

A new dual-Brillouin-peak optical fiber for simultaneous distributed strain and temperature measurement

Xiaoguang Sun, Ping Lu, Kyle Bedard, Jie Li and Robert S. Dyer
OFS, 55 Darling Drive, Avon, CT 06001

Abstract: A new single-mode optical fiber with two Brillouin gain peaks is designed and fabricated to increase the differences in the temperature and strain coefficients between the peaks. The gains of the two Brillouin peaks are at a similar level and the temperature coefficient difference is ~ 0.2 MHz/ $^{\circ}$ C. The fiber is well suited for simultaneous temperature and strain measurement with reduced uncertainties in Brillouin distributed fiber sensing applications. © 2022 The Author(s)

1. Introduction

Brillouin scattering based distributed optical fiber sensors have been widely used in structural health monitoring in civil infrastructure, aerospace and defense, providing a long-distance sensing range, high spatial resolution, and high measurement accuracy [1]. In conventional Brillouin optical time-domain reflectometer (BOTDR) and Brillouin optical time-domain analyzer (BOTDA) systems, temperature and strain determinations based on Brillouin frequency shift (BFS) measurement, however, exhibits high cross-sensitivity and makes it difficult to achieve simultaneous discriminative sensing. Since this fundamental limitation severely restricts its practical sensing capabilities, different methods based on fiber sensor interrogation advancement and novel Brillouin-tailored fiber development have been proposed to address the temperature and strain cross-sensitivity issue. For instance, a reference fiber method was first proposed in 1994 by using two fibers parallel to each other with one fiber isolated from the strain effects and used to determine temperature variations of the other fiber though the two fibers may be exposed to different temperature even in the same cable construction [2]. Simultaneous temperature and strain measurements were also demonstrated in a dual wavelength BOTDA scheme at 850 nm and 1550 nm wavelengths [3], BOTDA integrated with a Brillouin dynamic grating in a polarization-maintaining fiber [4], a hybrid Raman/BOTDA [5], and combined BOTDA and Rayleigh scattering based optical frequency-domain reflectometry [6] at the expense of more complex, high-cost fiber sensing systems. Different strain and thermal coefficients for distinct optical modes in multimode fibers or each core in multi-core fibers have been used for temperature-strain discrimination measurements in distributed Brillouin sensing applications [7-11]. However, all these approaches show relatively large measurement errors in field applications because mode coupling or core-to-core crosstalk is very sensitive to tight bends or external stress. Using one single-core single-mode optical fiber (SMF) for simultaneous detection of temperature and strain is always attractive since it allows simple and easy installations and more reliable measurements. Optical fibers with multi-peaked structures attributed to higher-order acoustic modes in the core have been proposed and manufactured to resolve temperature and strain simultaneously, including inverse-parabolic graded-index fiber [12], dispersion-shifted fiber [13, 14], photonic crystal fiber [15], and highly GeO₂-doped fiber [16-18]. However, these studies show large temperature and strain measurement uncertainties, hindering from achieving the desired temperature-strain discrimination measurements.

The frequencies of several peaks in the Brillouin gain spectrum (BGS) of a single-mode fiber are affected by changes in both surrounding temperature along the sensing fiber ΔT and applied strain on the fiber $\Delta \epsilon$. Thus, temperature and strain can be calculated from the frequency shifts of the main peak (Peak-1, $\Delta \nu_1$) and the higher-order Brillouin peak (Peak-2, $\Delta \nu_2$) by solving the following linear equation:

$$\begin{bmatrix} \Delta \nu_1 \\ \Delta \nu_2 \end{bmatrix} = \begin{bmatrix} C_1^T & C_1^\epsilon \\ C_2^T & C_2^\epsilon \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta \epsilon \end{bmatrix} \quad (1)$$

where $C_{1,2}^T$ and $C_{1,2}^\epsilon$ are the temperature and strain coefficients of Peak-1 and Peak-2, respectively. The measurement uncertainties of temperature δT and strain $\delta \epsilon$ can be calculated by the following equation derived from Equation-1 following the error analysis,

$$\begin{aligned} \delta T &= \frac{1}{|C_1^T C_2^\epsilon - C_2^T C_1^\epsilon|} \sqrt{(C_2^\epsilon \delta \nu_1)^2 + (C_1^\epsilon \delta \nu_2)^2} \\ \delta \epsilon &= \frac{1}{|C_1^T C_2^\epsilon - C_2^T C_1^\epsilon|} \sqrt{(C_2^T \delta \nu_1)^2 + (C_1^T \delta \nu_2)^2} \end{aligned} \quad (2)$$

where $\delta\nu_1$ and $\delta\nu_2$ are the measurement uncertainties of the BFS of the peaks. According to a figure-of-merit defined for BOTDA-based distributed fiber sensors, the frequency uncertainty depends on signal-to-noise ratio (SNR) of BOTDA traces at the peak gain frequency and other measurement parameters [19]. Since the uncertainty of the frequency measurement directly represents the inverse of the SNR, relatively low Brillouin gains of the higher-order acoustic modes becomes a major cause of large variations in measured temperature and strain. For a typical commercial fiber with multiple Brillouin peaks, the temperature coefficient difference is ~ 0.02 MHz/ $^{\circ}$ C, and the Brillouin frequency error obtained with a standard BOTDA method is ~ 1 MHz, and the temperature uncertainty reduces to $\delta T \sim \frac{1}{|C_1^T - C_2^T|} \sqrt{(\delta\nu_1)^2 + (\delta\nu_2)^2}$ and turns out to be tens of degrees Celsius. To achieve a minimum possible δT and $\delta\varepsilon$, the temperature and strain coefficients for the BFS need to be significantly distinct between Peak-1 and Peak-2 to increase the value of $|C_1^T C_2^{\varepsilon} - C_2^T C_1^{\varepsilon}|$. The intensities of Peak-1 and Peak-2 also need to be very comparable, so that $\delta\nu_1$ and $\delta\nu_2$ are similar too.

In this paper we present a new dual-Brillouin-peak optical fiber suitable for simultaneous distributed temperature and strain measurement. The fiber is fully compatible with existing typical SMFs with low splicing loss and has a low loss of 0.434 dB/km at 1550 nm. The acoustic index profile of the proposed SMF is modified to increase the overlap integrals between the fundamental optical mode and the higher-order acoustic modes. The Brillouin gain from the LP₀₂ acoustic mode is increased to a level closely matching that of the main peak corresponding to the LP₀₁ acoustic mode. The measured BGS agrees well with the theoretical simulation. The temperature and strain coefficients are also measured showing that the temperature coefficients of the two peaks are significantly different and it can improve the accuracy of the measured temperature and strain.

2. Fiber design

Our fiber design is similar to the one described in [16], but with improved glass composition in the core. Higher GeO₂ doping has been shown to significantly change the BFS, temperature and strain coefficients of the BFS [8, 17]. The fiber is designed to have a core diameter of 6 μ m and a cutoff wavelength < 1500 nm. The simulated BGS of the fiber is shown in Figure-1. The two peaks are close in their intensities and are separated by 500 MHz at room temperature.

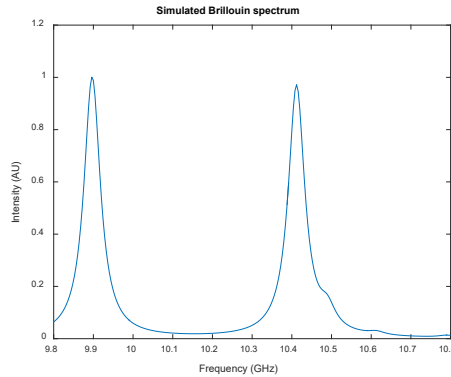


Figure 1. The simulated BGS of the proposed fiber.

3. Fiber properties

A GeO₂/F₂ co-doped preform was made with a modified chemical vapor deposition (MCVD) method based on the design described above. The preform was then drawn to fiber with 125 μ m cladding diameter and 250 μ m dual-acrylate coating. The mode field diameter (MFD) of the fiber was measured to be 7.2 μ m and the splice loss with a G.652 fiber was measured to be less than 0.1 dB. The measured fiber cutoff wavelength is 1210 nm.

The BGS was measured using a BOTDA system at 1550 nm and is plotted in Figure-2. The measured BGS is close to the simulation shown in Figure 1: the Brillouin gain from the LP₀₁ acoustic mode (Peak-1) is located 9.89 GHz; the gain from the LP₀₂ acoustic mode (Peak-2) is at 10.398 GHz and has a similar intensity to that of Peak-1.

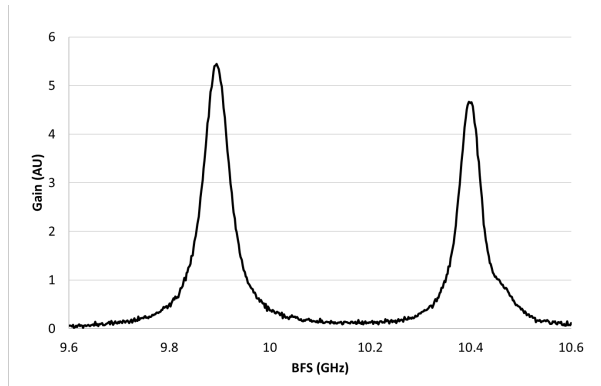


Figure 2. The measured BGS of the manufactured fiber at room temperature.

The temperature and strain coefficients of the fiber were measured using a BOTDA with pulse width of 30 ns and spatial sampling resolution of 0.5 m. The measured relative BFS vs. temperature and strain are shown in Figure-3. The strain coefficients of Peak-1 and Peak-2 are 0.0418 MHz/ $\mu\epsilon$ and 0.0472 MHz/ $\mu\epsilon$, respectively. The temperature coefficients of Peak-1 and peak-2 are 0.911 MHz/ $^{\circ}\text{C}$ and 1.11 MHz/ $^{\circ}\text{C}$. The temperature coefficient difference of the two peaks is ~ 0.2 MHz/ $^{\circ}\text{C}$ which is much larger than that of a typical commercial fiber, such as LEAF fiber [7].

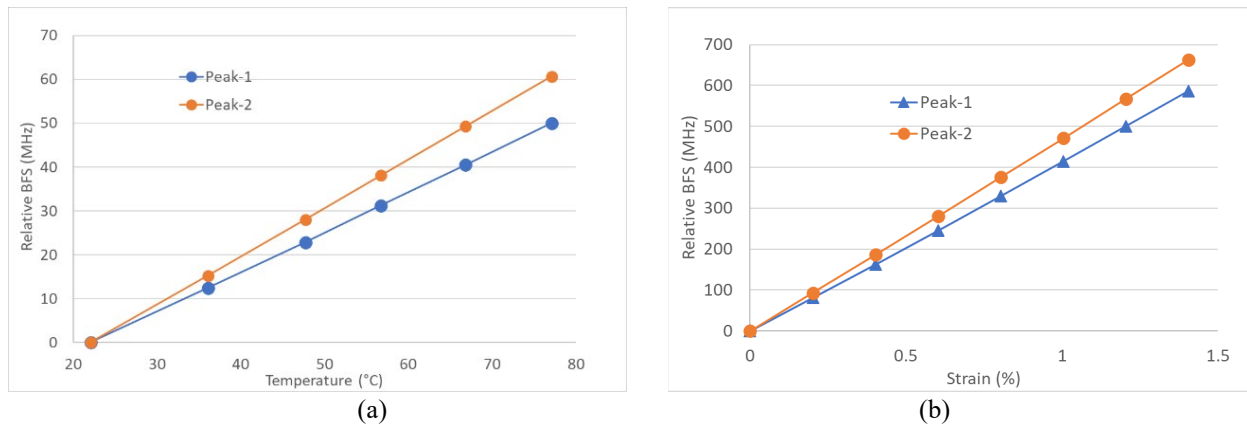


Figure 3. The measured temperature (a) and strain (b) coefficients of Peak-1 and Peak-2.

4. Discussion

A specialty optical fiber with a tailored index profile is proposed to support and enhance higher-order acoustic modes in SMF, showing high scattering efficiency and thermomechanical response of the Brillouin process. The fiber offers the maximum ratio of higher-order acoustic and optical interaction peak relative to the main Brillouin gain peak as well as the maximum separation between the two peaks. A standard BOTDA scheme integrated with the proposed fiber is experimentally demonstrated for performing the requested temperature-strain discrimination with high accuracy. It represents a promising solution to improve sensing capabilities of most commercially available Brillouin interrogators without increasing the system complexity and cost.

4. References

- [1] P. Dragic and J. Ballato, "A brief review of specialty optical fibers for Brillouin-scattering-based distributed sensors," *Appl. Sci.* 8, 1996 (2018).
- [2] X. Bao, D. J. Webb, and D.A. Jackson, "Combined distributed temperature and strain sensor based on Brillouin loss in an optical fiber," *Opt. Lett.* 19, 141 (1994).
- [3] A. Minardo, A. Coscetta, E. Catalano, and L. Zeni, "Simultaneous strain and temperature measurements by dual wavelength Brillouin sensors," *IEEE Sens. J.* 17, 3714 (2017).
- [4] W. Zou, Z. He, and K. Hotate, "Complete discrimination of strain and temperature using Brillouin frequency shift and birefringence in a polarization-maintaining fiber," *Opt. Express* 17, 1248 (2009).
- [5] M. Taki, A. Signorini, C.J. Oton, T. Nannipieri, and F.Di Pasquale, "Hybrid Raman/Brillouin-optical-time-domain-analysis-distributed optical fiber sensors based on cyclic pulse coding," *Opt. Lett.* 38, 4162 (2013).
- [6] D.P. Zhou, W. Li, L. Chen, and X. Bao, "Distributed temperature and strain discrimination with stimulated Brillouin scattering and Rayleigh backscatter in an optical fiber," *Sensors* 13, 1836 (2013).

- [7] X. Liu and X. Bao, "Brillouin spectrum in LEAF and simultaneous temperature and strain measurement," *J. Lightwave Technol.* 30, 1053 (2012).
- [8] W. Zou, Z. He, and K. Hotate, "Investigation of strain- and temperature-dependences of Brillouin frequency shifts in GeO₂-doped optical fibers," *J. Lightwave Technol.* 26, 1854 (2008).
- [9] M.A.S. Zaghloul, M. Wang, G. Milione, M.J. Li, S.P. Li, Y.K. Huang, T. Wang, and K.P. Chen, "Discrimination of temperature and strain in Brillouin optical time domain analysis using a multicore optical fiber," *Sensors* 18, 1176 (2018).
- [10] Y. Mizuno, N. Hayashi, H. Tanaka, Y. Wada, and K. Nakamura, "Brillouin scattering in multi-core optical fibers for sensing applications," *Sci. Rep.* 5, 11388 (2015).
- [11] H. Wu, M. Tang, M. Wang, C. Zhao, Z. Zhao, R. Wang, R. Liao, S. Fu, C. Yang, W. Tong, P.P. Shum, and D. Liu, "Few-mode optical fiber based simultaneously distributed curvature and temperature sensing," *Opt. Express* 25, 12722 (2017).
- [12] Y. Xu, M. Ren, Y. Lu, P. Lu, P. Lu, X. Bao, L. Wang, Y. Messaddeq, and S. LaRochelle, "Multi-parameter sensor based on stimulated Brillouin scattering in inverse-parabolic graded-index fiber," *Opt. Lett.* 41, 1138 (2016).
- [13] C.C. Lee, P.W. Chiang, and S. Chi, "Utilization of a dispersion-shifted fiber for simultaneous measurement of distributed strain and temperature through Brillouin frequency shift," *IEEE Photon. Technol. Lett.* 13, 1094 (2001).
- [14] Y. Lu, Z. Qin, P. Lu, D.P. Zhou, L. Chen, and X. Bao, "Distributed strain and temperature measurement by Brillouin beat spectrum," *IEEE Photon. Technol. Lett.* 25, 1050 (2013).
- [15] L. Zou, X. Bao, S. Afshar, and L. Chen, "Dependence of the Brillouin frequency shift on strain and temperature in a photonic crystal fiber," *Opt. Lett.* 29, 1485 (2004).
- [16] X. Sun, K. Bedard, J. Li, and R. Dyer, "A dual-Brillouin-peak optical fiber for simultaneous distributed strain and temperature measurement," *SPIE* 1082103 (2018).
- [17] M. Deroh, B. Kibler, H. Maillotte, T. Sylvestre, and J. Beugnot, "Large Brillouin gain in Germania-doped core optical fibers up to a 98 mol% doping level," *Opt. Lett.* 43, 4005 (2018).
- [18] C. Sabatier, S. Girard, L. Mescia, A. Ladaci, T. Robin, B. Cadier, A. Boukenter, Y. Ouerdane, and E. Marin, "Combined experimental and simulation study of the fiber composition effects on its Brillouin scattering signature," *J. Light. Technol.* 37, 4619 (2019).
- [19] M.A. Soto and L. Thévenaz, "Modeling and evaluating the performance of Brillouin distributed optical fiber sensors," *Opt. Express* 21, 31347 (2013).