Distributed temperature sensing based on birefringence effect on transient Brillouin grating in a polarization-maintaining photonic crystal fiber

Yongkang Dong, Xiaoyi Bao,* and Liang Chen

Fiber Optical Group, Physics Department, University of Ottawa, Ottawa, Canada, K1N 6N5

**Corresponding author: xbao@uottawa.ca*

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We demonstrate a time-domain distributed temperature sensing based on birefringence effect on transient Brillouin grating (TBG) in a polarization-maintaining photonic crystal fiber (PM-PCF), which uses two short pump pulses (2 ns) to excite a TBG and a long probe pulse (6 ns) to map the transient Brillouin grating spectrum (TBGS) associated with the birefringence. The 2 ns pump pulses defines a spatial resolution of 20 cm and a temperature measurement range of a few hundred degrees Celsius, and the long probe pulse provides a narrow TBGS with a temperature resolution of 0.07°C. © 2009 Optical Society of America

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The Brillouin-scattering-based distributed fiber sensor has been developed for two decades and shows capability of measuring temperature or strain for civil structural monitoring [1–3]. In a normal case, the spatial resolution is limited by the phonon lifetime (~10 ns) in optical fiber and is thus not better than 1 m. Light storage was recently described and experimentally demonstrated by stimulated Brillouin scattering in a single-mode fiber [4]. In this scheme, a transient Brillouin grating (TBG) was excited by two counterpropagating "data" and "write" pulses, and the reflection of the following "read" pulse from the TBG was utilized to retrieve the data information. In our previous work, a frequency-shifted light storage was realized in a high-birefringence polarization-maintaining fiber (PMF), and the optical frequency difference between the write and read pulses was proportional to the local birefringence [5]. It has also been recently demonstrated that the birefringence is temperature- and strain-dependent, so the dynamic grating spectrum generated in stimulated Brillouin scattering associated with the birefringence can be used as a sensing mechanism for temperature or stain variation [6]. More recently, a time-domain measurement of Brillouin dynamic grating spectrum in a conventional PM fiber with a spatial resolution of 2 m was demonstrated, where the Brillouin dynamic grating was excited continuously along the fiber by using one pump pulse and another cw pump [7]. In this scheme, the spatial resolution is not better than 1 m owing to the 10 ns phonon lifetime, and the temperature measurement range was a few tens degrees Celsius limited by the detuning of Brillouin resonant frequency within natural Brillouin spectral width.

In this Letter, we propose a distributed temperature sensing scheme based on birefringence effect on a local TBG in a polarization-maintaining photonic crystal fiber (PM-PCF). The length of the TBG (spatial resolution) is defined by two pump pulse widths, the position of TBG can be controlled by the time delay of the second pump pulse, and the measured temperature range is determined by the convolution of two pump pulse spectrum, which is a few hundred degrees Celsius for a 2 ns pump pulse. In addition, a PM-PCF could have a small core area, which provides a high-power density compared with conventional PM fiber and thus reduces the power of pump and probe pulses.

The schematic diagram of the distributed temperature sensing based on birefringence effect on TBG is shown in Fig. 1. In this scheme, two short counterpropagating pulses, pump1 and pump2, (corresponding to the data and write pulses in the storage

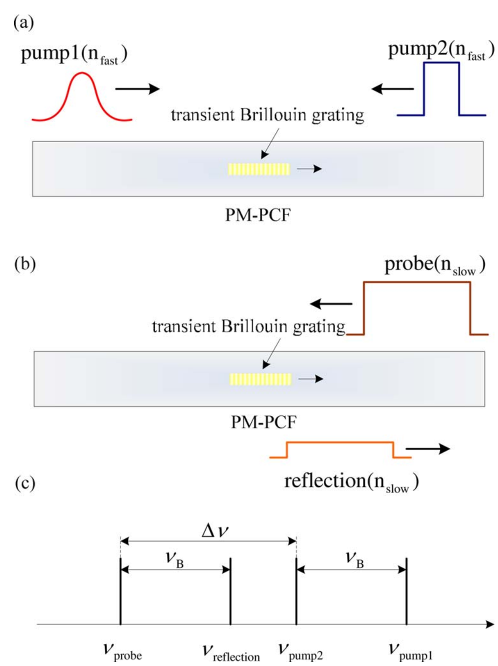

Fig. 1. (Color online) Schematic diagram of the distributed sensing based on birefringence effect on TBG. (a) The local TBG is excited by two short pump pulses; (b) the following long probe pulse is reflected by the local TBG, and the TBGS is obtained by sweeping the probe frequency; (c) the frequency relation of pump1 (ν_{pump1}), pump2 (ν_{pump2}), probe (ν_{probe}), and reflection ($\nu_{\mathrm{reflection}}$).

scheme) are launched into the fast axis of the PM-PCF to excite a TBG. The frequency of pump1 is larger than that of pump2 by the Brillouin frequency shift of the PM-PCF ν_B; therefore the energy of the pump1 pulse is partially depleted in the process. Following the pump2 pulse, a long probe pulse (corresponding to the read pulse) is launched into the slow axis, and energy from the probe pulse is partly transferred to the reflection pulse at the expense of TBG. A maximum reflection probe signal could be obtained when the frequency difference $\Delta\nu$ between the pump2 and probe satisfies the following equation [6]:

$$\Delta\nu = \frac{\Delta n}{n}\nu, \tag{1}$$

where $\Delta n = n_{slow} - n_{fast}$ is the local birefringence, n is the average refractive index, and ν is the optical frequency of probe pulse. The spatial resolution is the length of the local TBG determined by the pump pulses, so that a high spatial resolution can be obtained by using short pump pulses. The measured TBG spectrum (TBGS) is the convolution of the probe pulse spectrum $P(\nu_{probe})$ and the intrinsic TBGS $g_0(\nu)$,

$$g(\nu) = g_0(\nu) \otimes P(\nu_{probe}) \tag{2}$$

Therefore a long probe pulse is preferable to get a narrow TBGS. During this process, the probe pulse interacts with TBG instead of pump pulse, whereas this happens in a conventional Brillouin optical-fiber time-domain analysis using a single-mode fiber and causes the trade-off between the spatial resolution and the Brillouin spectrum width, which provides an opportunity to obtain a high spatial resolution through short pump pulses and a narrow TBGS using a long probe pulse.

The experimental setup of distributed sensing based on birefringence effect on TBG is shown in Fig. 2. A 3 m PM-PCF with 1.5 m segment located from 0.9 m to 2.4 m in the oven is used as the test fiber. The PM-PCF has a mode-field diameter of 8 μm and a mode-field area of 45 μm^2. The nominal birefringence Δn is $\sim 1.4 \times 10^{-4}$, which corresponds to a $\Delta\nu$ of $\sim$18.433 GHz according to Eq. (1). The measured ν_B of the PM-PCF at room temperature (23°C) is 11.131 GHz, and the Brillouin spectrum width is 60 MHz. Two narrow linewidth (3 kHz) fiber lasers operating at 1550 nm are used to provide pump1 and pump2, respectively, and the frequency difference between is locked by a frequency counter. A tunable laser with a wavelength resolution of 0.1 pm is used as probe light. The pump1 is pulsed to a 2 ns Gaussian shape and then amplified to 600 mW. Two high extinction ratio electro-optic modulators, EOM2 and EOM3, are used to generate the square-shaped 2 ns pump2 pulse and 6 ns probe pulse with the extinction ratio larger than 45 dB, which are then combined with a 3 dB coupler. The power of the pump1 pulse, the pump2 pulse, and the probe pulse in the PM-PCF are about 200 mW, 30 W, and 10 W, respectively. The two pump pulses are launched into the fast axis, and the delay between them is well controlled to excite the TBG at a specific location. Following the pump2 pulse with a time delay of 2 ns, the probe pulse is launched into the slow axis, and its reflection by the local TBG is detected by a 1 GHz detector.

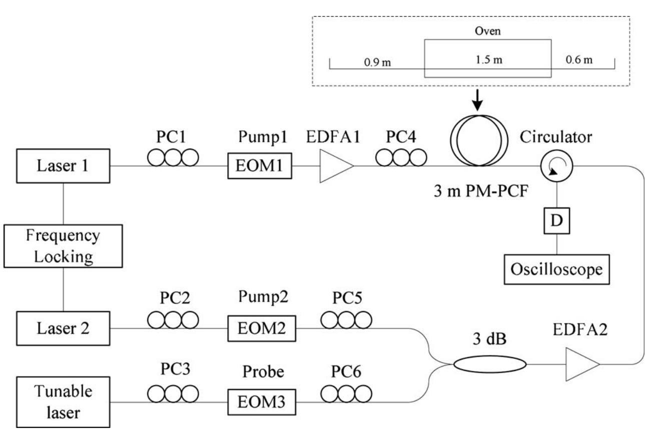

Fig. 2. Experimental setup. PC, polarization controller; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; D, detector.

Previously, distorted TBGSs [7] and a 320 MHz broadened Gaussian-shaped TBGS [8] were observed experimentally owing to the large nonuniformity of the birefringence within the length of spatial resolution. In our experiment, the effective length of the TBG is ~20 cm for the 2 ns pump pulses, so that the variation of the birefringence within the TBG is much smaller, and thus a more symmetric and narrower TBGS could be expected. The frequency difference of pump1 and pump2 is locked at 11.131 GHz with the PM-PCF in the room temperature, and the delay between them is controlled to excite the TBG at the location of 1.5 m. We first studied the dependence of TBGS on the probe pulse width. The probe pulse width is limited by the TBG lifetime of ~10 ns in optical fibers. Moreover, reflected light from the front part of the probe pulse could be depleted by the back part of the probe pulse, which decreases the signal intensity and is also a limitation to the probe pulse width. Probe pulses of 3 ns, 4 ns, and 6 ns, are used to measure the TBGS with a step of 25 MHz with the results showing in Fig. 3. The measured TBGS is 470 MHz, 370 MHz, and 230 MHz, respectively, dem-

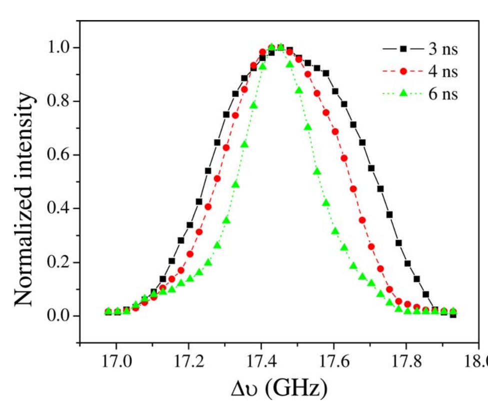

Fig. 3. (Color online) Measured TBGS with different probe pulses of 3 ns, 4 ns, and 6 ns.

onstrating that the TBGS width decreases when increasing the probe pulse width.

Fixing the frequency difference of pump1 and pump2 at 11.131 GHz, the TBGS is measured using a 6 ns probe pulse with the temperature at 15°C, 35°C, 55°C, and 75°C, respectively, and the results are provided in Fig. 4(a). As the temperature increases, the excitation efficiency of the TBG decreases because of the increasing detuning of Brillouin frequency shift in the heated section. However, owing to a few hundred megahertz bandwidth of 2 ns pump pulse, the TBG in the heated section could still be efficiently excited within a few hundred degrees Celsius. Because the Brillouin gain coefficient increases with the temperature [8], the amplitude of the TBGS increases with the temperature, as shown in Fig. 4(a). It is expected that the amplitude of the TBG has a maximum value at a high temperature and decreases beyond this point. The dependence of central frequency of TBGS on the temperature is plotted in Fig. 4(b). The slope of the temperature sensitivity is determined by temperature-induced birefringence change and is measured to be −23.5 MHz/°C. The negative slope is in agreement with the result measured in a conventional PM fiber [6–8]. The frequency uncertainty in Fig. 4(a) is about 1.6 MHz, so that the temperature resolution could be 0.07°C.

Figure 5 shows the reflection probe signal from different positions along the 3 m PM-PCF with the $\Delta\nu$ fixed at 17.482 GHz. The sampling interval is 0.5 ns corresponding to a spatial step of 5 cm. The squares show the results when the entire fiber is put in the room temperature. The amplitude variation at different positions reflects the fluctuation of the birefringence along the fiber. The dots are the results when the heated section is put in the oven to keep 45°C. The signals outside the oven are identical, while the birefringence change of the heated section is so large that no reflection probe signal could be observed. The

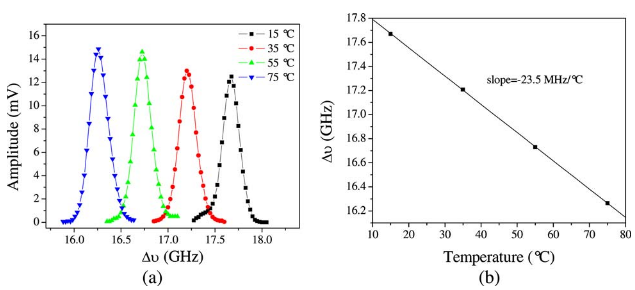

Fig. 4. (Color online) Measured TBGS at different temperature shows the dependence of the central frequency on temperature. (a) Brillouin transient grating spectrum, (b) central frequency versus temperature. Note that the frequency difference between pump1 and pump2 is fixed at 11.131 GHz during the measurement.

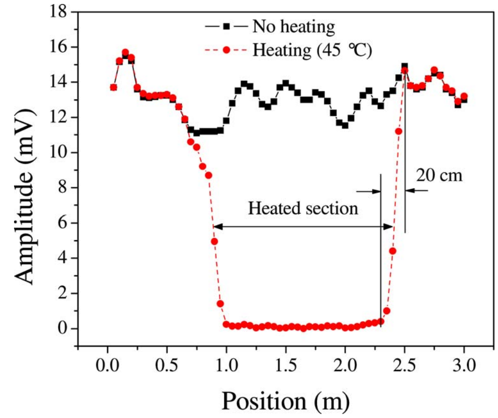

Fig. 5. (Color online) Reflection probe signal versus position for a PM-PCF when $\Delta\nu_B = \nu_{\text{pump2}} - \nu_{\text{pump1}} = 11131$ MHz. The heated section is located between 0.9 m and 2.4 m.

signal within the transition region shows a spatial resolution of 20 cm, which is determined by the 2 ns pump pulse.

In summary, we have proposed and demonstrated a time-domain distributed temperature fiber sensor based on birefringence effect on TBG by using two short pump pulses to excite a local TBG and a long probe pulse to measure the TBGS. A 20 cm spatial resolution and a temperature resolution of 0.07°C have been successfully realized. We believe that by increasing the peak power in the test fiber or using PM-PCF with smaller core area, a shorter pump pulse (for example 1 ns) could be used to further improve the spatial resolution and detectable temperature range. In addition, a pulse train of pump1 could be used to perform multiposition measurement simultaneously to reduce the measurement time.

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