Thermal Effects Study on Stimulated Brillouin Light Scattering in Photonic Crystal Fiber

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ABSTRACT— we investigate the temperature-dependences of the Brillouin frequency shift in three different kind of single-mode fibers using a heterodyne method for sensing temperature. Positive dependences coefficients of 0.77, 0.56 and 1.45MHz/^{0}C are demonstrated for 25 km long single-mode fiber, 10 km long non-zero dispersion shifted fiber and 100 m photonic crystal fiber, respectively. The results indicate that microstructure fibers with a partially Ge-doped small core have great potential for fiber Brillouin distributed sensing.

KEYWORDS: Stimulated Brillouin scattering, fiber optics sensors, microstructure fiber.

I. INTRODUCTION

Brillouin-based optical fiber sensors have been widely reported in recent years owing to their possibilities to perform distributed strain and temperature sensing along an optical fiber because Brillouin frequency shift (BFS) has a linear dependence on both temperature and strain [1], [2]. Several techniques have been proposed for effective sensing, and they can be classified into two types: spontaneous Brillouin scattering (SpBS) and stimulated Brillouin scattering (SBS). Two kinds of Brillouin reflectometry have been studied; A Brillouin optical time domain reflectometry (BOTDR) [3] ~~is~~ based on pulse launched laser and the recently proposed Brillouin optical correlation domain reflectometry (BOCDR) which is operating by continuous-wave [4]. The Brillouin reflectometry which offers the injecting of the one light beam into only one end of a fiber under test (FUT) is highly desirable in remote fiber sensors, whereas it is suffering small amplitude of the signal due to the use of spontaneous Brillouin scattering. The Brillouin analysis usually requires accesses from both ends of an FUT; it can provide much larger signal than the Brillouin reflectometry. Indeed, considering the one-end accessibility of the Brillouin reflectrometry can be more favorable due to high flexibility and reliability.

This paper studies measurement of the Brillouin scattering gain spectra which offers the injecting of the one light beam into only one end of a fiber under test (FUT) based on some different type of single mode fibers with a small core measured using the heterodyne method for various temperatures. The temperature dependence of the Brillouin spontaneous gain peak indicates that microstructures can be used as sensing fibers to improve the performance and extend the function of fiber Brillouin sensing systems.

II. EXPERIMENTAL SETUP

The proposed Brillouin fiber laser architecture is the cavity inserted at port 2 of the circulator as depicted in Fig. 1[2]. Heterodyne method has been used to measure the Brillouin frequency shift [2].

Different kinds of single mode fiber is incorporated as 25 km single-mode fiber (SMF) and 10 km long non-zero dispersion shifted fiber (NZ-DSF) and 100 m long of photonic crystal fiber (PCF). The used PCF exhibits a triangular core with average diameter of 2.1 ± 0.3 μm and cladding diameter of 128 ± 5 μm. The average air hole diameter of the fiber is 0.8 μm with 1.5 μm pitch. The PCF is made from pure silica with 17.4 wt% of Ge-doped core region. It is spliced to an intermediate fiber and then a single mode fiber (SMF) with a splice loss of 0.35 dB at each end. The threshold power of this PCF in backward direction is more than 19 dBm [5], however, the power of injected signal is about 14 dBm. So to reduce the threshold power, we incorporated the ring cavity to achieve Brillouin Stokes scattering in the right end of the setup.

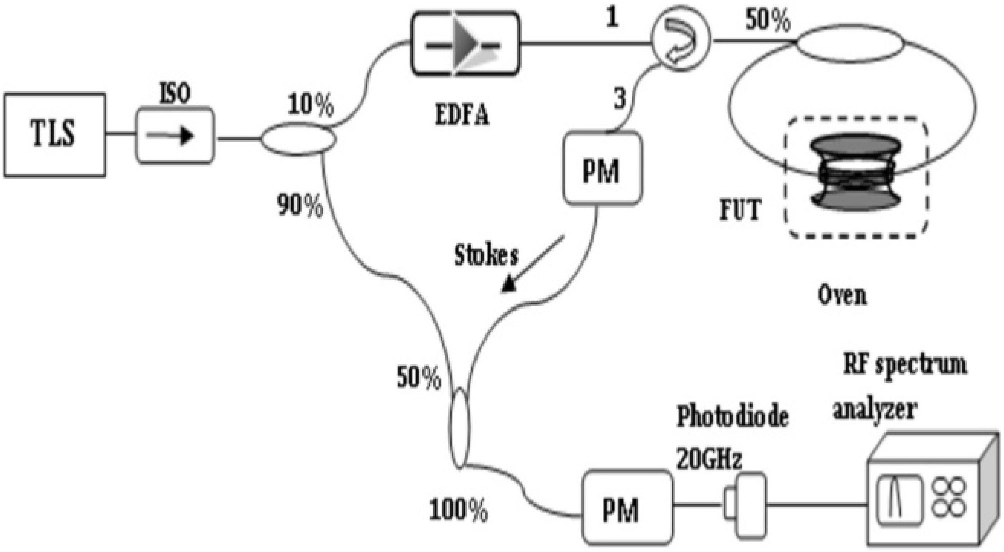


Fig. **1** Experimental setup for the spontaneous Brillouin scattering measurements

This proposed structure consists of two main sectors. A ring cavity as a Brillouin gain blocks which includes a piece of single mode fiber and a 3 dB coupler to provide backward propagating and Stokes line oscillation which is shown in the dashed square and it is located in an oven with temperature control. The other sector is a heterodyne method to measure the Brillouin scattering gain. The BP is an external cavity tunable laser source (TLS) with a line-width of approximately 20MHz, which is divided to two portions by a 9:1 coupler in which the 10% part is amplified by an erbium-doped fiber amplifier to provide sufficient power for this study. This amplified signal is launched through the optical circulator acting as an isolator to direct the propagation of Brillouin Stokes (BS) line in clockwise direction. Brillouin Stokes line which oscillates inside the resonator to generate the Brillouin Stokes at wavelength downshifted by 0.08 nm from the BP wavelength. Before combination of the Brillouin pump and Brillouin signal, the output of the BFL is characterized using an optical spectrum analyzer (OSA) with a resolution of 0.015 nm.

The BS light from the circulator which was about −5 dBm power is mixed with the nearly same power of 90% of the TLS output by a 3dB coupler for the heterodyne measurement after checking its power by power meter (PM). The BS gain spectrum of the FUT obtained by the beating signals of Brillouin pump and Brillouin Stokes line is measured by a RF spectrum analyzer with a photonic detector.

III. RESULTS AND DISCUSSION

Fig. 2 demonstrates the output spectrum of the BFL cavity at different lengths of PCF while the BP power is fixed at 15.7 dBm. The line spacing is obtained at approximately 0.08 nm in the wavelength domain, as measured by the OSA. The 3dB spectral bandwidth of the BFL is measured to be less than 0.02 nm, limited by the OSA resolution. The peak power of the laser is obtained as 0.9 dBm and -3.6 dBm at 50 m and 100 m, respectively. The peak power of 100 m long PCF is less than 50 m long PCF due to more absorption by longer length. However, as shown in Fig. 2, side mode suppression ratios (SMSRs) of the BFL are obtained at 26.4 dB and 22.2 dB with 100 m and 50 m long PCF respectively due to the Brillouin gain by longer length of PCF.

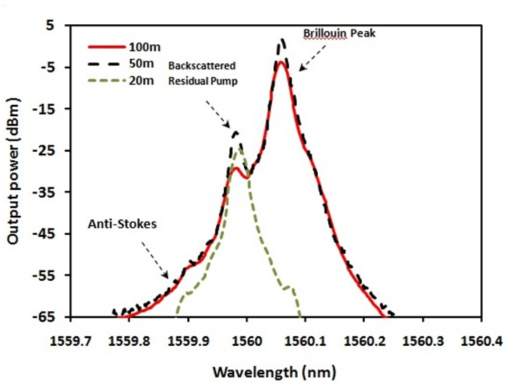


Fig.2 Output spectra of the ring BFL with different long PCF.

Although the longer PCF in the BFL resonator increases the cavity's loss, it provides a better nonlinearity characteristic to achieve an efficient SBS using a micro-structured cladding region with air holes to guide light in a pure silica core. No lasing is observed with the 20 m long PCF due to the insufficient fiber length is not enough to generate an adequate Brillouin gain to compensate for the cavity loss. Therefore, this length of fiber in conjunction with the presented configuration has been used to generate BFL.The BS in the fiber is generated from interactions between the optical mode and acoustic-modes in the fiber core. Thermally excited acoustic waves (acoustic phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti-Stokes components. This process can be stimulated when the interferences of the laser light and the Stokes wave reinforce the acoustic wave through electrostriction. Since the scattered light undergoes a Doppler frequency shift, the Brillouin shift depends on the acoustic velocity and is given in [3]

$$\upsilon_B = \frac{2nV_a}{\lambda} \tag{1}$$

where V_a is the acoustic velocity within the fiber, n is the refractive index and λ is the vacuum wavelength of the incident lightwave.

The strong attenuation of sound waves in silica determines the shape of the BGS. Actually, the exponential decay of the acoustic waves results in a gain presenting a Lorenzian spectral profile [6].

$$g_B(\upsilon) = g_0 \frac{(\Delta\upsilon_B/2)^2}{(\upsilon-\upsilon_B)^2 + (\Delta\upsilon_B/2)^2} \tag{2}$$

where Δv_B is the full-width at half maximum (FWHM). The Brillouin gain spectrum peaks at the Brillouin frequency shift v_B (or the frequency difference between the two beams), and the peak value is given by the Brillouin gain coefficient:

$$g_B(\upsilon) = g_0 = \frac{2\pi n^7 p_{12}^2}{c\lambda_p^2 \rho_0 V_a \Delta\upsilon_B} \tag{3}$$

where p_{12} is the longitudinal elasto-optic coefficient, ρ_0 is the density, λ_p is the pump wavelength and c is the vacuum velocity of light [7]. As shown in Fig. 3, the result of the back scattered Brillouin line of NZ-DSF after passing through the port 3 of the circulator measured by OSA versus different temperature. This scattering is widely used in fiber distributed sensing, since this process is sensitive to temperature and strain linearly [8]. The temperature-dependences of the BGS of SMF and PCF are shown in Fig. 4 by RF spectrum analyzer. The BGS peak power sifted toward higher frequency with increasing temperature. From these spectra for every different kind of single mode fibers of SMF, NZ-DSF and PCF, we can plot the temperature–dependences of the BSF as shown in Fig. 5. The error bars are ±3 MHz, corresponding to the BFS fluctuations when temperature was fixed. The dependences are almost linear, and their coefficients were calculated to be 0.77, 0.56 and 1.45MHz/^{0}C, respectively, while the pump laser operates at 1550 nm, experiment based on 100m long PCF shows $\partial \nu_B$ /∂T =1.45 MHz/0C. For every constant temperature, the uncertainty value was about 10 kHz (The resolution of RF spectrum analyzer).

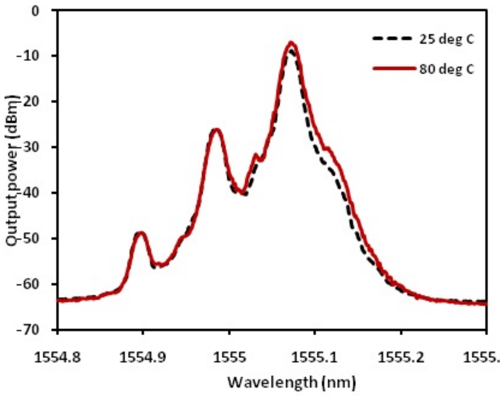
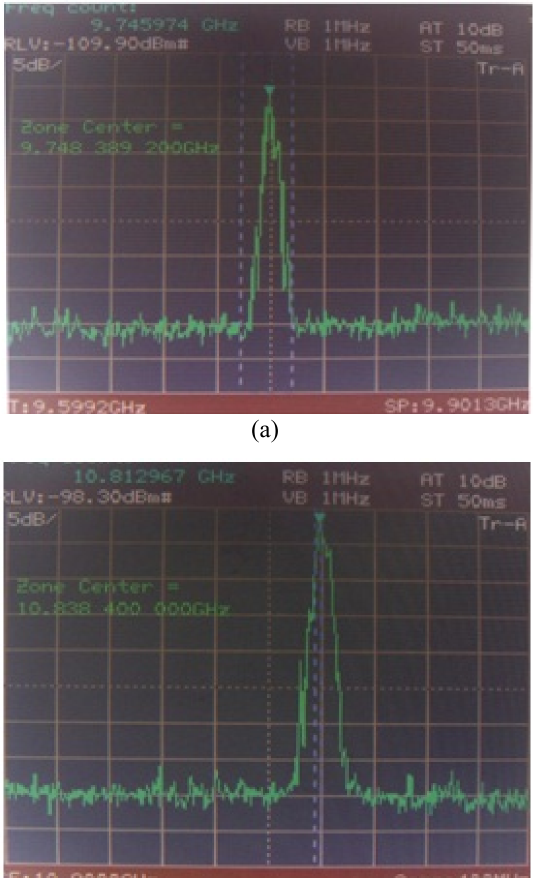


Fig. **3** Stimulated Brillouin scattering monitored by OSA in minimum and maximum used temperature.

As illustrated in Fig. 5, the value of the Brillouin shift in case of PCF is less than other silica fibers, however, its slope is the highest. The reason is the Germania concentration in the fiber core such that the inhomogeneous distribution within the core of the fiber is responsible for multi peak in Brillouin gain spectrum. These experiments show that the PCF with small core is preferable in these applications. Since the effective refractive index n_{eff} is determined with the air existence, it can be considered that light is confined to the core by the holes and the guidance is much more efficient. The parameter determining optical nonlinearity of fibers is normally measured in terms of its effective nonlinear coefficient



(a)

(b)

Fig. 4 Obtained Brillouin gain spectrum results by 100 m PCF, (a), and 25 km SMF, (b), with illustration of Brillouin frequency shift as a zone center in the graphs.

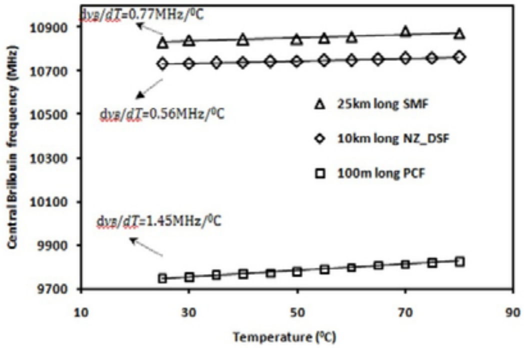


Fig. 5 Brillouin frequency shift as functions of temperature.

$$\gamma = \frac{n_2 \omega}{c A_{eff}} \qquad (4)$$

where c is the light speed, A_{eff} is the effective area of traveling mode, ω is the frequency of propagating optical field and n_2 is responsible for the nonlinear refractive index as defined in Kerr effect intensity which is dependent on the incident intensity. Small pitch size Λ and large d/Λ (d stands for core diameter) in PCFs confines light strongly within the core region so that results in small effective mode area [9] Such a small A_{eff} leads to a high nonlinear coefficient and then low level of incident intensity will be required for a certain nonlinearity value.

This is the particularly interesting class of PCFs composed of a small-scale a solid silica core comprising a Ge-doped center region with multiple air holes typically arranged in a hexagonal lattice around the core acting as the cladding. With the combination of a large refractive index contrast between the silica core and the air-filled microstructure, PCFs can be designed to enable tight mode confinement that results in a low effective mode area and thereby a large nonlinear coefficient. This characteristic avoids the difficulty in distributed fiber sensors that can happen by incorporating the long length of the SMF and NZ-DSF provides uncertainty in the sensing results. Although their long length which must be used to provide the SBS reduces the threshold, it gives arise other problems of less coefficient of sensing temperature for incorporation in distributed fiber sensors.

IV. CONCLUSION

The temperature-dependence using the stimulated Brillouin scattering spectrum of some single mode fibers are studied experimentally using the heterodyne method. The Brillouin frequency increases linearly with increasing temperature with temperature coefficients of 0.77, 0.56 and 1.45 MHz/^{0}C are demonstrated for 25 km long SMF, 10 km long NZ-DSF and 100 m PCF, respectively. These experiments show that microstructure fiber is a preferable versatile fiber for distributed Brllouin temperature sensors.

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VI. REFERENCES

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