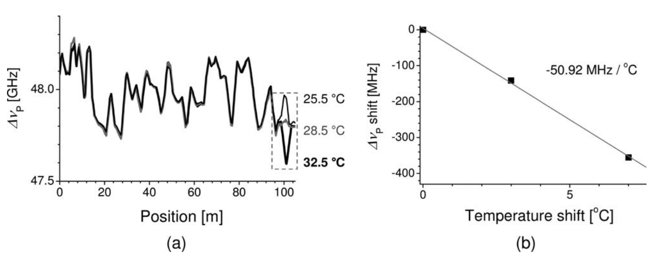

Fig. 5. (a) Measured distribution maps of $\Delta\nu_P$ along the FUT at different temperatures on 2 m test section (dashed box). Notice that the frequency offset between pump1 and pump2 was kept at 10.845 GHz during the measurement. (b) $\Delta\nu_P$ shift as a function of temperature change with a linear fit.

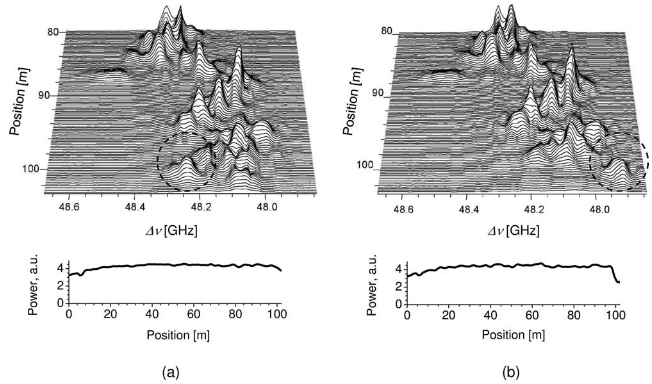

Fig. 6. Comparison of the BDGS distribution in 3D (top) and the relative powers of the probe reflection (bottom) with the test section at (a) 25.5°C and (b) 32.5°C.

When a large fluctuation (>46 MHz) appears in the BGS distribution, the BDGS measurement needs to be carried out multiple times based on discrete ν_B's to cover the whole BGS distribution.

In summary, we have proposed and demonstrated the time-domain distributed measurement of BDGS in a 100 m polarization-maintaining fiber with a 2 m spatial resolution. Synchronized pulse propagation of the pump and the probe was applied and the local BDGS was measured based on the distribution map of the Brillouin gain spectrum. The temperature sensitivity of the BDG peak frequency shift was measured to be about 50 times larger than that of ordinary Brillouin sensors with an opposite sign. We believe that further research is needed to enhance the spatial resolution and the measurement range to the levels of conventional Brillouin sensors.

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