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Refractive Index Sensor Based on Stress-Induced Long Period Grating

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We proposed a novel refractive index sensor based on a side-polishing fiber to be cascaded with a stress-induced long period fiber grating (LPG), which is created by applying a force to a V-grooved plate on the single mode fiber with micro-bending deformation. When the refractive index (RI) surrounding the side-polishing surface is changed, the LPG-induced cladding mode light could be coupled back to the core mode, so that it will result in the magnitude variation of LPG loss-peak. This property of index sensing based on the stress-induced LPG by monitoring the power-level change may be exploited in chemical sensing and environmental monitoring applications.

Keywords: fiber sensor, long period grating, stress, refractive index sensor

1. Introduction

Fiber gratings have been developed for various applications, such as telecommunications or fiber sensor systems.[1–4] Optical fiber sensors based on fiber gratings currently are attracting significant interest for civil engineering applications or biosensors, etc. For sensing applications, long period gratting (LPG) have been interesting for many applications, such as band-rejection filters and gain-flattening devices,[5] temperature sensors, strain sensors,[6,7] and refractive index sensors.[8] Many different fabrication methods of LPG have been presented. The traditional LPG is written directly into single mode fiber by using an ultraviolet laser for coupling propagating light from the core mode to cladding modes.[8] Structurally induced deformation of a LPG on B-Ge codoped fiber by using CO_2 laser has been presented, in which the resonance wavelengths are shifted as the surrounding refractive index is varied.[9] A LPG is realized by using the electric arc technique for making the grating in a Ge-free air-silica micro-structure fiber.[10] However, the facilities of the traditional amplitude-mask LPG fabrication are more expensive and complicated by using the laser. The mode-coupling properties of LPG formed in photonic crystal fibers (PCFs) is presented by means of periodic mechanical pressure.[11] A mechanically induced long-period fiber grating (MLPFG) made by pressing two grooved plates on single-mode taper fiber is proposed with wavelength-tunable property and a similar transmission spectrum which in comparison with that of photo-induced LPG.[12,13] Also, a tunable mechanical LPG is achieved by pressing a spring coil to the standard single mode fiber (SMF-28) with more than 200 nm wavelength-tuning range and with the attenuation of resonance loss-peak increases of 10 dB.[14] Moreover, the double cladding fiber is used to demonstrate a wavelength-tunable band pass filter based on the force-induced LPG induced by applying an external force on the spring coil.[15]

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In this study, a novel refractive index sensor based on combining a side-polishing single-mode fiber and a stress-induced LPG is the first experimentally demonstrated as our knowledge. This configuration would provide a simple and flexible sensor for refractive index sensing. When the refractive index surrounding the side-polishing surface is changed, the power-level of the stress-induced LPG resonant loss-peak will be varied. This phenomenon is due to the fact that the coupling between the cladding modes and core mode is affected by the surrounding refractive index (SRI) of the following cascaded side-polishing fiber. Thus, from this basic operating mechanism, the proposed fiber sensor can be used to detect the various solution concentrations of different mediums with different indices.

2. Basic Principles

The structure of the proposed refractive index (RI) sensor is composed of a side-polished single-mode fiber (SMF) and a stress-induced LPG as shown in Fig. 1. The broad-band light source is launched into the end of the LPG, and then the coupled cladding mode of the LPG would be affected by the SRI and be coupled back to the fiber core as the propagation light goes through the side-polished fiber.

The fabrication of the mechanically stress-induced LPG is shown in Fig. 2. A SMF is placed between a periodical V-grooved plate and a flat plate and then the pressure is applied in the V-grooved plate for producing periodic stress on the SMF thought the V-grooved plate.

When the periodic stress is applied in the fiber by V-grooved plate, the periodic index modulation could be created owing to that the V-grooved plate induces the photo-elastic effect and micro-bending deformation in the fiber to result in the effective mode coupling.[12] Thus a LPG has been achieved with the periodic index modulation along the fiber axis. The transmission spectrum of the loss-peaks of the stress-induced LPG is similar to that of the conventional LPG due to the fact that the forward fundamental core mode is coupled into cladding modes in the case of satisfying phase match conditions as

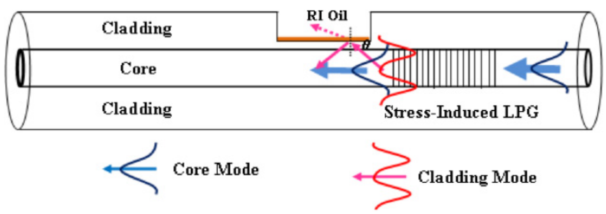

Fig. 1. (Color online) Schematic diagram of RI sensor.

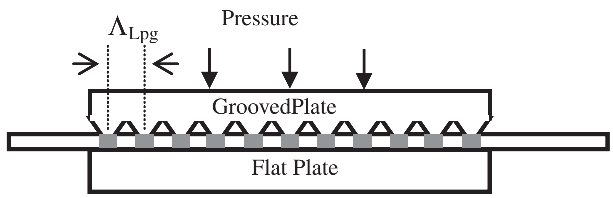

Fig. 2. Fabrication of the stress-induced LPG.

$$\beta_{01} - \beta_{cl}^{(m)} = 2\pi/\Lambda_{LPG}, \tag{1}$$

where $\beta_{01} = n_{co}^{eff}\, 2\pi/\lambda_m$ is the propagation constant of the forward fundamental core mode (LP_{01}). $\beta_{cl}^{(m)} = n_{cl,m}^{eff}\, 2\pi/\lambda_m$ is the propagation constant of the m-th cladding mode (LP_{0m} ($m = 2, 3, 4, \ldots$)). n_{co}^{eff} and $n_{cl,m}^{eff}$ are respectively the effective core index and m-th cladding modes at the wavelength of λ_m. For the grating period of Λ_{LPG}, the grating resonant wavelength λ_m with the given n_{co}^{eff} and $n_{cl,m}^{eff}$ can be expressed as $\lambda_m = (n_{co}^{eff} - n_{cl,m}^{eff})\Lambda_{LPG}$.

Even though the mode coupling mechanism of the stress-induced LPG is the same as traditional amplitude mask-making LPG, the fabrication of the proposed stress-induced LPG is easier and the loss-peak-depth of the stress-induced LPG can be adjusted simply by applying different levels of pressure on the SMF. As the applied pressure is increased, the loss-peak-depth becomes deeper. This is attributed to that the effective refractive index modulation is increased to raise the coupling intensity from the core mode to the cladding modes.

For the proposed sensor, as the coupled cladding mode signals of the stress-induced LPG propagate forward along the fiber axis direction and go through the side-polishing sections, the specific RI surrounding the side-polishing surface facilitates Fresnel reflection due to the Fresnel theory. The propagation light could be leaked out at a specific angle θ when the light is incident on the interface between the RI oil and cladding.[16] The power-level of the stress-induced LPG loss-peak would be affected by the SRI variation on side-polishing surface.

3. Experimental Results

The experimental setup is shown in Fig. 3, including a stress-induced LPG of around 60 mm in length, an optical spectra analyzer (OSA), and a broad-band light source (BBS) for monitoring the transmission spectrum of stress-induced LPG for the index measurement. The period of the stress-induced LPG is around 500 µm. The side-polishing fiber section of the proposed sensor is achieved by the fiber side polishing technique to remove the cladding layer of around 45 µm and remain the cladding layer with the thickness of 80 µm, which corresponds to have the 17.5 µm separation between the core center and the polished-surface. The transmission spectra both of the stress-induced LPG to be connected to the polished fiber and unpolished fiber are similar with a little bit difference due to the cladding mode to be affected by the air layer with the surrounding index of unity ($n = 1$). For the proposed sensor, when the input light passes through the stress-induced LPG, the forward propagation cladding modes are created and kept propagating through the side polished fiber section, and then the signal is reflected back to the fiber core or leaked out of the fiber at the interface between the SRI and the polished-surface with the specific angles. Furthermore, the power-level variations of the stress-induced LPG loss-peaks are investigated by monitoring the transmission spectra of the sensor with dropping the various RI oils surrounding the side-polishing fiber region.

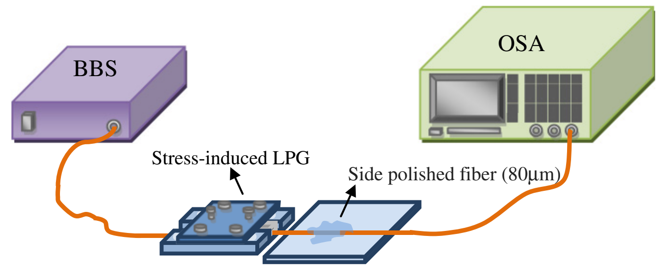

Fig. 3. (Color online) Experimental setup of the RI measurement with cascading a stress-induced LPG and a side-polished fiber.

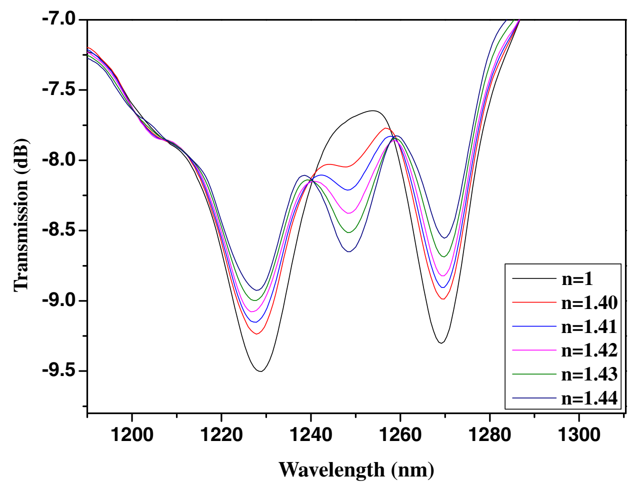

Fig. 4. (Color online) Transmission spectra of stress-induced LPG in various SRIs of the side-polished fiber.

Figure 4 shows the transmission spectra of the stress-induced LPG with various SRIs on the side-polished fiber. As the RI is increased to 1.40, the power-levels of the loss-peaks are increased to be −9.236 dB at the wavelength of 1230 nm and to be −8.986 dB at the wavelength of 1270 nm

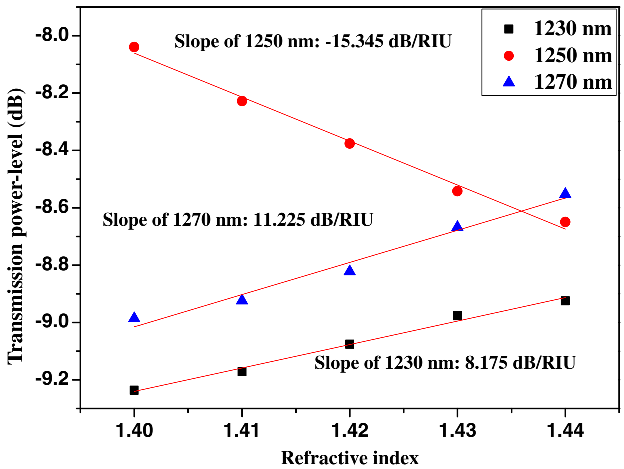

Fig. 5. (Color online) Relationship between the loss-peak power-level versus the refractive index.

due to that the increment of RI leads to the light to be coupled back to the fiber core. At the same time, a new induced loss-peak can be observed at the wavelength of 1250 nm, because the core mode leaks out of the fiber at the specific angle as the phase match conditions of Fresnel reflection are satisfied. When the RI is increased from 1.41 to 1.44, the power-levels of loss-peaks are increased from −9.172 to −8.925 dB at 1230 nm and from −8.924 to −8.553 dB at the wavelength of 1270 nm. However, for the wavelength of 1250 nm, the power-level of loss-peak is decreased from −8.228 to −8.65 dB. The experimental results demonstrate that the variation of loss-peak power-level is proportional to the increment of refractive index at the wavelengths of 1230 and 1270 nm. The loss-peak grows at the wavelength of 1250 nm when the SRI is increased, which is different from the loss-peaks wavelength of 1230 and 1270 nm.

Figure 5 indicates the relationship between the power-level of loss-peak versus the refractive index surrounding side-polishing surface. Referring to this figure, the sensitivities both of 8.175 and 11.225 dB/RIU at the wavelengths of 1230 and 1270 nm are obtained, respectively. For the induced loss-peak at the wavelength of 1250 nm, the sensitivity is −15.345 dB/RIU. The different sensitivities are related to the different propagation cladding-modes of the LPG, due to that the higher mode index of the LPG becomes more sensitive to the SRI. These experimental results demonstrate that the loss-peak depth variation is linearly proportional to the refractive index change. Moreover, this proposed sensor applied in different pressures is experimentally demonstrated to have a similar sensitivity for the refractive index measurement. This is due to that in the case of different pressures the cladding mode signal is coupled back to the core mode with an equal proportion as the refractive index is increased.

4. Conclusions

This study demonstrates a novel optical RI sensor including a side-polishing single-mode fiber to be cascaded with a stress-induced LPG. When the RI is increased from 1.40 to 1.44, the optimum RI sensitivity of −15.345 dB/RIU is achieved. In the future, the sensitivity of this refractive index fiber sensor can be improved by using different thicknesses of D-type fibers or coating thin films of different sensing materials for developing a wide range of refractive index sensing applications.

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