Bend and Temperature Sensing with Arc-Induced Phase-Shifted Long-Period Fiber Grating

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Abstract: A phase-shifted long-period fiber grating sensor fabricated by electric arc technique is used to measure bending curvature and temperature.

OCIS codes: (060.2310) Fiber optics and (060.2370) Fiber optics sensors

1. Introduction

Long period fiber grating (LPG) is an optical device that couples light from core mode into copropagating cladding modes at specific resonance wavelengths [1]. LPG can be used as optical sensors since the resonance wavelength positions depend on the effective refractive indices of the core and cladding modes. Temperature, strain, bend, torsion, and refractive index are some of the parameters that LPG can measure [2, 3].

The transmission spectral characteristics of long-period fiber grating structures can be changed by cascading two or more LPGs with same grating period [4, 5]. When two LPGs are cascaded with a separation length of L_p between them and this section of optical fiber does not have buffer (acrylate coating), either a Mach-Zehnder interferometer ($L_p > \Lambda$) or a phase-shifted long-period fiber grating (PS-LPG) is produced ($L_p < \Lambda$). Ke *et al* [5] have theoretically analyzed the spectral responses of LPGs with single or multiple phase shifts and Humbert and Malki [6] have used such analysis to fabricate PS-LPGs by using the electric-arc technique.

Although the use of PS-LPGs enables more flexible control over the transmission spectrum profile compared to cascaded LPGs, which allows better position design of the grating resonances, and they are better substitutes for two concatenated LPGs [7], there are few works about phase-shifted long-period grating for sensing purposes. Han *et al* [7] have demonstrated discrimination between bending and temperature with phase-shifted long-period grating where the phase-shift was produced by post-exposure UV method and showed that the curvature sensitivity depends on the initial coupling strength of the grating. Zhu *et al* [8] measured strain and temperature sensitivity of PS-LPGs fabricated by using CO_2 laser and point-by-point process of surface deformation.

In this work, we study a PS-LPG with a phase shift close to $\pi/2$ produced by electric arc-discharge method and its application for bending curvature and temperature sensing. We show that temperature and bend can be determined by measuring the resonant wavelength shift and the resonant peak amplitude change of PS-LPG resonances.

2. Preparation of PS-LPGs

PS-LPGs are written in Corning SMF-28 fiber using the electric arc-discharge technique [9]. An uncoated fiber is placed between the electrodes of a splice machine set for an electric current of 9.5 mA and arc duration of 1.0 s. To keep the fiber under constant axial tension during the fabrication process, one end of the fiber is clamped in a holder on top of a computer controlled translation stage with 0.1 μm of spatial resolution and a small weight (5.1 g) is attached to the fiber at the other end. An arc discharge is then produced exposing a short length of the fiber and, after the arc-discharge, the translation stage displaces the fiber by a distance equal to Λ, the period of the grating. This process of exposure the fiber to an arc discharge and displace the fiber with the translation stage is repeated several times (N) until a required attenuation loss-peak is obtained. The gratings spectra are recorded using an ANDO AQ–6315B optical spectra analyzer (OSA) set to a resolution of 1.0 nm and the illumination is provided by a white light source.

The electric arc-discharge technique using point-to-point method allows the introduction of any phase-shift during the fabrication process by translating the fiber by a distance L_p equivalent to the required phase-shift [6]. In our case, the period of the grating is 540 μm and the phase-shift close to $\pi/2$, which corresponds to a displacement of 118 μm, is introduced when the transmission at the resonance wavelength is approximately −6.9 dB. The total length of the grating can be obtained from (N-1)*Λ+L_p and it is 30.36 mm. Figure 1 shows the experimental and the theoretical spectral evolution of a phase-shifted grating fabricated using the parameters described above.

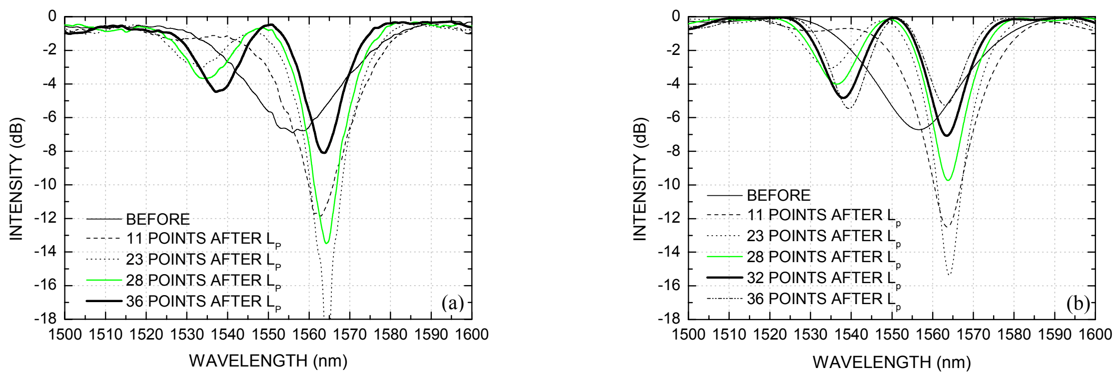

Fig. 1. Evolution of spectrum of phase-shifted long-period fiber grating during fabrication: (a) experimental results and (b) theoretical results.

As can be seen in Fig. 1(a), this grating needed 32 arc-discharges before L_p to obtain an attenuation peak at 1556.4 nm close to 6.9 dB and has 36 arc-discharges after L_p, resulting in a grating with N = 68. The experimental spectral evolution has the following behavior. Eleven arc-discharges after the distance L_p a small dip resonance appears on the left side of the spectrum whilst the right resonance continues growing at the same position. After 23 arc-discharges the left resonance has increased its amplitude and shifted to longer wavelengths while the right dip has also its amplitude increased to the maximum amplitude but its position has not changed. Subsequent to this point, point after point the right dip does not change its position but its amplitude decreased while the amplitude of the left dip continues increasing and shifts to longer wavelengths. The final transmission spectrum shows two band rejections peaks: the first one is at 1538.0 nm (referred as LOSS 1) and the second one is at 1563.5 nm (LOSS 2). The band-pass peak (PS-PEAK), between the two band-rejection peaks, is at 1550 nm.

The theoretical spectra, Fig. 1(b), are obtained using the Optiwave IFO_Gratings 4.0 simulator and the following fiber and grating parameters: 1.44995 and 1.444565 for the refractive index of core and cladding, respectively; core, cladding, and air radius of 4.15 μm, 62.5 μm, and 20 μm, respectively; grating period of 540 μm, phase shift length of 118 μm, and refractive index modulation of 3.5 x 10^{-4}. To simulate the fabrication of the phase-shifted grating, the parameters given above are kept constant and the second grating section, the one fabricated after L_p, has its length changed according the arc-discharges or point numbers determined by Fig. 1(a).

There are a number of similarities between the two spectra, Fig. 1. Besides the central wavelength of PS-PEAK appears on the left side of the band rejection obtained before L_p, the simulation also verified the experimentally obtained spectral behavior for both LOSS 1 and LOSS 2. Additionally, Figure 1(b) shows the main problem of arc-discharge technique, the lack of amplitude reproducibility. Although the simulated spectrum of the PS-LPG, bold solid line in Fig. 1(b), has only used 32 arc-discharges to produce similar experimental spectrum, bold solid line in Fig. 1(a), the grating has 68 points, 32 and 36 points from the first and second grating section, respectively.

3. Bend and temperature sensitivity of the PS-LPG

The bend sensitivity of the PS−LPG was studied using the experimental set-up shown Fig. 2. The fiber with PS−LPG in the center is first fixed on the fiber holders using epoxy. Precautions were taken to avoid fiber twist influence in the bend measurement. Second, the fiber is held flat horizontally (h = 0, zero bending curvature) and the first of the transmission spectrum is measured. After this measurement, different curvatures are applied to the PS−LPG by translating one of the fiber holders inward in the z-direction and for each curvature the transmission spectrum is measured. The curvature was estimated according to $R= (2h)/(h^2+(L_0/2)^2)$, where h is the distance of the sensor from flat horizontally position and L_0 is the distance between the edges of the two fiber holders [10]. The transmission spectra are taken using a broadband optical source (BBOS), which is an erbium doped fiber amplifier (EDFA model FIBREAMP-BT 1400 from Photonetics with a gain bandwidth of 100 nm around 1550 nm), and the OSA set to resolution of 0.1 nm for both bend and temperature measurements. The initial distance between the edges of the two fiber holders is 400 mm.

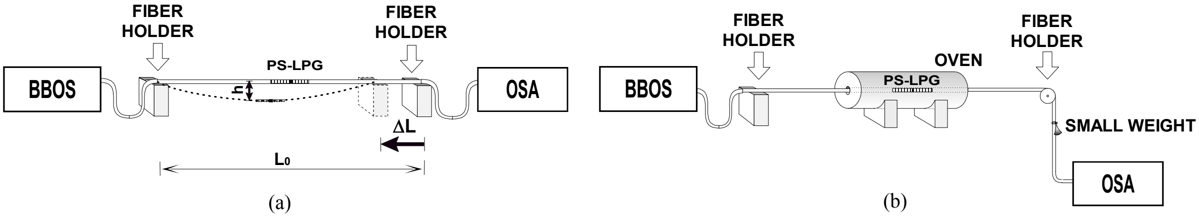

Fig. 2. Experimental set-up used for (a) bend and (b) temperature tests.

For temperature measurements, the experimental set-up shown in Fig. 2(b) is used. The optical fiber with PS−LPG is inserted into an oven with two openings, which were used to insert the optical fiber with PS−LPG. After the sensor is inserted into the oven, one end of the optical fiber with PS−LPG is clamped on the fiber holder and at the other end a small weight (5.1g) is attached to the fiber to keep the fiber under constant axial tension. The temperature range used to determine the temperature sensitivity of PS-LPG is from 24 ºC to 200 ºC with steps of 10 ºC.

Figure 3(a) and 3(b) respectively shows the changes in the transmission spectra of the PS-LPG with increasing of bending curvature and temperature. When curvatures are applied to the PS-LPG, LOSS 2 has its wavelength position almost constant and its amplitude increases in depth, while LOSS 1 shifts to shorter wavelengths and its amplitude is the almost constant. On the other hand, the spectral changes, when different temperatures are applied to the PS-LPG, are mainly in wavelength shifts and hardly affected the amplitude depth, Fig. 3(b).

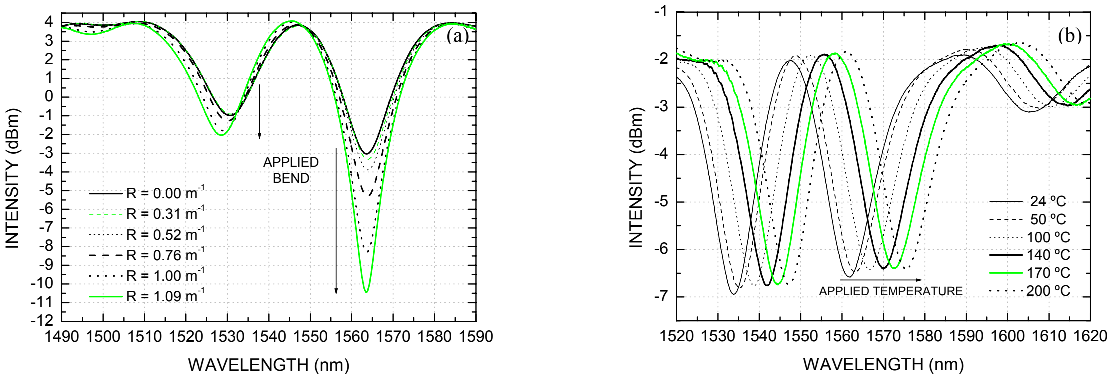

Fig. 3. Evolution of the spectrum of PS-LPG when (a) curvature bending and (b) temperature are separatelly applied to the grating.

The amplitude and wavelength bending sensitivity of LOSS 1, LOSS 2 and PS-PEAK are shown in Fig. 4, the lines through the data points are solely a visual aid. As can be seen, when bending curvature changes from 0.3 m^{-1} to 1.1 m^{-1} the wavelength shifts are approximately 1.5 nm and 2.0 nm for PS-PEAK and LOSS 1, respectively, while LOSS 2 only has a wavelength change of ± 0.2 nm. On the other hand, for the same curvature range, amplitude changes as small as 1.0 dB were obtained for PS−PEAK and LOSS 1, while LOSS 2 has an amplitude variation 7 times greater (7.1 dB).

The wavelength shift of LOSS 1, PS-PEAK and LOSS 2 on temperature have a quadratic dependence and they are respectively given by [11]: $(1532.29+0.0469\cdot T+1.210\text{x}10^{-4}\cdot T^2)$, $(1546.41+0.0505\cdot T+1.205\text{x}10^{-4}\cdot T^2)$, and $(1561.14+0.0510\cdot T+1.254\text{x}10^{-4}\cdot T^2)$, where T is in Celsius degree and the wavelength is in nanometer. Considering the amplitude changes in LOSS 1, LOSS 2 and PS-PEAK due to applied temperature, the highest amplitude change is found in LOSS 1 and it is 0.22 dB, while LOSS 2 and PS-PEAK have their amplitude changed by 0.18 dB and 0.19 dB. Therefore, the amplitude changes of PS-LPG resonances for the applied temperature range are almost constant.

The wavelength and amplitude sensitivities obtained for curvature and temperature, and shown in Fig. 3, indicate that the PS-LPG can be an interesting sensor for simultaneous measurement of these parameters, since the LOSS 1 and LOSS 2 have different behavior when they are applied.

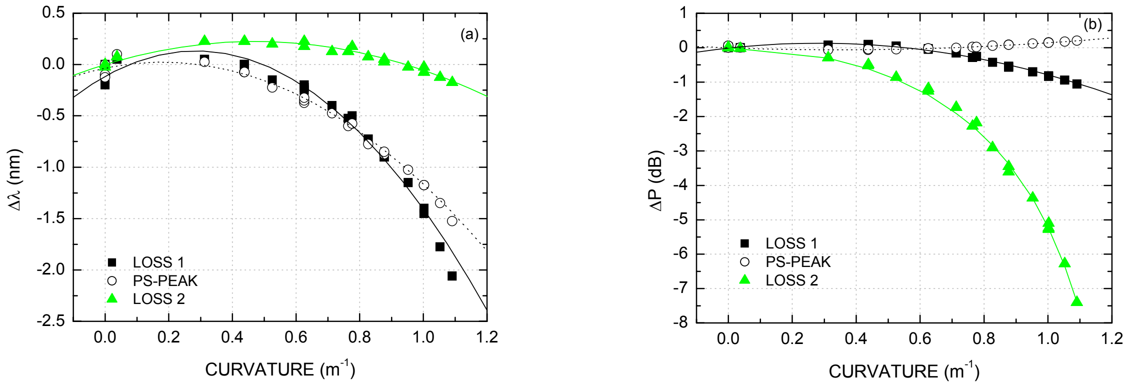

Fig. 4. (a) Changes of the resonance wavelength and (b) changes of the resonance amplitude when different curvatures are applied to PS-LPG.

An example of simultaneous measurement of curvature and temperature method is by direct measurement of changes in the resonant wavelength and the amplitude of LOSS 2, since the resonant wavelength of LOSS 2 is sensitive to temperature while its amplitude changes with bending.

4. Conclusion

Phase-shifted long-period gratings were produced by the arc-discharge method. The evolution of transmission spectrum of these gratings during fabrication process can be well fitted by simulation. It was observed that the two grating resonances are differently modified in both amplitude and center wavelength when curvature and temperature were applied. Furthermore, the rejection band located at longer wavelengths has either its amplitude or center wavelength independent of these parameters. Those features allow using a single PS-LPG for simultaneous measurements of temperature and bending curvature.

Acknowledgements

R. Falate has her work supported in part by Brazilian Agencies: CAPES and CNPq. G. Rego is thankful for the grant through the Program PRODEP III - Medida 5 - Acção 5.3. - Formação Avançada de Docentes do Ensino Superior.

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