Potential of Discriminative Sensing of Strain and Temperature Using Perfluorinated Polymer FBG

Yosuke Mizuno, *Senior Member, IEEE*, Ryo Ishikawa, Heeyoung Lee, Antreas Theodosiou, *Student Member, IEEE*, Kyriacos Kalli, *Member, IEEE*, and Kentaro Nakamura, *Member, IEEE*

***Abstract*—Though the strain characteristics of fiber Bragg gratings (FBGs) inscribed in perfluorinated graded-index (PFGI) polymer optical fibers (POFs) have been reported, their temperature characteristics have not yet been detailed. In this paper, we experimentally investigate the temperature dependence of the Bragg wavelength of a PFGI-POF-FBG. With the increasing temperature, each peak of the FBG-reflected spectrum shifted to longer wavelength with different coefficients. The temperature coefficient of one of the clearest peaks was 0.09 nm/°C, which was eight times larger than those of FBGs in silica single-mode fibers and almost the same as those of FBGs in polymethyl methacrylate POFs. A temperature-independent but strain-dependent peak was also observed, which indicates the potential of discriminative sensing of strain and temperature.**

***Index Terms*—Polymer optical fibers, fiber Bragg gratings, temperature sensing, strain sensing.**

I. Introduction

SENSING of a variety of physical, chemical, and biological parameters has been one of the major applications of optical fibers [1], [2]. Configurations of fiber-optic sensors are generally categorized into two: distributed sensors and single- (or multiple-) point sensors. The former include strain and/or temperature sensors based on some nonlinear phenomena [3]–[5], which operate in a distributed manner at the cost of relatively low sensitivity (for instance, it is difficult for such distributed sensors to detect small strain of $<< 10\ \mu\varepsilon$). The latter include fiber-grating-based sensors [6]–[13]. Although the number of sensing points is limited, their sensitivity is generally much higher than that of distributed sensors. Here, let us focus on fiber Bragg grating (FBG) sensors.

FBGs have been reported to have measurement capability of strain [8], [13], temperature [8], humidity [9], refractive index [10], pressure [11], [12], and many others. Of all these parameters, strain and temperature are two of the most common measurands of FBG sensors. To date, an FBG inscribed in a standard silica single-mode fiber (SMF) has been reported to have a strain sensitivity of 6.3 nm/% at ~800 nm [14] (corresponding to 12.2 nm/% at ~1550 nm) and a temperature sensitivity of ~0.011 nm/°C at ~1550 nm [6], [7]. Silica SMFs, however, suffer from their fragility and easily break if a ~3% strain is applied. One method for tackling this problem is to use polymer optical fibers (POFs) [15], which are so flexible that they do not break even if a large strain of tens of percent is applied [16]. Therefore, POF-FBGs have gathered a lot of attention to extend the measurable maximal strain [17].

POFs have several types, of which the most widely used are poly(methyl methacrylate) (PMMA)-POFs. FBGs inscribed in PMMA-POFs have been reported to have a strain sensitivity of 7.1 nm/% at ~800 nm [18] (corresponding to 13.8 nm/% at ~1550 nm) and a temperature sensitivity of 0.088 nm/°C at ~1560 nm [19]; their potential strain dynamic range is 13% [20]. However, PMMA-POF-FBGs suffer from extremely high propagation loss (>>100 dB/m) at telecom wavelength. Therefore, it is not easy to employ high-performance but relatively inexpensive devices designed for telecom use, such as amplified spontaneous emission (ASE) sources, to observe the FBG-reflected spectra. To solve this issue, recently, FBGs have been inscribed not only in PMMA-POFs but also in perfluorinated graded-index (PFGI-) POFs, which have been developed for short distance communication systems (relatively low propagation loss (0.25 dB/m) even at 1550 nm) [21], [22].

As PFGI-POFs are commercially available only as multimode fibers and not photosensitive at ultraviolet wavelength [22], it was difficult to inscribe FBGs in PFGI-POFs. However, by using femtosecond laser irradiation, FBG inscription in PFGI-POFs has now turned out feasible [22]–[30]. PFGI-POF-FBGs have lower optical loss, and their Bragg wavelengths at ~1550 nm can be investigated using ASE sources. In addition, by exploiting their core refractive index close to that of water, they are sometimes beneficial for bio-sensing applications [23]. To date, their sensing characteristics of strain, pressure, bending, etc., have been well documented [12], [13], [22], [27], [31], [32], but no detailed reports have been given to their temperature dependence. More specifically, the temperature dependence of the Bragg wavelength of a PFGI-POF-FBG has been roughly reported [22]–[24],

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Y. Mizuno, R. Ishikawa, H. Lee, and K. Nakamura are with the Institute of Innovative Research, Tokyo Institute of Technology, Yokohama 226-8503, Japan (e-mail: ymizuno@sonic.pi.titech.ac.jp; rishikawa@sonic.pi.titech.ac.jp; hylee@sonic.pi.titech.ac.jp; knakamur@sonic.pi.titech.ac.jp).

A. Theodosiou and K. Kalli are with the Photonics and Optical Sensors Research Laboratory, Cyprus University of Technology, Limassol 3036, Cyprus (e-mail: theodosiou.antreas@gmail.com; kyriacos.kalli@cut.ac.cy).

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but more precise measurement of each Bragg wavelength of multiple spectral peaks, corresponding to different propagation modes, has not yet been clarified.

Motivated by this situation, in this work, we precisely investigate the temperature dependence of the Bragg wavelength of a PFGI-POF-FBG at 1550 nm. We show that, with increasing temperature, all the spectral peaks shift to longer wavelength with different coefficients. One of the clearest peaks exhibits a temperature coefficient of 0.09 nm/°C, which is 8 times the value of an FBGs in a silica SMF and almost identical to that of a PMMA-POF-FBG. One of the other peaks is found to be temperature-independent but strain-dependent, which indicates that discriminative sensing of strain and temperature is potentially feasible by using multiple spectral peaks of a single PFGI-POF-FBG.

II. Principle

FBGs can be inscribed not only in SMFs but also in MMFs. Suppose a GI-MMF with a refractive index profile expressed as ($0 < r < R$):

$$n(r) = n_1\sqrt{1 - 2\Delta\left(\frac{r}{R}\right)^g}, \quad (1)$$

and as ($R \leq r$):

$$n(r) = n_1\sqrt{1 - 2\Delta}, \quad (2)$$

where n_1 is the maximal value of the core refractive index, R is the core radius, Δ is the relative index difference between core and cladding, and g is the parabolic profile parameter. The approximate number of modes in the GI-MMF M is then given by [33]:

$$M = \left(\frac{2\pi a}{\lambda}n_1\right)^2 \Delta\frac{g}{g+2}, \quad (3)$$

where λ is the FBG reflection wavelength. By substituting the parameters of a standard PFGI-POF ($n_1 = 1.347$, $a = 25$ um, $\Delta = \sim 0.01$, $g = 2$, $\lambda = \sim 1560$ nm), the number of modes is roughly estimated to be 90 at this wavelength. Without special control for exciting only the fundamental mode [34], light injected into this PFGI-POF excites some of these modes (especially, lower-order modes) and generates multiple peaks at slightly different wavelengths in the FBG-reflected spectrum.

When an PFGI-POF-FBG is strained or heated, each spectral peak shifts with its own dependence coefficient. At 1550 nm, a typical strain-dependence coefficient is ~14 nm/% [22], [28], which is ~1.1 times the value of an FBG in a silica SMF [6]. A temperature dependence coefficient is reported to be ~0.015 nm/°C [22] or 0.028 nm/°C [23], [24]. However, here we should note that these values were obtained using some demodulation techniques [28], [35]; namely, these values were kinds of averaged values of all the peaks in the spectrum. In the case of strain, each peak has been shown to exhibit its own dependence coefficient, ranging from 12.6 nm/% to 14.3 nm/% [35]. In contrast, such a detailed measurement has not been performed for temperature dependence.

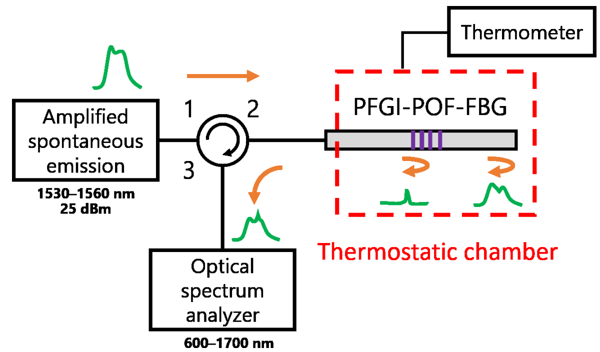

Fig. 1. Experimental setup for measuring the temperature dependence of the Bragg wavelength of the PFGI-POF-FBG.

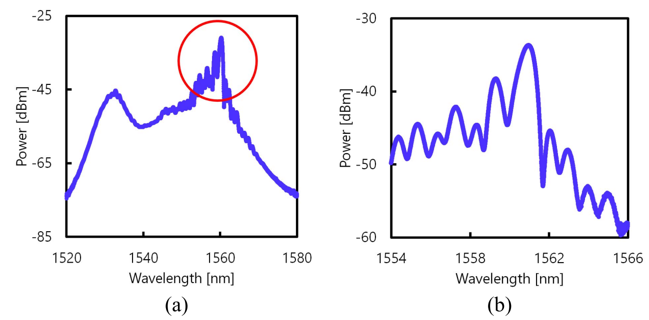

Fig. 2. (a) Measured spectrum of the FBG-reflected light. (b) Magnified view of the red-circled part in (a), around the FBG-induced peaks.

III. FBG Inscription and Measurement Setup

An FBG was inscribed in a 1.2-m-long PFGI-POF using a femotosecond laser irradiation method [29], [34]. The length of the FBG was 2 mm. The PFGI-POF (GigaPOF−50SR, Chromis Fiberoptics) was composed of three layers: core (diameter: 50 μm; refractive index: ~1.35), cladding (diameter: 70 μm, refractive index: ~1.34), and overcladding (diameter: 490 μm). The core and cladding layer were doped and undoped amorphous fluoropolymer (CYTOP®), respectively, and the overcladding layer was polycarbonate. The optical propagation loss was ~0.25 dB/m at 1550 nm, and the numerical aperture was ~0.19. The FBG was inscribed directly, without removal of the overcladding layer, using a femtosecond laser system (High Q femtoREGEN, High Q Laser) at 517 nm. The pulse duration was 220 fs, the repetition rate was 1 kHz, and the pulse energy was ~100 nJ [22], [29]. The POF was mounted on an air bearing translation system (Aerotech), which can achieve two-axis motion with high resolution and high accuracy. A long-working-distance objective (x50) was mounted on a third axis, and the laser beam was irradiated focusedly into the fiber. Accurate synchronization of the laser pulse repetition rate and the stage motion enabled plane-by-plane grating inscription with a desired length and an index-modulation value [22], [26], [29], [34].

Figure 1(a) shows an experimental setup for measuring the temperature dependence of the FBG-reflected spectrum. All the optical paths except the POF were silica SMFs. The output from an ASE source was injected into the POF, and the

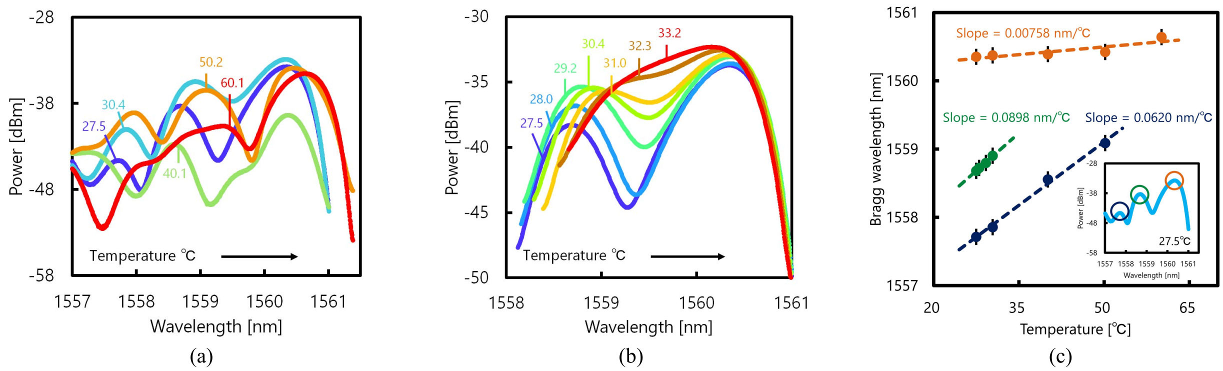

Fig. 3. Temperature dependence of the POF-FBG-reflected spectrum. (a) Spectral change when temperature increased from 27.5°C to 60.1°C. (b) Spectral change when temperature increased from 27.5°C to 33.2°C. (c) Central wavelengths of the three spectral peaks plotted as functions of temperature. The error bars were calculated using the standard deviations of 20 measurements. The dashed lines are linear fits.

FBG-reflected light was guided via an optical circulator to an optical spectrum analyzer (AQ6370, Yokogawa Electric Corp). We used a reflectometric (not transmissive) configuration to reduce the influence of modal interference [36], [37]. The POF was placed in a thermostatic chamber. As the temperature accuracy of the chamber was not sufficiently high, a thermocouple was placed near the POF-FBG to calibrate the temperature. One end of the POF was connected to a silica SMF outside the chamber using a butt-coupling technique [38], and the other end was cut with an 8° angle to suppress the Fresnel reflection. Note that the following experimental results were highly repeatable as long as the alignment of the fibers in the setup was maintained.

IV. Experimental Results

First, we measured the optical spectrum of the FBG-reflected light, as shown in Fig. 2(a). Though the spectrum of the light Fresnel-reflected mainly at the SMF-to-POF boundary was overlapped, it was clearly observed at ∼1560 nm. Figure 2(b) shows the magnified view of the FBG-reflected spectrum around its peaks. Multiple peaks and dips, caused by the multimode nature of the POF [39], were observed in the spectrum.

Subsequently, we measured the FBG-reflected spectra while changing the temperature from 27.5°C to 60.1°C, as shown in Fig. 3(a). At 27.5°C, three peaks were observed at 1557.7, 1558.7, and 1560.4 nm in this range. With increasing temperature, all these peaks moved to longer wavelength but with different dependence coefficients. As some of the peaks were buried by another peak, it was not easy to trace particular peaks in this wide temperature range. The spectral dependence on temperature in the narrow range from 27.5°C to 33.2°C is shown in Fig. 3(b), The temperature dependence of the peak at 1558.7 nm was almost linear, but at ∼33°C, it became non-observable because of the overlap with the peak at 1560.4 nm.

Figure 3(c) shows the temperature dependence of the central wavelengths of the three peaks. The temperature-dependence coefficients of the peaks at 1557.7 and 1558.7 were 0.062 nm/°C and 0.090 nm/°C (coefficients of determination R^2: 0.995 and 0.993), respectively. The latter is ∼8 times as large as that of a silica SMF-FBG (0.011 nm/°C) [6] and almost the same as that of a PMMA-POF-FBG (0.088 nm/°C) [19]. In contrast, the peak at 1560.4 nm was almost constant while the temperature increased from 27.5°C to ∼50°C. When the temperature increased to ∼60°C, the peak exhibited a clear upshift, and the linear fit in the wide temperature gave a dependence coefficient of 0.0076 nm/°C ($R^2 = 0.777$), which is much smaller than those of the other peaks.

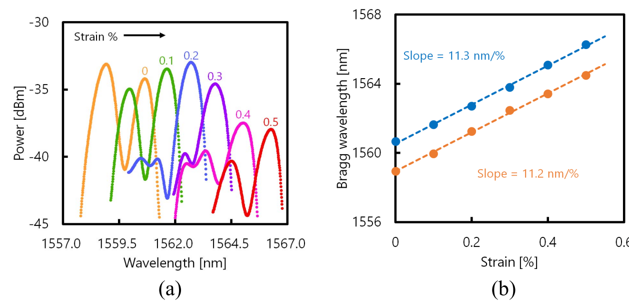

Fig. 4. (a) Strain dependence of the POF-FBG-reflected spectrum. (b) Central wavelengths of the two peaks plotted as functions of temperature. The dashed lines are linear fits.

Finally, as shown in Fig. 4(a), we measured the strain dependence of the FBG-reflected spectrum including the two peaks, one of which is dependent on temperature (at 1558.7 nm) and the other is not largely dependent on temperature (at 1560.4 nm). Strains from 0% to 0.5% were applied to a 10-cm-long section including the FBG. With increasing strain, both of the peaks shifted to longer wavelength. The strain dependence of the central wavelengths of the two peaks is shown in Fig. 4(b). Another peak sometimes appeared near the two peaks, but we traced the initial two peaks by continuous observation. The dependence was almost linear for both peaks, and the coefficients were almost the same (11.2 nm/% at 1558.7 nm and 11.3 nm/% at 1560.4 nm; these values are smaller than previously reported value [22], [28], [35], but it is not unnatural considering that the previous report estimated the Bragg wavelength using some unique demodulation methods [28], [35]; their R^2 values were both ∼0.998). These results indicate that highly accurate discrimination of strain and temperature is potentially feasible by simultaneously employing the multiple peaks (i.e., the temperature-dependent and strain-dependent peak and the temperature-independent but strain-dependent peak) of the POF-FBG-reflected spectrum. Note that the spectral peak at 1557.7 nm had a strain sensitivity of 12.2 nm/%, which is slightly higher than those of the other two peaks, but it suffered from a relatively low R^2 value of 0.971. This indicates that there is a trade-off relationship between the temperature range and the measurement precision. One advantage of this method is its simple calculation procedure (i.e., strain information can be directly obtained), in which we do not need to use matrix-based discrimination of strain and temperature [40]–[43]. The achievable temperature range is limited by the overlap of two spectral peaks, but it can be extended to up to ~50°C, if we permit a lowered measurement precision.

V. Conclusion

The temperature dependence of the POF-FBG-reflected spectrum was experimentally measured. As the temperature increased, all the spectral peaks shifted to longer wavelength with different coefficients. The temperature coefficient of one of the clearest peaks was 0.09 nm/°C (within a limited temperature range below ~33°C), which was 8 times the value of a silica SMF-FBG and almost identical to that of a PMMA-POF-FBG. In contrast, one of the peaks showed almost no shift while the temperature increased to ~50°C. Both the temperature-dependent and independent peaks showed identical dependence on strain, which indicates that highly accurate discriminative sensing of strain and temperature may be possible by using both the peaks simultaneously. We believe that our finding will greatly stimulate the FBG-sensing community.

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Yosuke Mizuno (M'14–SM'17) was born in Hyogo, Japan, in 1982. He received the B.E., M.E., and Dr. Eng. degrees in electronic engineering from the University of Tokyo, Japan, in 2005, 2007, and 2010, respectively. From 2007 to 2010, he was engaged in the Brillouin optical correlation-domain reflectometry at the University of Tokyo, for his Dr. Eng. degree.

From 2010 to 2012, he was with the Tokyo Institute of Technology, Japan, where he worked on polymer optics. In 2011, he stayed at the BAM Federal Institute for Materials Research and Testing, Germany, as a Visiting Research Associate. Since 2012, he has been an Assistant Professor with the Precision and Intelligence Laboratory (presently the Institute of Innovative Research), Tokyo Institute of Technology, where he has been active in fiber-optic sensing, polymer optics, and ultrasonics.

Dr. Mizuno is a member of the IEEE Photonics Society, the Japan Society of Applied Physics, the Optical Society of Japan, and the Institute of Electronics, Information, and Communication Engineers, Japan. He was a recipient of the Konica Minolta Imaging Science Award 2014, the ESPEC Prize for the Encouragement of Environmental Studies 2016, the Funai Information Technology Award 2017, and the Optics Design Award 2018. From 2007 to 2010, he was a Research Fellow (DC1) of the Japan Society for the Promotion of Science, where he was also a Research Fellow (PD) from 2010 to 2012.

Ryo Ishikawa was born in Kanagawa, Japan, in 1994. He received the B.E. degree in electrical and electronic engineering from the National Institute of Technology, Tokyo College, Japan, in 2017. He is pursuing the M.E. degree in electrical and electronic engineering (optical fiber sensing) with the Tokyo Institute of Technology, Japan. His research interests include fiber Bragg gratings and polymer fiber sensing.

Mr. Ishikawa is a Student Member of the Japan Society of Applied Physics and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He received the Outstanding Student Award 2018 from the Optical Fiber Technologies Conference and IEICE.

Heeyoung Lee was born in Seoul, South Korea, in 1990. She received the B.E. degree in mechanical engineering from Kyungpook National University, South Korea, in 2014, and the M.E. degree in information processing from the Tokyo Institute of Technology, Japan, in 2017, where she is pursuing the Dr. Eng. degree in electrical and electronic engineering (fiber-optic sensors). Her research interests include fiber-optic sensing and polymer optics.

Ms. Lee is a Student Member of the Japan Society of Applied Physics and the Optical Society of Japan. She was a recipient of the Optics Design Award in 2018. She received the Best Student Paper Award from the 26th International Conference on Plastic Optical Fibers in 2017, the Student Award from the 22nd International Microoptics Conference in 2017, the Outstanding Student Award 2017 from the Optical Fiber Technologies Conference and the Institute of Electronics, Information and Communication Engineers, Japan, and the Student Paper Award from the 7th Asia–Pacific Optical Sensors Conference in 2018. Since 2017, she has been a Research Fellow (DC1) of the Japan Society for the Promotion of Science.

Antreas Theodosiou received the B.Sc. degree in electrical engineering and the M.Sc. degree in electrical engineering, with specialization in communication systems from Frederick University, Cyprus, in 2011 and 2013, respectively, and the Ph.D. degree, with specialization in photonics and optical sensing, from the Cyprus University of Technology in 2018. His current research interests include the development of optical fiber sensors using femtosecond lasers.

Kyriacos Kalli (M'00) received the B.Sc. (Hons.) degree in theoretical physics and the Ph.D. degree in physics from the University of Kent, U.K., in 1988 and 1992, respectively, where he studied linear and non-linear phenomena in optical fibers.

In 2008, he joined the Cyprus University of Technology, where he is an Associate Professor with the Department of Electrical Engineering, Computer Engineering and Informatics and the Director of the Photonics and Optical Sensors Research Laboratory.

Dr. Kalli has more than 230 journal and conference publications. He is a co-author of *Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing* and many book contributions. His research interests are in Bragg grating and optical fiber sensors, femtosecond laser micro-fabrication of photonic devices, microfluidics, and plasmonics. He is a Chartered Physicist and a Senior Member of OSA. He is currently on the Board of the Directors of the Cyprus Organization for Standardization.

Kentaro Nakamura (M'00) was born in Tokyo, Japan, in 1963. He received the B.E., M.E., and Dr. Eng. degrees from the Tokyo Institute of Technology, Japan, in 1987, 1989, and 1992, respectively.

Since 2010, he has been a Professor with the Precision and Intelligence Laboratory (presently the Institute of Innovative Research), Tokyo Institute of Technology. His research field is the applications of ultrasonic waves, measurement of vibration and sound using optical methods, and fiber-optic sensing.

Dr. Nakamura is a member of the Acoustical Society of Japan (ASJ), the Japan Society of Applied Physics (JSAP), the Institute of Electronics, Information and Communication Engineers (IEICE), and the Institute of Electrical Engineers of Japan. He was a recipient of the Optics Design Award 2018. He received the Awaya Kiyoshi Award for encouragement of research from ASJ in 1996, the Best Paper Award from IEICE in 1998, the Best Paper Award from the Symposium on Ultrasonic Electronics in 2007 and 2011, and the Japanese Journal of Applied Physics Editorial Contribution Award from JSAP in 2007.