



Strain dependence of perfluorinated polymer optical fiber Bragg grating measured at different wavelengths

Ryo Ishikawa¹, Heeyoung Lee¹, Amédée Lacraz², Antreas Theodosiou², Kyriacos Kalli², Yosuke Mizuno^{1*}, and Kentaro Nakamura¹

¹*Institute of Innovative Research, Tokyo Institute of Technology, Yokohama 226-8503, Japan*

²*Nanophotonics Research Laboratory, Cyprus University of Technology, Limassol 3036, Cyprus*

*E-mail: ymizuno@sonic.pi.titech.ac.jp

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We measure the strain dependence of multiple Bragg wavelengths (corresponding to different diffraction orders) of a fiber Bragg grating (FBG) inscribed in a perfluorinated graded-index polymer optical fiber (PFGI-POF) in the wavelength range up to 1550 nm. On the basis of this result, we show that the fractional sensitivity, which has been conventionally used as a wavelength-independent index for fair comparison of the FBG performance measured at different wavelengths, is dependent on wavelength in this range. The reason for this behavior seems to originate from the non-negligible wavelength dependence of refractive index and its strain-dependence coefficient. Using the wavelength dependence of the refractive index already reported for bulk, we deduce the wavelength dependence of the strain coefficient of the refractive index. This information will be a useful archive in implementing PFGI-POF-based strain sensors based on not only FBGs but also Brillouin scattering in the future.

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For the past several decades, fiber-optic sensing technology has been extensively studied to measure various physical parameters.^{1–26} In general, optical fiber sensors are categorized into two configurations. One is distributed sensing,^{1–14} which includes strain and temperature sensing based on Brillouin^{3–12} or Raman scattering.^{13,14} Its distributed measurement capability is an attractive feature, but its sensitivity is sometimes insufficient. The other configuration is single-point or multiplexed sensing,^{15–26} which includes sensing based on fiber Bragg gratings (FBGs).^{17–26} Although it suffers from dead zones where measurements cannot be performed, its sensitivity is generally higher than that of distributed sensing, rendering FBG sensing more suitable for some applications, such as high-frequency dynamic measurements. Here, we focus on FBG-based sensing.

FBGs have been used to measure a variety of parameters, such as strain,^{19,20} temperature,¹⁹ humidity,²¹ pressure,²² refractive index,²³ and many others.^{24–26} Among them, strain sensing is one of the most common purposes of FBG sensors, and numerous reports have been provided especially on the FBGs inscribed in standard silica single-mode fibers (SMFs).¹⁹ For instance, a strain sensitivity of 6.3 nm/% has been reported at ~800 nm.²⁰ However, silica SMFs are relatively fragile and cannot withstand strains larger than ~3%. One solution to this problem is to employ polymer optical fibers (POFs),²⁷ which have extremely high flexibility and can sometimes withstand strains of 50% or larger.²⁸ Therefore, FBGs inscribed in POFs (POF-FBGs) have attracted considerable attention to enhance the strain dynamic range of the sensors.²⁹

The most widely used POFs are poly(methyl methacrylate) (PMMA-) POFs,²⁷ and PMMA-POF-FBGs have been reported to have a strain sensitivity of 7.1 nm/% at ~800 nm³⁰ and a strain dynamic range of 13% (potential).³¹ However, the optical propagation loss of PMMA-POFs is lowest at visible wavelengths (~600 nm) and is extremely high ($\gg 100$ dB/m) at 1550 nm. Consequently, many high-performance yet relatively inexpensive devices designed to be optimal at telecom wavelength, including amplified spontaneous emission sources, cannot be used to interrogate the Bragg wavelengths. To tackle this issue, the use of FBGs inscribed in perfluorinated

graded-index (PFGI-) POFs³² has recently become one of the hot topics in the POF-FBG sensing community.

PFGI-POFs are designed for short distance communication systems,³² with their propagation loss relatively low (0.25 dB/m) even at 1550 nm. In addition, the refractive index of their core is close to that of water; this property is potentially useful in some biosensing applications.³³ However, the inscription of FBGs in PFGI-POFs was extremely difficult, because they are commercially available only as multimode fibers and are sometimes not photosensitive in the ultraviolet wavelength region.³⁴ Only recently, some inscription techniques for PFGI-POF-FBGs have been developed,^{34,35} including a femtosecond-laser-based method.³⁴ To date, their strain, temperature, and pressure sensing performances have been investigated and found to be quite different from those of silica-SMF-FBGs and PMMA-POF-FBGs.^{36–38}

In addition to the fundamental characterization at 1550 nm,³⁶ the strain sensing properties of PFGI-POF-FBGs have been investigated in a wide range of wavelengths from 517 to 883 nm.³⁶ The Bragg wavelengths of six peaks (corresponding to the diffraction orders³⁹ from 7th to 12th) were shown to have different strain sensitivities, which were almost linearly dependent on the wavelength. This result is natural if we neglect the dependence of the refractive index (and its strain-dependence coefficient) on wavelength.³⁹ Therefore, in order to fairly compare the strain sensitivities measured at different wavelengths, researchers have defined a “fractional sensitivity” as the value of the strain sensitivity divided by the wavelength.^{38,40–44} For instance, the strain sensitivity of 8.12 nm/% at 883 nm and that of 4.82 nm/% at 517 nm (corresponding to the fractional sensitivities of $9.20 \times 10^{-3}/\%$ and $9.32 \times 10^{-3}/\%$, respectively) were regarded as almost the same.³⁶ However, it has not been guaranteed that the fractional sensitivity is constantly used as an indicator for a fair comparison of the strain sensitivities measured at different wavelengths of up to 1550 nm.

In this work, using a PFGI-POF-FBG, we measure the strain dependence of four Bragg wavelengths (corresponding to the orders from 4th to 7th) up to 1550 nm, and show that the fractional sensitivity is not constant but dependent on wavelength in this range. The wavelength dependence of the frac-

tional sensitivity may originate from the non-negligible dependence of refractive index and its strain-dependence coefficient on wavelength. Using the refractive index dependence on wavelength already reported for bulk perfluorinated polymers, we then deduce the wavelength dependence of the strain coefficient of the refractive index. This result will be of crucial importance in fairly evaluating the PFGI-POF-FBG performance at different wavelengths and in developing PFGI-POF-based sensors working at different wavelengths in the future.

We employed a PFGI-POF (Chromis Fiberoptics GigaPOF-62SR)³² with a length of 1.4 m. This POF has 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 are composed of doped and undoped amorphous fluoropolymer (CYTOP[®]), respectively, while the overcladding is composed of polycarbonate. The optical propagation loss is ~ 0.25 dB/m at 1550 nm. An FBG was inscribed in the middle of this PFGI-POF directly, without removing the overcladding, with a femto-second laser system (High Q Laser High Q femtoREGEN) at 517 nm.^{34,45} The pulse duration was 220 fs, the repetition rate was 1 kHz, and the pulse energy was close to 100 nJ. The PFGI-POF was placed on a two-axis translation system (Aerotech) with high resolution and high accuracy. Using a long-working-distance objective ($\times 50$) mounted on the third axis, the laser beam was focused into the PFGI-POF. By synchronizing the laser pulse repetition rate and the stage motion accurately, plane-by-plane gratings were inscribed with a desired length and an index-modulation value.^{34,45,46} In this experiment, the FBG-inscribed length was 2 mm. The experimental setup is shown in Fig. S1 in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia>.

First, we measured the wide-wavelength-range optical spectrum of the FBG-reflected light. Two partial spectra (885–1090 and 1100–1680 nm) measured using different circulators are shown in Fig. 1. The whole spectra were somewhat distorted because of the non-flat output spectrum of the light source (note that the relatively broad peak at ~ 1065 nm was due to the seed of the supercontinuum generation) and of the transmission band of the circulators. The FBG-reflected spectra were, however, still clearly observed at 895, 1043, 1248, and 1560 nm. These peaks correspond to the diffraction orders of 7th, 6th, 5th, and 4th, respectively. The peaks of the other orders (for instance, the peak of the 8th order is expected to appear at 781 nm) were not observed in this measurement because of the limited bandwidths of the circulators used in the experiment (although high-order peaks are potentially measurable in the visible wavelength spectrum).³⁶

The magnified view of the FBG-reflected spectrum around 1043 nm is shown in Fig. S2(a) in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia>. Multiple peaks and dips, caused by the multimode nature of the POF,⁴⁷ were observed in the spectrum. We selected the clear and highest peak (which we call the main peak hereafter) at 1043.03 nm and defined its central wavelength as the Bragg wavelength of this diffraction order (6th). We then measured the strain dependence of the main peak as shown in Fig. S2(b) in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia>, where the other peaks were not shown. As the applied strain was increased, the main peak shifted to longer wavelengths. The change in the spectral shape (peak

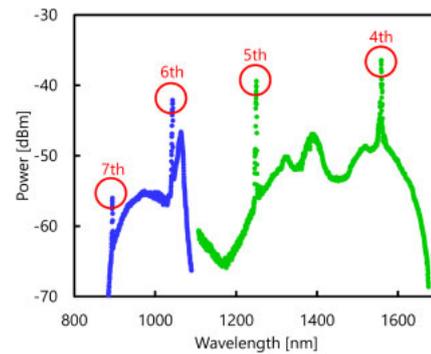


Fig. 1. (Color online) Wide-wavelength-range optical spectrum of the FBG-reflected light. Two partial spectra (885–1090 and 1100–1680 nm) were measured using different circulators. Four FBG-reflected spectral peaks that correspond to the diffraction orders from 4th to 7th were clearly observed.

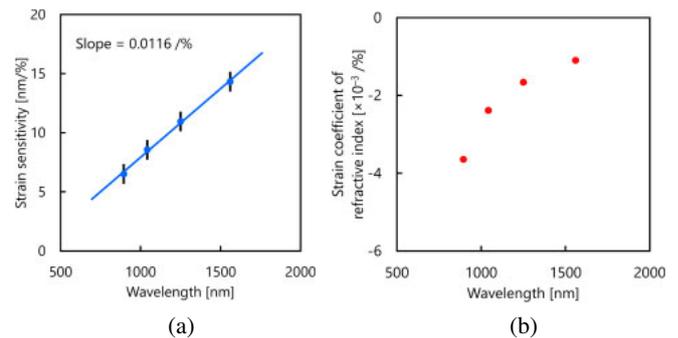


Fig. 2. (Color online) (a) Strain sensitivity of the PFGI-POF-FBG plotted as a function of wavelength. The solid line is a linear fit. The error bars were calculated using the maximal and minimal slopes of Fig. S2(c) in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia>. (b) Wavelength dependence of the strain coefficient of the refractive index.

power and linewidth) was probably caused by the multimode nature of POF.⁴⁷ Figure S2(c) in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia> shows the Bragg wavelength dependence on strain. The Bragg wavelength increased linearly with increasing strain with a dependence coefficient of 8.56 nm/%. Subsequently, the same measurement was performed for the FBG-reflected peaks at three other wavelength regions (895, 1248, and 1560 nm). The main peaks were located at 895.32, 1248.78, and 1560.65 nm, and the obtained strain-dependence coefficients of the Bragg wavelengths were 6.52, 10.95, and 14.32 nm/%, respectively.

Figure 2(a) shows the strain sensitivity plotted as a function of wavelength. With increasing wavelength, the strain sensitivity increased almost linearly with a dependence coefficient of 0.0116/%. We subsequently calculated the fractional sensitivity by dividing the strain sensitivity with the wavelength, and its dependence on wavelength is shown in Fig. S3 in the online supplementary data at <http://stacks.iop.org/JJAP/57/038002/mmedia>. Conventionally, the fractional sensitivity has been treated as a constant that does not depend on wavelength, but in this experiment, it exhibited clear dependence on wavelength (it slowly saturated towards longer wavelengths). According to the theory, this result seems to have been caused by two factors: (i) the wavelength dependence of the refractive index, and (ii) the wavelength dependence of the strain coefficient of the refractive index. The former (i) has already been studied in perfluorinated polymer bulk, and the dependence coefficient is reported to

be $4.25 \times 10^{-6}/\text{nm}$.⁴⁸⁾ Therefore, by using this value and our result, the influence of the latter (ii) can be calculated. As shown in Fig. 2(b), the strain coefficient of the refractive index in the PFGI-POF was found, in this wavelength range, to depend on wavelength, saturating toward longer wavelength, and to constantly take a negative value (this is valid considering that, when strain is applied, the density is reduced, leading to a lower refractive index). As n becomes smaller with increasing wavelength (in bulk), it is natural that the absolute value of $\partial n/\partial \epsilon$ should also become smaller with increasing wavelength. In addition, if we assume that $\partial n/\partial \epsilon$ does not saturate at longer wavelengths, it needs to change from negative to positive at a certain wavelength, which contradicts the fact that $\partial n/\partial \epsilon$ constantly takes a negative value; thus the saturation behaviour is also natural.

This newly obtained data will be a useful archive for the future development of PFGI-POF-based strain sensors based on not only FBGs but also Brillouin scattering (and combinations of the two), because the Brillouin frequency shift is proportional to the refractive index in the same way as the Bragg wavelength.⁴⁹⁾ Note that the strain dependence of the Brillouin frequency shift in PFGI-POFs has been reported only at the 1550 nm region,^{50,51)} and that its wavelength dependence is unknown as yet (the propagation loss of PFGI-POFs becomes approximately 10 times lower at 1000 nm than at 1550 nm;³²⁾ this property will be beneficial for the development of PFGI-POF-based long-measurement-range Brillouin sensors working at nontelecom wavelengths).

In conclusion, the strain dependence of the four Bragg wavelengths of an FBG inscribed in a PFGI-POF was investigated in the wavelength range up to 1550 nm, and the fractional sensitivity, which was conventionally regarded as a wavelength-independent gauge for fair performance comparison, was shown to clearly depend on wavelength in this range. This result probably originated from the non-negligible dependence of refractive index and its strain-dependence coefficient on wavelength. On the basis of the wavelength dependence of the refractive index already reported for perfluorinated polymer bulk, the wavelength dependence of the strain coefficient of the refractive index was calculated. We believe that this information will be of great use not only in fairly evaluating the PFGI-POF-FBG performance at different wavelengths but also in implementing PFGI-POF-based strain sensors exploiting the mechanism of Brillouin scattering, as well as FBGs, in the future.

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Strain dependence of perfluorinated polymer optical fiber Bragg grating measured at different wavelengths

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Kyriacos Kalli², Yosuke Mizuno^{1*}, and Kentaro Nakamura¹

¹*Institute of Innovative Research, Tokyo Institute of Technology, Yokohama 226-8503, Japan*

²*Nanophotonics Research Laboratory, Cyprus University of Technology, Limassol 3036, Cyprus*

*E-mail: ymizuno@sonic.pi.titech.ac.jp

Theory

In an FBG, its periodical refractive index perturbation reflects a narrow band, the central wavelength of which is called the Bragg wavelength λ_B and is given by^{17,39)}

$$\lambda_B = \frac{2n\Lambda}{m}, \quad (1)$$

where n is the effective refractive index of the fiber core, Λ is the grating pitch, and m ($= 1, 2, 3, \dots$) is the diffraction order. When a relatively small strain ε ($\ll 1$) applied to an FBG is increased by $\Delta\varepsilon$, the Bragg wavelength shift $\Delta\lambda_B$ is given by^{17,39)}

$$\Delta\lambda_B = \lambda_B \left(\frac{1}{n} \frac{\partial n}{\partial \varepsilon} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \varepsilon} \right) \Delta\varepsilon = \lambda_B \left(\frac{1}{n} \frac{\partial n}{\partial \varepsilon} + 1 \right) \Delta\varepsilon. \quad (2)$$

As the strain sensitivity defined as $\Delta\lambda_B/\Delta\varepsilon$ is thus in proportion to λ_B , strain sensitivities measured at different wavelengths cannot be directly compared. To overcome this inconvenience, conventionally, we have made use of the fractional strain sensitivity ($= \Delta\lambda_B/\Delta\varepsilon$)^{38,40-44)} that unambiguously compares the sensitivities measured at different wavelengths. The fractional sensitivity is given by

$$\frac{1}{\lambda_B} \frac{\Delta\lambda_B}{\Delta\varepsilon} = \frac{1}{n} \frac{\partial n}{\partial \varepsilon} + 1, \quad (3)$$

which indicates that the fractional sensitivity can be regarded as a wavelength-independent constant only when we assume that n and $\partial n/\partial\varepsilon$ are not dependent on wavelength. Therefore, it is not necessarily reasonable to compare the strain sensitivities at different wavelengths using the fractional sensitivity.

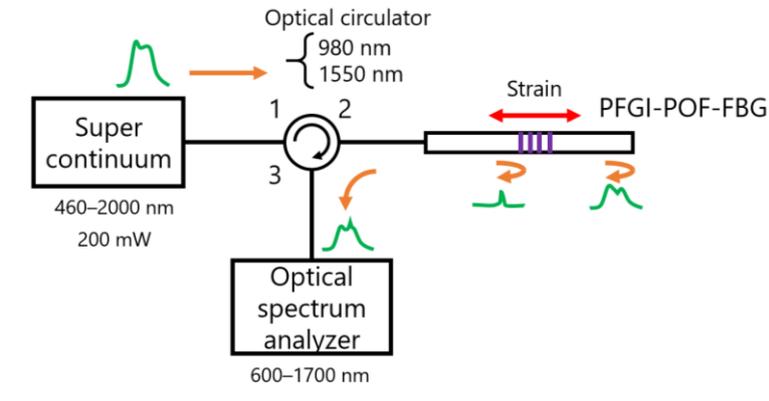
Experimental setup

Figure S1 shows the experimental setup for measuring the Bragg wavelengths of the PFGI-POF-FBG. All the optical paths except the PFGI-POF were silica SMFs. One end of the PFGI-POF was connected to a silica SMF using the so-called butt-coupling technique,⁵⁰⁾ and the other end was kept open. The output from a supercontinuum source (SC-5, Yangtze Soton Laser; wavelength range: 460–2000 nm; output power: 200 mW) was injected into the PFGI-POF, and the reflected light was guided to an optical spectrum analyzer (AQ6370, Yokogawa Electric) via an optical circulator. According to the wavelength range where the Bragg wavelengths were located, two optical circulators with different operating wavelength ranges (central wavelengths: approximately 980 and 1550 nm) were employed. Strains from 0 to 0.4% were applied to the whole length of the PFGI-POF fixed on translation stages. Considering the possible modal dispersion, a mode scrambler should be employed in the system,^{S1)} but its considerable loss prevents us from measuring the FBG reflected spectra at shorter wavelengths (the modal dispersion was experimentally confirmed to be negligibly smaller than the chromatic dispersion, at least at 1560 nm).

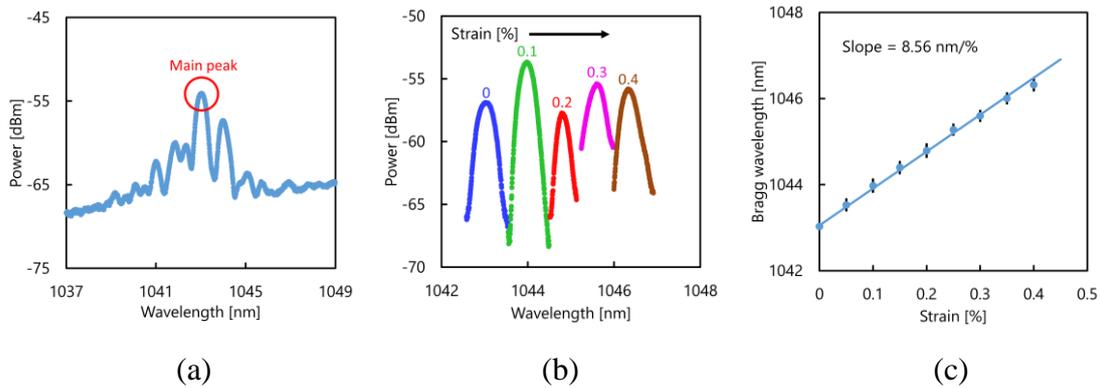
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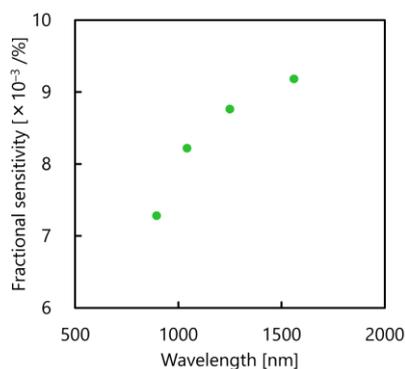
Supplementary Figures



Supplementary Figure S1 | Experimental setup for measuring the Bragg wavelengths of the PFGI-POF-FBG.



Supplementary Figure S2 | (a) FBG-reflected spectrum magnified around 1043 nm. The highest peak was defined as the main peak. (b) Strain dependence of the main peak. (c) Bragg wavelength dependence on strain. The solid line is a linear fit. The error bars were calculated using the standard deviations of 20 measurements.



Supplementary Figure S3 | Dependence of the fractional strain sensitivity on wavelength.