Dependence of the Brillouin frequency shift on strain and temperature in a photonic crystal fiber

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Received March 9, 2004

The dependence of the Brillouin frequency shift on strain in a photonic crystal fiber (PCF) was measured at a wavelength of 1320 nm for the first time to the authors' knowledge. Together with measurements of the dependence of the Brillouin frequency shift on temperature in the PCF, we demonstrate the feasibility of the highly precise simultaneous measurement of temperature and strain by use of the PCF in a distributed Brillouin sensing system with a spatial resolution of 15 cm.

OCIS codes: 290.5830, 060.2370, 290.5900, 190.5890, 060.2280, 060.2310.

Photonic crystal fibers (PCFs) have been of great interest in recent years, mainly because of their novel optical characteristics. One particularly interesting class of PCF is composed of a small, solid-silica core with multiple air holes typically arranged in a hexagonal lattice about the core to act as a cladding. It has been reported that in this kind of PCF the spontaneous Brillouin spectrum has a non-Lorentzian shape with a linewidth of hundreds of megahertz.[1] Recently we showed[2] that a PCF with a partially Ge-doped core has a multipeak Brillouin spectrum that is due to waveguide and antiwaveguide types of sound propagation and suggested the possibility of using PCFs as simultaneous distributed temperature and strain sensors based on Brillouin scattering.

The simultaneous measurement of temperature and strain is not directly possible for the usual Brillouin-based sensors with a single-mode fiber because the Brillouin spectrum has only one peak whose frequency is sensitive to both temperature and strain variations. Simply neglecting the effect of temperature will lead to substantial errors in strain measurements for field applications, as strain changes in structures are usually small ($<100\ \mu\epsilon$).[3] An early solution to this problem was to add a second fiber that was isolated from strain effects and was used for temperature monitoring only.[4] One could then subtract the frequency shift that resulted from any temperature effects from the combined frequency shift to determine the strain on the structure. This method was used to measure strain and temperature with a spatial resolution of 5 m. As a second solution to this problem, interest was focused on both Brillouin backscattered intensity and frequency shifts,[5,6] because they both exhibit dependence on strain and temperature. However, the spatial resolution achieved is tens of meters because of power (intensity) fluctuations induced by lasers and by the accuracy of intensity measurement. Another solution, which was recently proposed by Lee *et al.*,[7] is to use a large-effective-area fiber with a multicomposition fiber core that results in a multipeak Brillouin spectrum. Lee *et al.* achieved the simultaneous measurement of temperature and strain with a spatial resolution of 2 m, using the fact that the dependence on frequency shift of the first and second Brillouin peaks is different for temperature but the same for strain, even though those two peaks come from different composition materials of the core. For a PCF we demonstrated that the temperature coefficients were different for two Brillouin peaks that originated from two different doping concentration materials of the core.[2] We also found the strain coefficients to be different for these two peaks in the PCF described in this Letter. This research was conducted for a spatial resolution of 15 cm, a value that is important because a spatial resolution of centimeters is required for field application of strain sensing to monitor structural health.[3] In this Letter we present what we believe to be the first measurements of the dependence of Brillouin frequency shifts of these Brillouin peaks on strain, and we combine them with measurements of the dependence of their Brillouin frequency shifts on temperature to show that a simultaneous distributed strain-and-temperature sensor can be obtained with a spatial resolution of 15 cm.

The experimental setup for measurement of the Brillouin loss spectrum in a PCF is the same as was reported previously,[2] except that we designed a new stretching unit to measure strain or both temperature and strain. The system is based on the interaction of a pulsed laser and a counterpropagating cw laser for distributed Brillouin sensors at a wavelength of 1320 nm. The PCF has a 2.3-μm-diameter solid-silica core that comprises a 0.8-μm-diameter Ge-doped center region with a parabolic refractive-index profile. The cladding material of the PCF includes air holes and silica matrix. The 2-m-long PCF with 1-m-long standard single-mode-fiber pigtails in both ends of the PCF was connected to the pump laser and the probe laser for the measurements.

To measure temperature effects, we launched 5-dBm pump power into one end and 15-dBm probe power into the other end of the 2-m PCF that we subjected to various temperatures in an oven. The optical fiber was kept loose during the temperature measurements. To measure strain effects, we launched the same pump and probe powers into the PCF. The 1.4-m PCF sample was subjected to various strains by our strain system based on Hooke's law experiment. The strain measurements were conducted at room temperature (24 °C). We obtained spatial information along the fiber length through Brillouin optical time-domain analysis by measuring the propagation times for light pulses traveling in the fiber, in which the spatial resolution is determined by $\delta z = cW/(2n)$, where c, n, and W are the speed of light in vacuum, the refractive index of the fiber core, and the pulse width, respectively. A pulse of 1.5-ns width (equivalent to 15-cm spatial resolution) was used in both temperature and strain measurements.

A typical Brillouin loss spectrum measured at 24 °C and in a loose state is shown in Fig. 1. The multipeak structure in the Brillouin spectrum is due to the presence of an acoustic waveguide and an acoustic antiwaveguide.[2] Peaks a and c are due to the scattering from longitudinal acoustic waves in the Ge-doped center region and the solid pure-silica region of the core, respectively. Their central frequencies increase linearly with temperature, as shown in Fig. 2. The slopes are 0.96 ± 0.01 and 1.25 ± 0.02 MHz/°C for peaks a and c, respectively.

Acoustic velocity v_a is strain dependent in optic fibers; therefore the central frequency of Brillouin spectrum v_B is expected to vary when the fiber is under tension. The effects of strain on Brillouin loss spectra are shown in Fig. 3. The solid curves represent the Lorentzian fits that match well the experimental data based on which we get the uncertainties of $\delta v_B{}^{\mathrm{pk\,a}} = 0.23$ MHz and $\delta v_B{}^{\mathrm{pk\,c}} = 0.32$ MHz in measuring the Brillouin frequencies of peaks a and c, respectively. The central frequency of peak a shows a strong dependence on strain of 252 MHz for a 0.52% elongation. The high accuracy of the experimental setup clearly demonstrates that linewidth Δv and the power loss of peak a remain unchanged with strain up to the elongation 0.52%. The central frequency of peak c displays a strong dependence on strain too. The excellent correlation of central frequency v_B of peaks a and c with strain is confirmed in the detailed measurement shown in Fig. 4. Because peaks a and c arise from different acoustic velocities because there are different Ge-doping concentrations in the core of the PCF, their strain coefficients are different, as shown in Fig. 4 as 0.048 ± 0.0003 and 0.055 ± 0.0009 MHz/$\mu\epsilon$ for peaks a and c, respectively.

For an optical fiber with different Ge-doping concentrations in the core, the Brillouin frequency shifts $v_B{}^{\mathrm{pk}\,1}$ and $v_B{}^{\mathrm{pk}\,2}$ of the two main peaks (peaks 1 and peak 2) that relate to strain ϵ and temperature T are given as

$$\begin{bmatrix} \Delta v_B{}^{\mathrm{pk}\,1} \\ \Delta v_B{}^{\mathrm{pk}\,2} \end{bmatrix} = \begin{bmatrix} C_\epsilon{}^{\mathrm{pk}\,1} & C_T{}^{\mathrm{pk}\,1} \\ C_\epsilon{}^{\mathrm{pk}\,2} & C_T{}^{\mathrm{pk}\,2} \end{bmatrix} \begin{bmatrix} \Delta\epsilon \\ \Delta T \end{bmatrix}, \qquad (1)$$

where $\Delta v_B{}^{\mathrm{pk}\,1(2)} = v_B{}^{\mathrm{pk}\,1(2)}(\epsilon, T) - v_{B0}{}^{\mathrm{pk}\,1(2)}(\epsilon_0, T_0)$, $\Delta\epsilon = \epsilon - \epsilon_0$, $\Delta T = T - T_0$, and ϵ_0 and T_0 are the strain and temperature that correspond to a reference Brillouin frequency $v_{B0}{}^{\mathrm{pk}\,1(2)}(\epsilon_0, T_0)$. If the strain coefficients $C_\epsilon{}^{\mathrm{pk}\,1}$ and $C_\epsilon{}^{\mathrm{pk}\,2}$ and the temperature coefficients $C_T{}^{\mathrm{pk}\,1}$ and $C_T{}^{\mathrm{pk}\,2}$ for peaks 1 and 2, respectively, satisfy

$$\begin{vmatrix} C_\epsilon{}^{\mathrm{pk}\,1} & C_T{}^{\mathrm{pk}\,1} \\ C_\epsilon{}^{\mathrm{pk}\,2} & C_T{}^{\mathrm{pk}\,2} \end{vmatrix} \neq 0\,, \qquad (2)$$

the change in temperature ΔT can be given by

$$\Delta T = \frac{\Delta v_B{}^{\mathrm{pk}\,2} C_\epsilon{}^{\mathrm{pk}\,1} - \Delta v_B{}^{\mathrm{pk}\,1} C_\epsilon{}^{\mathrm{pk}\,2}}{C_\epsilon{}^{\mathrm{pk}\,1} C_T{}^{\mathrm{pk}\,2} - C_\epsilon{}^{\mathrm{pk}\,2} C_T{}^{\mathrm{pk}\,1}}\,, \qquad (3)$$

and the change in fiber strain can be obtained by

$$\Delta\epsilon = \frac{\Delta v_B{}^{\mathrm{pk}\,1} C_T{}^{\mathrm{pk}\,2} - \Delta v_B{}^{\mathrm{pk}\,2} C_T{}^{\mathrm{pk}\,1}}{C_\epsilon{}^{\mathrm{pk}\,1} C_T{}^{\mathrm{pk}\,2} - C_\epsilon{}^{\mathrm{pk}\,2} C_T{}^{\mathrm{pk}\,1}}\,. \qquad (4)$$

For the PCF we can choose peaks a and c as the subjects investigated in strain and temperature measurements. As mentioned above, $C_\epsilon{}^{\mathrm{pk\,a}} = 0.048$ MHz/$\mu\epsilon$, $C_\epsilon{}^{\mathrm{pk\,c}} = 0.055$ MHz/$\mu\epsilon$, $C_T{}^{\mathrm{pk\,a}} = 0.96$ MHz/°C, and $C_T{}^{\mathrm{pk\,c}} = 1.25$ MHz/°C, and $C_\epsilon{}^{\mathrm{pk\,a}} C_T{}^{\mathrm{pk\,c}} - C_\epsilon{}^{\mathrm{pk\,c}} C_T{}^{\mathrm{pk\,a}} = 7.2 \times 10^{-3} \neq 0$. Therefore we can obtain the changes in strain and temperature from Eqs. (3) and (4). Considering the uncertainties in measuring $v_B{}^{\mathrm{pk\,a}}$ and $v_B{}^{\mathrm{pk\,c}}$ ($\delta v_B{}^{\mathrm{pk\,a}} = 0.23$ MHz and $\delta v_B{}^{\mathrm{pk\,c}} = 0.32$ MHz) and following the error analysis for the simultaneous measurement of strain and temperature reported by Jones,[8] we found the maximum errors of temperature and strain to be 3.9 °C and 83 $\mu\epsilon$, respectively, in our measurements with

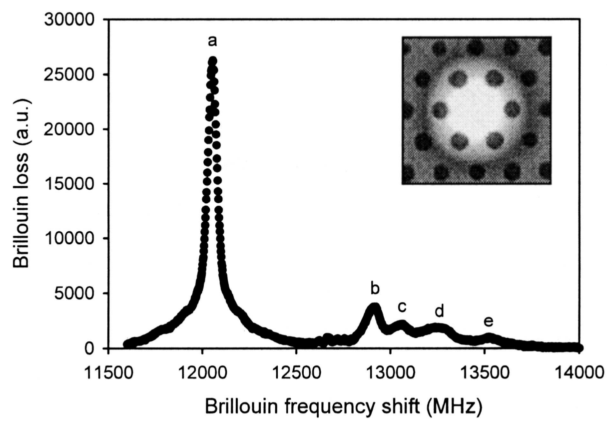

Fig. 1. Brillouin loss spectrum of a 2-m photonic crystal fiber with a partially Ge-doped core measured at 24 °C and in a loose state. Inset, near-field microscope picture of the PCF.

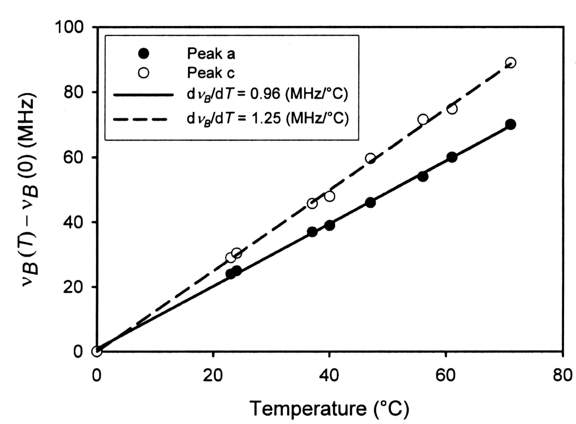

Fig. 2. Central frequencies of peaks a and c as functions of temperature. $[v_B(T) - v_B(0)]$ is given by either $[v_B{}^{\mathrm{pk\,a}}(T) - v_B{}^{\mathrm{pk\,a}}(0)]$ or $[v_B{}^{\mathrm{pk\,c}}(T) - v_B{}^{\mathrm{pk\,c}}(0)]$.

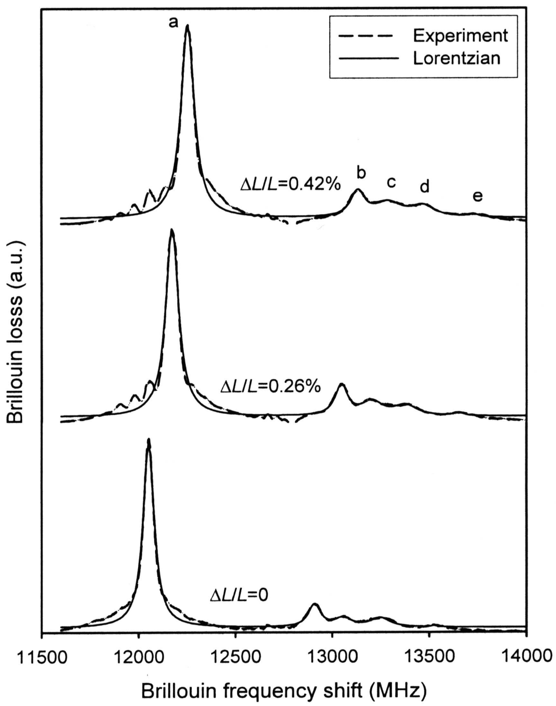

Fig. 3. Brillouin loss spectra of a PCF measured for different fiber elongations at room temperature (24 °C). The experimental data fit the Lorentzian functions very well.

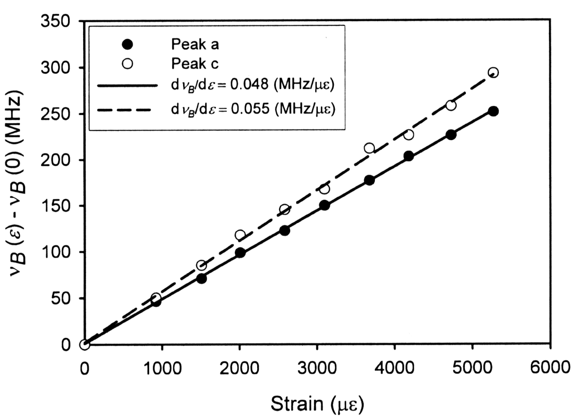

Fig. 4. Central frequencies of peaks a and c as functions of strain. $[v_B(\epsilon)-v_B(0)]$ is given by either $[v_B{}^{\mathrm{pk\,a}}(\epsilon)-v_B{}^{\mathrm{pk\,a}}(0)]$ or $[v_B{}^{\mathrm{pk\,c}}(\epsilon)-v_B{}^{\mathrm{pk\,c}}(0)]$.

a spatial resolution of 15 cm. These results show higher measurement accuracy compared with the values of ~27 °C and ~570 $\mu\epsilon$ for a larger-effective-area fiber reported in Ref. 9 for the simultaneous temperature and strain measurement and 2-m spatial resolution.[7] This difference may be attributed to the higher power density for a small core of the PCF, which results in higher Brillouin gain–loss and a better signal-noise ratio. To compare with the results for a single–mode fiber [~4.1 °C and ~140 $\mu\epsilon$ (Ref. 9) with 10-m spatial resolution[6]], our results show similar temperature but better strain accuracy and higher spatial resolution. This comparison clearly demonstrates the ability of our system to measure temperature and strain simultaneously. For example and as a special case used for strain coefficient measurements, when 24 °C and 1509 $\mu\epsilon$ were set, the measured Brillouin frequency shifts for peaks a and c were 12.1225 and 13.1357 GHz, respectively. At a temperature of 24 °C and a strain of 2582 $\mu\epsilon$, the measured Brillouin frequency shifts of peaks a and c were 12.1746 and 13.1956 GHz, respectively. So we had $\Delta v_B{}^{\mathrm{pk\,a}} = 52.1$ MHz and $\Delta v_B{}^{\mathrm{pk\,c}} = 59.9$ MHz. Then we could calculate $\Delta T = 1.3$ °C according to Eq. (3), which was different from our expectation of 0 °C (=24 °C−24 °C). From Eq. (4) we calculated the strain difference $\Delta\epsilon = 1059\ \mu\epsilon$, which resulted in a difference of 14 $\mu\epsilon$ from the measurement of 1073 $\mu\epsilon$ (=2582−1509 $\mu\epsilon$). Based on all experimental data analysis, our simultaneous strain and temperature measurements with the PCF were off by 1.3 °C and 15 $\mu\epsilon$ from the actual temperature and strain variations, values that are within the maximum error.

In summary, we have presented what we believe to be the first measurement of the strain and temperature coefficients in a photonic crystal fiber with Brillouin scattering. For the two main peaks that are attributed to the scattering from longitudinal acoustic waves in the Ge-doped center region and the solid pure-silica region of the core of the PCF, the strain coefficients are 0.048 and 0.055 MHz/$\mu\epsilon$ and temperature coefficients are 0.96 and 1.25 MHz/°C at 1320 nm. Together with measurements of the dependence of the Brillouin frequency shift on temperature and strain, we have demonstrated a highly precise simultaneous distributed strain and temperature sensor with a spatial resolution of 15 cm along a single PCF.

The authors thank Sylvain Robineau for providing the setup of the Hooke law experiment used in these experiments. L. Zou's e-mail address is lufan.zou@science.uottawa.ca.

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