Strain and Temperature Characteristics of a Long-Period Grating Written in a Photonic Crystal Fiber and Its Application as a Temperature-Insensitive Strain Sensor

Chun-Liu Zhao, Limin Xiao, Jian Ju, M. S. Demokan, *Senior Member, IEEE*, and Wei Jin, *Senior Member, IEEE*

***Abstract*—Strain and temperature characteristics of a long-period grating (LPG) written in an endless-single-mode photonic crystal fiber (ESM-PCF) are investigated theoretically and experimentally. By use of a dispersion factor γ, a deeper understanding of the behavior of LPG in the ESM-PCF is achieved. The negative strain sensitivity of the LPG is explained by the negative value of the dispersion factor γ. Our analysis clearly reveals the significant effect of the waveguide dispersive characteristics of the cladding modes on the strain and temperature characteristics of the LPG in the ESM-PCF. By selecting an appropriate grating period, a simple, low-cost LPG sensor with approximately zero temperature sensitivity but large strain sensitivity is realized.**

***Index Terms*—Long-period grating, optical fiber sensor, photonic crystal fiber, strain and temperature sensitivity, strain sensor.**

I. INTRODUCTION

PHOTONIC crystal fibers (PCFs), sometimes also called microstructured optical fibers or holey fibers, are a new class of optical fibers that have attracted significant attention recently [1]–[3]. Typically these fibers incorporate a number of air holes that run along the length of the fiber, and the shape, size, and distribution of the holes can be designed to achieve various novel waveguiding properties that may not be achieved readily in conventional fibers [2]–[17].

A long-period grating (LPG) is formed by introducing periodic modulation of the refractive index along a single-mode optical fiber. It resonantly couples light from the fundamental core mode to some cladding modes and leads to dips in the transmission spectrum. LPGs have been widely used in optical fiber communications and sensors. Examples of LPG-based devices include all-fiber band-rejection filters [18], [19], gain flatteners in erbium-doped fiber amplifiers [20], and sensors for strain, temperature, and external refractive index measurement [21]–[23]. Since LPGs couple light between two different modes, their property can be very different from those of fiber Bragg gatings (FBGs). An LPG can have very different temperature sensitivity depending on the fiber type and the period of the LPG. By choosing a fiber type and the coupled modes, the stain and temperature response of a LPG resonance can be positive, negative, or zero [21]–[28]. Temperature-insensitive LPGs have attracted particular attention because of their potential applications in achieving stable optical filters, attenuators, and gain flatteners without requiring any complex packaging, as well as in realizing temperature-insensitive sensors [24], [26]. In general, as fiber devices and sensing elements, LPGs have the advantage of low insertion loss, small backward reflection, immunity to electromagnetic interference, low cost, and small size [21], [29].

Unlike conventional fibers—which contain at least two different glasses, each with a different thermal expansion coefficient, thereby giving rise to a relatively high thermal expansion coefficient—PCFs are virtually insensitive to temperature because it is made of only one material (and air holes). This property can be utilized to obtain temperature-insensitive PCF-based devices, as demonstrated in [14]. However, the single material property of PCFs leads to nonphotosensitivity to ultraviolet (UV) light; therefore FBGs and LPGs cannot normally be formed in PCFs by use of the conventional UV-written technique, unless a PCF with a Ge-doped photosensitive core is used [30]. Recently, several alternative methods for making LPGs in PCFs with nonphotosensitive cores were introduced, including glass structure change [31], periodic structural and/or residual stress relaxation induced by arc discharge or a CO_2 laser [32]–[35], refractive index modulation by periodically applied mechanical pressure [36], and by the use of an acoustic wave [37]. The properties of LPGs in PCFs have been investigated experimentally, and it has been found that the resonance wavelength of an LPG in PCF shifts toward short wavelengths when the grating period increases, which is in contrast to an LPG in a conventional fiber [31], [36], [37]. LPGs fabricated by use of a CO_2 laser are stable because the perturbation is everlasting; whereas in LPGs fabricated by UV light in conventional fibers, the refractive index modulation caused by UV light is prone to aging, therefore making LPGs in conventional fibers unstable over time. Another unique property of LPGs

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in PCFs is that the resonance wavelength blue-shifts under an applied strain [34], [35], which is also contrary to that of a conventional LPG. All of these have shown that large difference exists in the properties of LPGs written in PCF and conventional fibers. Although there have been several studies on strain and temperature sensitivities of LPGs in PCFs, all of them are focused on experimental observations. A deeper and clearer understanding of the strain and temperature sensitivity of LPGs in PCFs is important and fundamental for possible novel applications of such LPGs, even though the analogous studies have been done experimentally and theoretically for LPGs in conventional single-mode fiber (SMF), B-Ge codoped fiber, and three-layered optical fiber [22], [27], [28]. This is because PCFs have some unique properties that cannot be held by other fibers, and hence the properties of LPGs in PCF will be quite different from those of conventional fibers.

In this paper, we investigate in detail the strain and temperature characteristics of an LPG written in an endlessly single-mode (ESM) solid silica core PCF both theoretically and experimentally. To account for the effect of dispersive characteristics of the PCF, we identify a dispersion factor γ, which offers a deeper understanding into the behavior of LPGs in ESM-PCF. Theoretical results show that γ is always negative, and this causes blue+shifting of the resonant wavelength when an axial strain is applied. By choosing appropriate grating period, we can design an LPG with specific strain and temperature properties. We have fabricated an LPG in PCF and demonstrated that the resonant wavelength shifts toward shorter wavelength while the light intensity at the resonant transmission dip increases with the applied axial strain. These experimental observations agree with the theoretical predictions. Furthermore, by utilizing the facts that the light intensity at the resonant wavelength is strongly affected by the applied strain and the resonant dip (both wavelength and intensity) is insensitive to temperature, we propose a low-cost temperature-insensitive strain sensor based on the LPG in ESM-PCF. The sensor uses a distributed feedback (DFB) laser as the light source, and the light power at the sensor output is directly proportional to the applied strain; hence only an optical power meter is sufficient to detect strain variation, avoiding the need for an expensive optical spectrum analyzer (OSA). Our experimental results show that the strain sensor works well under different environmental temperatures.

The remainder of this paper is constructed as follows. Section II present the theory of LPGs. Section III describes the theoretical characteristics of a LPG in ESM-PCF. A full-vector finite-element method (FEM) with perfectly matched layers (PMLs) as absorbing boundary conditions is used to analyze the effective indexes of the core and cladding modes in ESM-PCF. The dispersion factor γ is identified and discussed. The variation of resonance wavelength due to applied strain and the temperature is predicted theoretically. Section IV presents the experimental verification of the theory. The measurements to determine strain and temperature dependence are described and compared with the theoretical analysis. Furthermore, the experimental details of a temperature-insensitive strain sensor using an LPG in ESM-PCF are also presented. Section V contains the conclusion.

II. Theory of an LPG

An LPG is formed usually by a periodic modulation of the refractive index in a fiber core, which allows coupling from the fundamental core mode to some resonant cladding modes and leads to some dips in the transmission spectrum at wavelengths that satisfy the resonant condition. The phase matching condition of a LPG can be expressed as [21]

$$\lambda = (n_{co} - n_{cl})\Lambda \tag{1}$$

where λ is the resonant wavelength, Λ is the index modulation period of the LPG, and n_{co} and n_{cl} are the effective indices of the fundamental core mode and the forward-propagating cladding mode, respectively.

When an axial strain is applied on the LPG, the resonant wavelength of the LPG will shift because the Λ of the LPG will increase with stretching axially and at the same time the effective refractive index of both core and cladding modes will decrease due to the photoelastic effect of the fiber [29]. Meanwhile, if the ambient temperature changes, the wavelength of the LPG may also be changed by linear expansion or contraction and the thermooptic effect. From (1), the sensitivity of the LPG to strain or temperature is a function of the differential effective index between the core and cladding modes (or the differential propagation constant). Thus, from (1), the strain and temperature sensitivity can be written as [27]

$$\frac{d\lambda}{d\varepsilon} = \lambda \cdot \gamma \cdot \left(1 + \frac{\eta_{co}n_{co} - \eta_{cl}n_{cl}}{n_{\bar{co}}n_{cl}}\right) \tag{2}$$

$$\frac{d\lambda}{dT} = \lambda \cdot \gamma \cdot \left(\alpha + \frac{\xi_{co}n_{co} - \xi_{cl}n_{cl}}{n_{co} - n_{cl}}\right) \tag{3}$$

where ε is the axial strain, T is the ambient temperature, η_{co} and η_{cl} are strain-optic coefficients of the core and cladding, ξ_{co} and ξ_{cl} are the thermooptic coefficient of the core and cladding, respectively, and α is the linear expansion coefficient. η and ξ are defined as [21]

$$\eta = \frac{1}{n}\frac{dn}{d\varepsilon} \tag{4}$$

$$\xi = \frac{1}{n}\frac{dn}{dT}. \tag{5}$$

Different materials have different η and ξ. η and ξ may also have some difference due to the different effective index of waveguides made by the same material [39].

Since the effective index (or propagation constant) both of the fundamental mode in the fiber core and cladding modes in the fiber cladding will be affected by the waveguide change, which is caused by the applied axial strain on the LPG, the dispersion factor γ is used to describe the effect of waveguide dispersion and is expressed as [26], [27]

$$\gamma = \frac{\frac{d\lambda}{d\Lambda}}{n_{co} - n_{cl}} = \frac{\Delta n_e}{\Delta n_e - \lambda\frac{d\Delta n_e}{d\lambda}} = \frac{\Delta n_e}{\Delta n_g} \tag{6}$$

where $\Delta n_e = n_{co} - n_{cl}$ and $\Delta n_g = n_{co}^g - n_{cl}^g$ are, respectively, the differential effective index and differential group index between the core mode and the cladding mode. As will be discussed in Section III, γ plays a significant role on the strain and temperature sensitivity of an LPG based on the ESM-PCF.

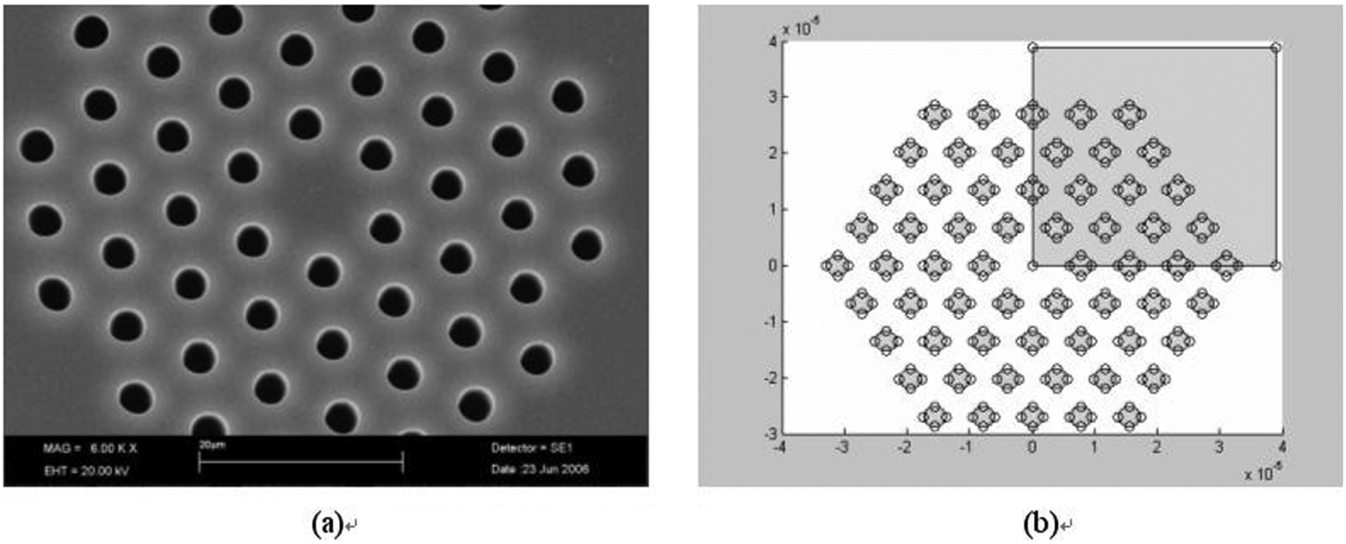

Fig. 1. (a) Micrograph of the PCF used in the experiment. (b) Schematic cross-section of a PCF, showing the quarter used in calculation.

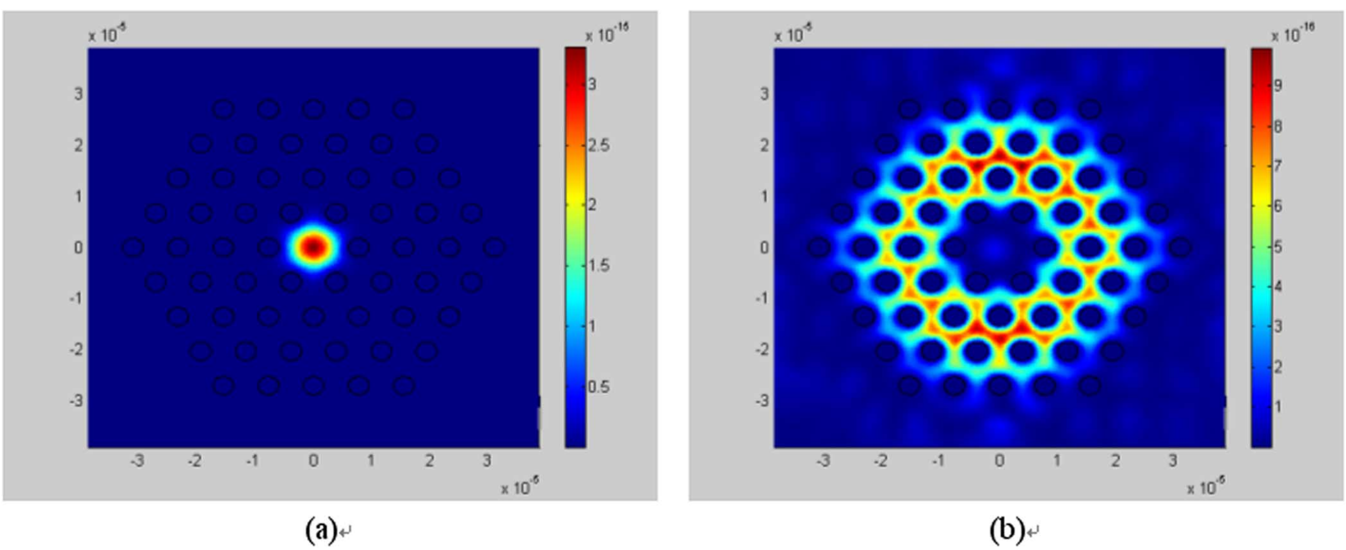

Fig. 2. Calculated intensity distribution of the PCF with $L = 7.78\ \mu$m and $d = 3.55\ \mu$m. (a) The fundamental core mode and (b) the cladding mode.

III. Theoretical Properties of an LPG Based on PCF

A. Properties of the ESM-PCF

The PCF used in our experiment is an endlessly single-mode PCF fabricated by Crystal Fiber A/S. The fiber has a standard triangular air/silica cladding structure, as shown in Fig. 1(a). The mode field diameter is $\sim$ 6.4 μm, the center-to-center distance between the air holes (L) is $\sim$ 7.78 μm, and the diameter of the air holes is $\sim$ 3.55 μm. The diameter of the entire holey region is $\sim$ 60 μm, and the outer cladding diameter of the PCF is 125 μm. A full-vector FEM is used to calculate the effective index of modes of PCF. Because of the symmetric nature of the PCF, only a quarter of the cross-section as shown in Fig. 1(b) is used during calculation. A perfect electric or perfect magnetic conductor (PEC or PMC) is applied at boundaries [8]. The refractive index of pure silica is taken as 1.444.

Fig. 2(a) and (b) shows the intensity distribution of the core and the cladding mode, which are considered as the two coupling modes in our LPGs based on the ESM-PCF. Fig. 3 shows the effective indexes of the fundamental and cladding modes as functions of wavelength in the ESM-PCF. The group indexes of these two modes, which are calculated by using $n_g = n_e - \lambda(dn_e/d\lambda)$, are also shown in Fig. 3. The curves of n_g are not so smooth because of the limited data available for the calculation of $(dn_e/d\lambda)$, but the trend is clear. The curve n_{g-cl} shows the highly dispersive characteristics of the cladding mode. For any wavelength in the range of 1.2–1.8 μm, the group index of the cladding mode is higher than that of the core mode, which is in contrast to a conventional SMF.

B. Properties of LPGs Based on the ESM-PCF

Fig. 4 shows the calculated resonance wavelength as a function of the period of LPG in the ESM-PCF. It is clear that the resonance wavelength of LPG in the PCF decreases with increasing

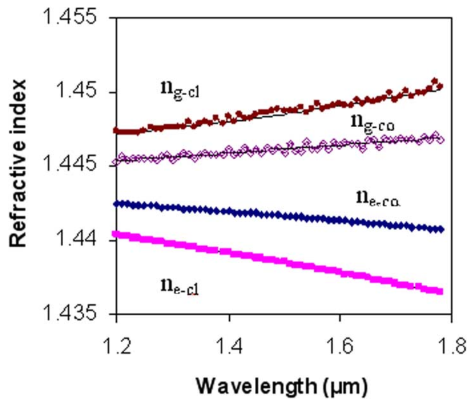

Fig. 3. Calculated dispersion curves for core and cladding modes as shown in Fig. 2.

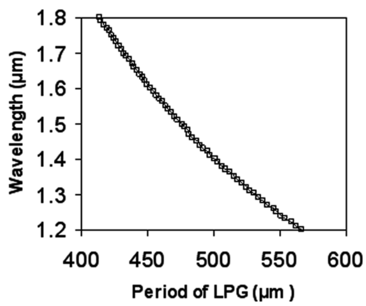

Fig. 4. Calculated resonance wavelength as a function of grating period.

LPG period, which is consistent with other experimental observations [31], [36], [37]. This is in contrast to LPGs written in conventional SMFs and is because of the highly dispersive property of the cladding mode due to the existence of the air-holes. In other words, $(n_{co}^{-} n_{cl})$, as shown in (1), varies significantly with wavelength.

As mentioned in Section II, γ is a special factor to describe the effect of waveguide dispersion and may be positive or negative. Because Δn_e is always positive, the sign of γ is determined by Δn_g. When Δn_e equals to Δn_g, the factor γ is one. This means dispersive properties of the core and the cladding mode are similar, and this is the case normally for SMFs. When the group indexes of the core mode are less than that of the cladding mode, γ will be negative. This has been observed in the case of the coupling from core mode to higher order cladding modes in B-Ge codoped fiber [27]. For PCFs, no relevant results have been reported so far to our knowledge. In Fig. 5, we show the relationship of γ with the period of an LPG based on the theory of ESM-PCF, and γ is in the range of $-1.15 \sim -1.35$ for LPG period of from 420 to 570 μm.

The strain sensitivity $d\lambda/d\varepsilon$ of an LPG in the ESM-PCF is determined by four parameters: the elastooptic coefficients of the core and cladding materials, waveguide properties (γ), the period of the LPG, and the mode order. In [26] and [27], researchers analyzed the mode order effect in detail. Now, we choose the same coupling modes and focus on the effect of the first three parameters on the strain sensitivity of an LPG in the PCF. Fig. 6 shows the calculated strain sensitivity as a function of LPG period with different η_{cl} when we assume $\gamma = 1$. In the calculation, η_{co} is assumed to be constant at a value of -0.22 for the pure silica core [27], [29]. For LPGs with period ranging from 400 to 600 μm, the strain sensitivity is positive and relatively independent of the grating period when $|\eta_{cl}|$ is larger than 0.22. The strain sensitivity becomes negative and decreases with grating period when $|\eta_{cl}|$ is smaller than 0.218. On the other hand, when the value of γ is taken as shown in Fig. 5, the strain sensitivity as a function of LPG period is as shown in Fig. 7. The strain sensitivity is negative when $|\eta_{cl}|$ is larger than 0.22. This is the opposite of what is shown in Fig. 6. In [39], Bertholds *et al.* showed that the strain-optic coefficients of a bulk silica and a silica fiber are different. It is believed that, owing to the different geometry of solid core and microstructured air-silica cladding of the ESM-PCF, η_{co} will be slightly different from η_{cl}. Since the effective index n_{co} is considerably larger than n_{cl} for the ESM-PCF, from (4), we expect $|\eta_{cl}| > |\eta_{co}| = 0.22$. This expectation is verified by our experiment in Section IV.

Similarly, the temperature sensitivity $d\lambda/dT$ of an LPG is determined by the thermooptic coefficients of the core and cladding materials, waveguide properties (γ), period of LPG, and mode order. We calculated the temperature sensitivity as a function of LPG period by assuming that the thermooptic coefficient of the pure silica core is $\xi_{co} = 7.8 \times 10^{-6}$/°C and thermal expansion coefficient is $\alpha = 4.1 \times 10^{-7}$/°C. Figs. 8 and 9 show, respectively, the results for the cases of $\gamma = 1$ and

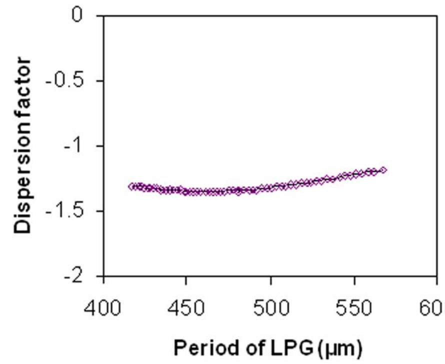

Fig. 5. Dispersion factor γ at the resonance wavelengths versus grating period of the LPG in the ESM-PCF.

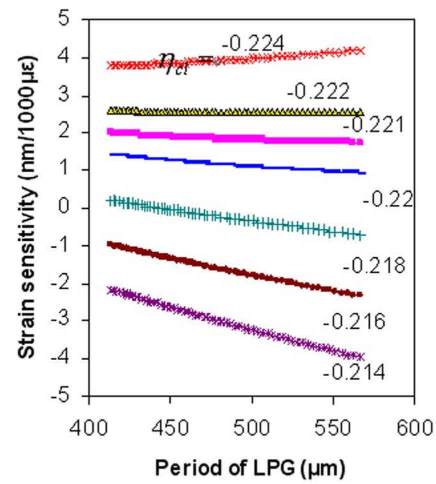

Fig. 6. Theoretical strain sensitivity at resonance wavelength versus LPG period for various values of η_{cl} and $\gamma = 1$.

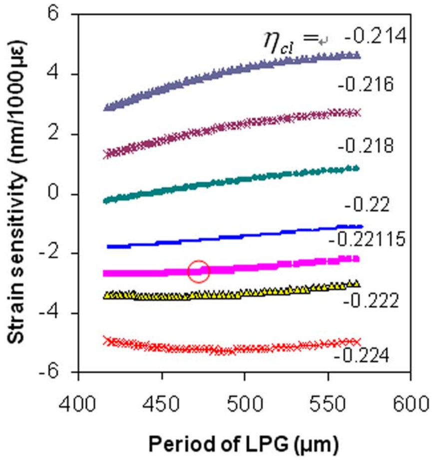

Fig. 7. Theoretical strain sensitivity at resonance wavelength versus LPG period for various values of η_{cl} and with γ taken from Fig. 5.

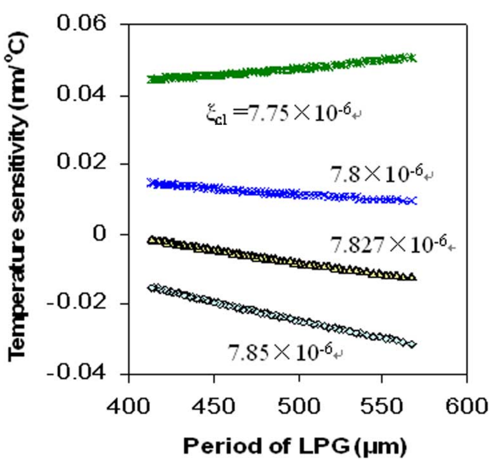

Fig. 8. Theoretical temperature sensitivity at resonance wavelength versus LPG period for various values of ξ_{cl} and $\gamma = 1$.

γ taking from Fig. 5. The temperature characteristics are quite different for the two cases. With ξ_{cl} less than $\xi_{co} = 7.8 \times 10^{-6}$, the LPG has positive temperature sensitivity for $\gamma = 1$ but negative temperature sensitivity for the case of γ taking from Fig. 5. Furthermore, the dependence of temperature sensitivity on the grating period is approximately linear for $\gamma = 1$ while it is nonmonotonic for the other case. Similar to the discussion for the strain coefficient, for the ESM-PCF, since the effective index n_{co} is larger than n_{cl} [from (5)], we expect that ξ_{co} is slightly smaller than ξ_{cl}, which has also been verified by our experiment in Section IV.

IV. Experiment

Fig. 10 shows the experimental setup. The total length of the ESM-PCF used is 25 cm, and both ends of the PCF are fusion spliced to SMFs. The loss for each splice is about 0.5 dB. A CO_2 laser (SYNRAD) is used for the fabrication of LPGs in the ESM-PCF. The CO_2 laser operates at a frequency of 10 kHz and has a maximum power of 10 W. The laser power is controlled by the width of the laser pulses. In our experiment, the pulse-width of the CO_2 laser is chosen to be 3.8 μs. The laser beam is focused to a spot with a diameter of $\sim$ 60 μm and scanned across

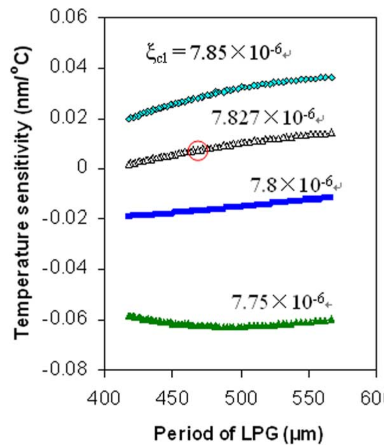

Fig. 9. Theoretical temperature sensitivity at resonance wavelength versus LPG period for various values of η_{cl} and with γ taken from Fig. 5.

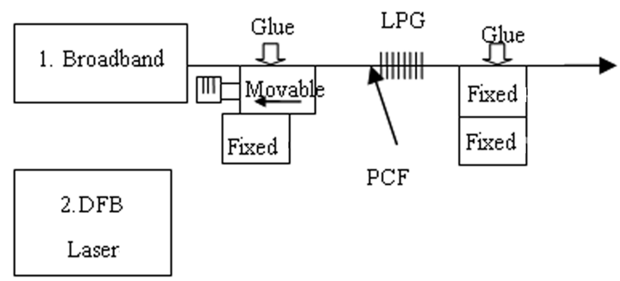

Fig. 10. Experimental setup for 1) measuring the temperature and strain characteristics of the LPG in the ESM-PCF, where a broadband source and an OSA are used, and 2) the proposed temperature-insensitive strain sensor where a DFB laser and an optical power meter are used.

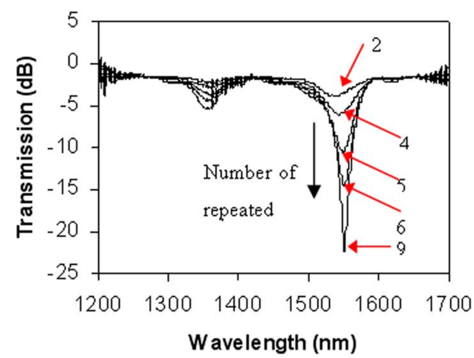

Fig. 11. Transmission spectra of the LPG in the ESM-PCF with various numbers of repeated scans.

the ESM-PCF transversely and longitudinally along the fiber by use of a two-dimensional optical scanner attached to the laser head. The scanning step of the focused beam is 1 μm and the delay time of each step is 350 μs. The LPG inscribed has a period of about 467 μm and a period number of 40. The process of the CO_2 laser scanning is repeated nine times, which results in an LPG with a deep transmission dip and no observable deformity in the fiber structure. Fig. 11 shows the growing process of a LPG in the PCF as a function of the number of scanning procedures. The spectrum measurements are performed using a broadband light-emitting diode source in combination with an OSA (ADVANTEST Q8384) with a resolution of 0.5 nm. As

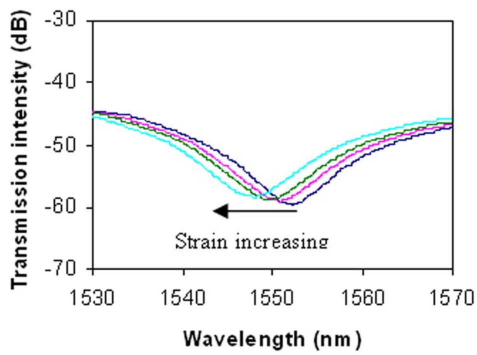

Fig. 12. Transmission spectra of the LPG in the ESM-PCR for applied strain of (from right to 1eft) 0, 535, 936, and 1604 $\mu\varepsilon$.

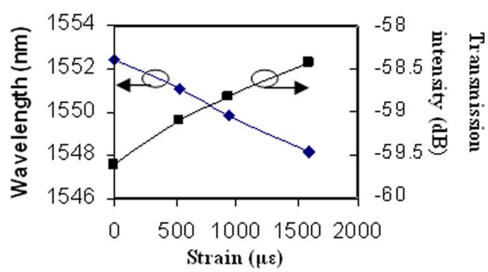

Fig. 13. Resonant wavelength and the intensity at the transmission dip as functions of applied strain.

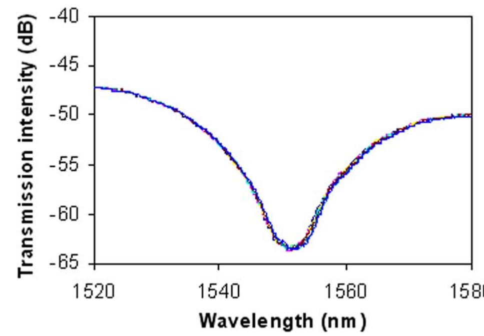

Fig. 14. Transmission spectra of the LPG in the ESM-PCF at various ambient temperatures.

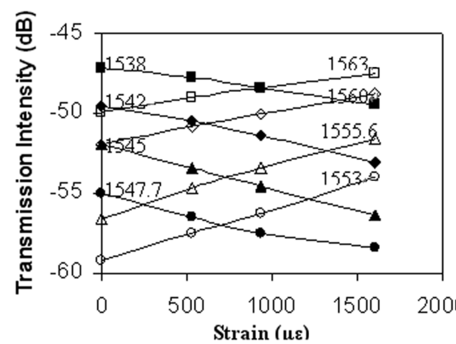

Fig. 15. Strain dependence of the transmission intensity of the LPG at different wavelengths.

shown in Fig. 11, the resonant wavelengths of the LPG in the ESM-PCF are about 1552.45 and 1363.3 nm, which are due to coupling of the fundamental core mode to two different cladding modes. The dip at the wavelength 1552.45 nm is nearly 20 dB. The insertion loss of the LPG is about 1.5 dB. The resonance at 1552.45 nm is due to coupling of the core mode to the cladding mode shown in Fig. 2(b) and is in good agreement with the theoretical result (1552.45 nm resonance wavelength corresponds 467.2 μm LPG period) in Fig. 4 . The small error between experiment and theory may come from the error of cross-section measurement by scanning electron micrograph (SEM) and the error of in controlling the LPG period by scanning motor.

The strain characteristics of the LPG in the ESM-PCF were tested by stretching the ESM-PCF by moving the translation stage shown in Fig. 10 from 0 to 0.5 mm in four steps (corresponding to a strain variation of from 0 to 1604 $\mu\varepsilon$). The center wavelength of the transmission dip shifts toward shorter wavelength, as shown in Fig. 12. This is opposite to an LPG in a conventional SMF, where the transmission dip shifts toward longer wavelengths [21]. The strain dependence of the resonance wavelength 1552.45 nm on axial strain is shown in Fig. 13. The strain sensitivity, which is the slope of the curve, is estimated to be -2.68 nm/1000 μm and shown in Fig. 7 as a small circle. By varying the strain coefficient of the cladding material η_{cl} to fit the experimental data, we found the value of η_{cl} that best fits the experimental sensitivity is $\eta_{cl} = -0.22115$. The transmitted intensity at resonance wavelength was found to increase with the applied axial strain, and this is also shown in Fig. 13.

To test the temperature characteristics of the LPG in the ESM-PCF, the ambient temperature of the LPG was varied by using a temperature chamber whose temperature can be controlled within the range of 25–100 °C. As shown in Fig. 14, the transmission spectrum hardly changes when the temperature is raised from 25 to 100 °C. The estimated sensitivity of the resonant wavelength to temperature is about 0.007 nm/°C. Again, the temperature sensitivity of the LPG in the ESM-PCF is marked as a circle in Fig. 9. The cladding temperature coefficient ξ_{cl} that fits this temperature insensitivity is $\xi_{cl} = 7.827 \times 10^{-6}$. This value is slightly larger than that of the core and agrees with the prediction at the end of Section V. It should be noted that the difference between ξ_{co} and ξ_{cl} for the ESM-PCF is six times smaller than that of conventional Ge-doped fiber and 18 times smaller than that of B-Ge codoped fiber [40].

By exploiting the LPG's large sensitivity to strain and insensitivity to temperature, temperature-insensitive strain sensors may be realized in such ESM-PCFs. These sensors can be based on either wavelength or intensity measurement. Dobb and coworkers [34] have demonstrated a temperature-insensitive sensor based on an LPG fabricated in an ESM-PCF by arc discharge, in which a broadband light source and an OSA are used to measure strain-induced variation in the resonant wavelength. We propose here a simple, low-cost strain sensor based on the measurement of the transmitted light intensity at a wavelength close to the LPG resonance.

Fig. 10 shows the proposed strain sensor that uses the LPG in PCF as the sensing element. A single wavelength such as a wavelength tunable laser or a DFB laser is used as a light source. The wavelength of the DFB laser is near the resonant wavelength of the LPG and hence the output light intensity from the LPG will be directly related to the LPG's transmission at the wavelength of the DFB laser. Since the LPG's transmission is insensitive to temperature, the output power will only be affected by the transmission spectrum change caused by the strain applied to the LPG. At the output, an optical power meter will be adequate to deduce the strain information and an expensive OSA would not be needed.

Fig. 15 shows the measured relationship between the output intensity of the LPG sensor and the applied axial strain for various laser wavelengths. In our experiment, a tunable laser was used for easiness of wavelength adjustment. In practice, a DFB laser with appropriate wavelength would be a better for the purpose of reducing cost. As shown in Fig. 15, for laser wavelengths of 1538, 1542, 1545, and 1547.7 nm, which are shorter than the resonant wavelength (1552.45 nm) of the LPG, the output intensity decreases with applied strain and the strain sensitivity is negative and, respectively, -1.41, -2.17, -2.80, and -2.41 dB/1000 $\mu\varepsilon$ for 1538, 1542, 1545, and 1547.7 nm. The relationship is approximately linear for strains from 0 to 1600 $\mu\varepsilon$. Similarly, for laser wavelength longer than the resonant wavelength (1552.45 nm), the output intensity increases with applied strain and the intensity sensitivities are positive and, respectively, 3.25, 3.11, 2.01 and 1.53 dB/1000 $\mu\varepsilon$ at 1553, 1555.6, 1560, and 1563 nm. Therefore, the setup shown in Fig. 10 converts directly the strain variation to intensity variation. Assuming that we choose a DFB laser at 1553 nm as source and use an optical power meter with a resolution of 0.001 dB, we may achieve a strain resolution of ~ 0.3 $\mu\varepsilon$.

V. Conclusion

We studied the strain and temperature characteristics of an LPG written in the ESM-PCF experimentally and theoretically. Theoretical calculation shows that by selecting proper grating period, it is possible to design an LPG that is sensitive to strain but not sensitive to temperature. Experimental results show that an LPG with a period of 467 μm fabricated in the ESM-PCF is temperature insensitive. This allows the temperature-insensitive filtering devices and sensors to be designed and implemented. For example, temperature-insensitive strain measurement, which is important for a number of industrial applications, may be achieved by using a combination of a broadband source and an OSA to measure the resonant wavelength, or by using a DFB laser with its wavelength near the LPG resonance and an optical power meter. The latter is particularly attractive due to its advantages of simplicity and low cost.

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