LETTER
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Strain and temperature sensing based on multimode interference in partially chlorinated polymer optical fibers

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Abstract: We develop strain and temperature sensors based on multimode interference in a partially chlorinated graded-index polymer optical fiber (PCGI-POF) and experimentally investigate their sensing performance at room temperature using incident light of ~1300 nm wavelength. The length of the PCGI-POF was 0.7 m. The measured strain and temperature sensitivities were −4.47 pm/με and +9.66 nm/°C/m, respectively, the absolute values of which were 0.29 times and over 350 times the values in a silica GI-MMF. This result suggests that the modal interference in PCGI-POFs is potentially applicable to high-sensitivity temperature measurement with low strain sensitivity.

Keywords: polymer optical fibers, strain sensors, temperature sensors
Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Strain and temperature sensing using optical fibers has been extensively studied owing to its advantages such as small size, light weight, and immunity against electromagnetic noise. A number of methods based on fiber Bragg gratings (FBGs) [1, 2], long-period gratings (LPGs) [3, 4], Rayleigh scattering [5, 6], Raman scattering [7, 8], and Brillouin scattering [9, 10, 11, 12, 13] have been developed, and one of the most simple and cost-efficient techniques involves the exploitation of modal interference in a multimode fiber (MMF) [14, 15, 16, 17, 18, 19]. To date, various structural implementations have been proposed (see Table 1 in Ref [14]). Among them, a structure comprising an MMF sandwiched between two single-mode fibers (SMFs) — often referred to as a single-mode-multimode-single-mode (SMS) structure — has been most widely studied because of its simplicity and ease of fabrication.

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A strain sensitivity of +18.6 pm/με and a temperature sensitivity of +32.5 pm/°C/m have been reported at 1550 nm (corresponding to +15.6 pm/με and +27.3 pm/°C/m at 1300 nm, respectively) by using the SMS structure with a 1.8-m-long silica graded-index (GI) MMF [15]. Subsequently, it was proven that the fiber structure (e.g., core diameter) and core material (e.g., dopant) of silica MMFs significantly influence not only the absolute values but also the signs of the strain and temperature sensitivities [17]. However, glass fibers are generally so fragile that they cannot be utilized as sensor heads for monitoring large strains of over ~3%.

One method for extending the maximal measurable strain involves the use of a polymer optical fiber (POF) as an MMF; a POF can endure large strains of over several tens of percent. Based on the SMS structure comprising a 0.16-m-long polymethyl methacrylate (PMMA)-based step-index POF, strain and temperature sensitivities of −2.82 pm/με and +581.9 pm/°C/m, respectively, have been obtained at 1570 nm (corresponding to −2.34 pm/με and +481.8 pm/°C/m at 1300 nm) [19]. Subsequently, in order to lower the propagation loss at telecom wavelengths, SMS-based sensors have been developed using perfluorinated (PF) GI-POFs [20], and ultra-high strain and temperature sensitivities of −112 pm/με and +49.8 nm/°C/m, respectively, have been achieved at 1300 nm with a core diameter of 62.5 μm [21]. The absolute values of these sensitivities are 12.9 and >1800 times those in a silica GI-MMF [15]. However, PFGI-POFs, composed of cyclic transparency optical polymer (CYTOP®), have two drawbacks: high fabrication cost and low thermal resistance (<70°C). Recently, partially chlorinated (PC) GI-POFs have attracted considerable attention because of their low propagation loss at the 650–690/760–790 nm region, relative cost efficiency, and high thermal resistance of >100°C [22, 23], which may enable higher-temperature sensing.

In this study, we implement and characterize strain and temperature sensors based on the SMS structure comprising a 0.7-m-long PCGI-POF of core diameter 120 μm at a wavelength of ~1300 nm. The measured strain sensitivity is −4.47 pm/με, the absolute value of which is 0.29 times the value in a silica GI-MMF. In contrast, the measured temperature sensitivity at room temperature is +9.66 nm/°C/m, which is over 350 times that in a silica GI-MMF. This result indicates that the multimodal interference in PCGI-POFs is potentially applicable to highly sensitive temperature sensing with low strain sensitivity.

2 Principle

The SMS structure consists of an MMF connected at both ends to identical SMFs. At the first SMF/MMF interface, light enters the MMF through the lead-in SMF. Because the spot size of the fundamental mode of the MMF is generally different from that of the SMF, a few lower modes are excited. The excited modes propagate through the MMF with their respective propagation constants. At the second SMF/MMF interface, the relative phase differences among the different modes of the MMF determine the net field coupled from these modes to the lead-out SMF. When the fibers are axially aligned at the first SMF/MMF interface, only the axially

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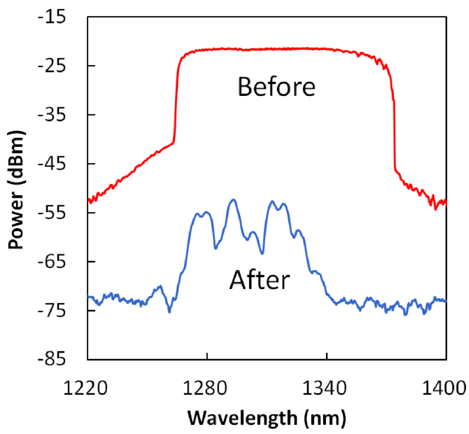

Fig. 1. Measured optical spectra before and after transmission through the PCGI-POF.

symmetric modes are excited in the MMF. According to a detailed calculation [16], the optical power in the lead-out SMF can be expressed as

$$P_{out} = |a_0{}^2 + a_1{}^2 \exp i(\beta_0 - \beta_1)L + a_2{}^2 \exp i(\beta_0 - \beta_2)L + \cdots|^2, \quad (1)$$

where a_i is the field amplitude of the i-th mode at the first SMF/MMF interface, β_i is the propagation constant of the i-th mode, and L is the MMF length. Equation (1) indicates that the optical power in the lead-out SMF is affected by changes in physical properties (such as strain and temperature) influencing the propagation constants and/or length of the MMF. Therefore, such changes can be quantified by measuring the shift in either the power or the spectral location of a peak/dip.

3 Experimental setup

We employed a PCGI-POF (VT120, Sekisui Chemical) with an outer diameter of 750 µm, a core diameter of 120 µm, and a core refractive index of ~1.52. This is the only commercially available specification. Considering the high propagation loss at telecom wavelengths (approximately 47 dB/m, measured by a simple cut-back method), the length of the PCGI-POF was set as 0.7 m.

The experimental setup was essentially the same as that used in Ref [21]. The PCGI-POF was connected to silica SMFs by butt-coupling [24, 25], i.e., the ends of the SMFs fitted with 'FC' connectors were connected to both ends of the PCGI-POF fitted with 'SC' connectors via FC/SC adaptors. A swept-source laser with a 20-kHz sweep rate was used as a broadband light source with a central wavelength of 1320 nm and a bandwidth of 110 nm. The laser output was passed into the PCGI-POF, and the spectrum of transmitted light was monitored using an optical spectrum analyzer. The polarization state was optimized using a polarization controller. The entire length of the PCGI-POF was strained or heated. The room temperature was approximately 27°C.

4 Experimental results

Fig. 1 shows the measured optical spectra before and after transmission through the PCGI-POF. As the propagation loss of the PCGI-POF at 1300 nm is extremely high, the spectrum after transmission was drastically diminished in intensity, but

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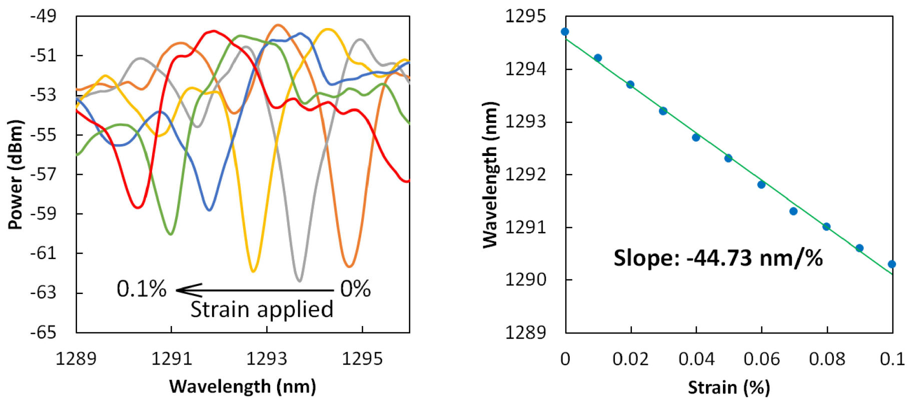
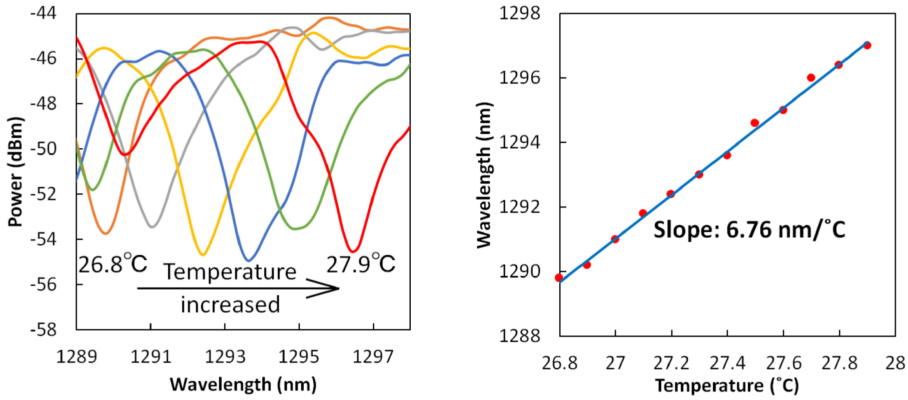


(a) (b)

Fig. 2. Measured strain dependence of (a) spectral dip and (b) dip wavelength.



(a) (b)

Fig. 3. Measured temperature dependence of (a) spectral dip and (b) dip wavelength.

several characteristic dips were still observed. Among them, the spectral dip at ~1290 nm was the most stable with respect to changes in the polarization state; therefore, the sensing properties were investigated using this dip. Note that the spectral distortion was significant in PCGI-POFs because of their imperfect end faces, asymmetric coupling to the SMFs, and longitudinal non-uniformity of the fiber structure (fabrication technology of special POFs has not been satisfactorily established yet).

The measured dependence of the spectral dip on strain is shown in Fig. 2(a). The dip shifted to shorter wavelengths with increasing applied strain. Fig. 2(b) shows the dip wavelength plotted as a function of strain. The dependence was almost linear with a slope of −44.7 nm/% (= −4.47 pm/με), the absolute value of which is approximately 0.29, 1.9, and 0.040 times the value in a silica GI-MMF [15], a PMMA-based POF [19], and a PFGI-POF [21], respectively. The dependence of the dip on temperature was also measured (Fig. 3(a)). The dip shifted to longer wavelengths as temperature increased. Fig. 3(b) shows the dip wavelength plotted as a function of temperature; the dependence was almost linear with a slope of +6.76 nm/°C, which corresponds to 9.66 nm/°C/m. Although this (abso-

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lute) value is ~0.2 times that in a PFGI-POF [21], it is still over 350 and ~20 times the value in a silica GI-MMF [15] and a PMMA-based POF [19], respectively. The large slope of the dip-wavelength-temperature plot indicates highly sensitive temperature measurability, while the small slope of the dip-wavelength-strain plot indicates that PCGI-POF-based SMS sensors are less sensitive to applied strain. Thus, the modal interference in PCGI-POFs, which have high thermal resistance and cost efficiency compared to PFGI-POFs, can be potentially exploited to develop high-sensitivity temperature sensors with reduced strain sensitivity.

In this experiment, the core diameter of the PCGI-POF was 120 µm. It is worth noting that if PCGI-POFs with different core diameters are available in the future, their sensing characteristics may differ substantially from that observed in this study [17, 21].

5 Conclusion

Strain and temperature sensors based on multimode interference in an SMS structure composed of a 0.7-m-long PCGI-POF were developed, and their sensing properties were experimentally investigated at room temperature with incident light of ~1300 nm wavelength. Strain and temperature sensitivities of $-4.47\,\mathrm{pm}/\mu\varepsilon$ and $+9.66\,\mathrm{nm}/°\mathrm{C}/\mathrm{m}$ were obtained, the absolute values of which are 0.29 times and over 350 times the values in a silica GI-MMF, respectively. This result suggests that the heat-resistant and cost-effective PCGI-POF-based SMS sensor is a good candidate for performing high-sensitivity temperature measurement with low strain sensitivity.

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