IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 4, Number 1, February 2012

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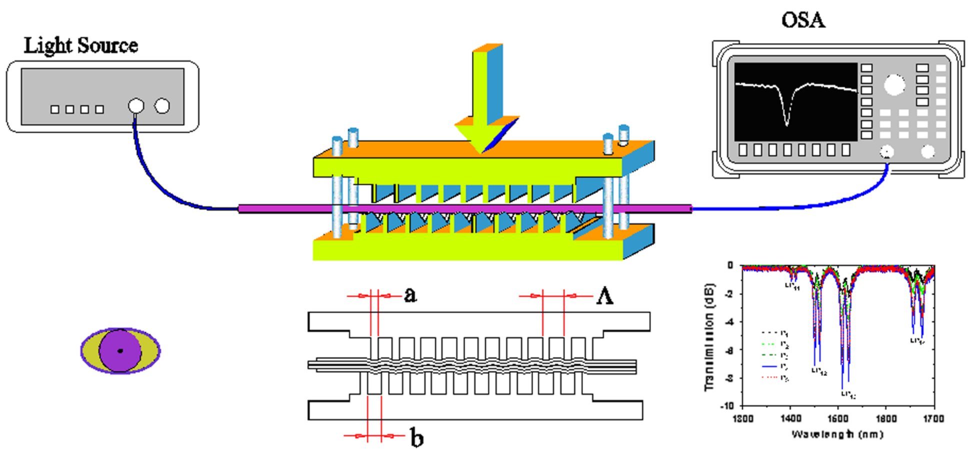

DOI: 10.1109/JPHOT.2011.2179977

Refractive Index Sensing by Using Mechanically Induced Long-Period Grating

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DOI: 10.1109/JPHOT.2011.2179977
1943-0655/$26.00 ©2011 IEEE

Manuscript received December 4, 2011; accepted December 8, 2011. Date of publication December 15, 2011; date of current version January 6, 2012. This work was supported by the National Natural Science Foundation of China under Grant 60925019 and Grant 61090393 and in part by the 973 Program under Grant 2011CB301705. Corresponding author: X. Zhou (e-mail: xjzhou@uestc.edu.cn).

Abstract: In this paper, a refractive index sensor using a mechanically induced long-period grating is proposed and experimentally demonstrated. The sensing element is based on a composite optical waveguide, which is made of a single-mode fiber, a Teflon-cannula, and the medium pending to test. The research shows that the resonant wavelength of the high-order mode coupling is sensitive to the refractive index of the liquid. The pressure applied on the experimental setup should keep constant in the refractive index measurements for different liquids, where the mode coupling is in the undercoupling state. The sensitivity of the sensor for LP_{14} mode resonance is about 2.78×10^{-4} refractive index unit in the refractive index range from 1.33 to 1.43.

Index Terms: Gratings, sensors, waveguides.

1. Introduction

Long-period fiber gratings (LPFGs) have attracted extensive interest over the past few years because of their ability to offer couplings from fundamental core mode to cladding modes in a single-mode fiber (SMF) [1]. The mode couplings result in the notches at resonant wavelengths in the transmission spectra of the LPFG, which can be used as spectral filters in fiber-optic communication with low back-reflection and low insertion loss [2]. Another attractive characteristic of the LPFG is that it is intrinsically sensitive to the refractive index of surrounding-media owing to the electrical field distribution of the cladding modes from the cladding layer to the surrounding-media, which can be used as a surrounding refractive index (SRI) sensing [3], [4]. The refractive index sensor presents many advantages, such as low background reflections and insertion losses, immunity to electromagnetic interference, wavelength-encoded measurements, simple multi-plexing, suitability for remote measurements, and compatibility with fiber communication networks.

To extend the measurable refractive index range of the surrounding-medium, the LPFG written in the core of a fiber is coated with an overlay on it, where the refractive index of the overlay is higher than that of the cladding [5]–[7]. Higher refractive index coating promotes a significant modification of the cladding mode distribution, leading to a dramatic increase in the measure sensitivity to the surrounding-media refractive index, which can be used as optical chemosensor with high sensitivity [8]–[10].

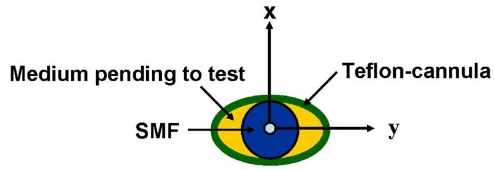

Fig. 1. Elliptical composite waveguide.

Several techniques are used in fabrication of the LPFGs, such as by ultraviolet exposure through an amplitude mask, irradiation by CO_2 lasers or by femtosecond laser pulses in the infrared, electric discharge-induced LPFGs and mechanically induced ones. The mechanically induced LPFG (MI-LPFG) is implemented by pressing a fiber with a periodically grooved plate [11] or two periodically grooved ones [12]. Thus, the MI-LPFG is able to be induced in any fiber and can be reconstructed, i.e., the grating appears once a pressure is applied on the fiber and vanishes without pressure. Besides, the mode coupling intensity of the MI-LPFG can be tuned, which is flexible in many applications.

For the SRI sensing, the MI-LPFG cannot be directly placed in the surrounding-medium because of the pressure setup. Instead, a side-hole SMF-based MI-LPFG and a photonic-crystal-fiber-based one are applied [13], [14], where the media are injected into the airholes of the fibers. In the schemes, a specially designed side-hole fiber or a photonic crystal fiber is required, which is inconvenient in refractive index sensing.

In this paper, a refractive index sensor using a MI-LPFG is proposed and experimentally demonstrated. The sensing element is based on a composite optical waveguide, which is made of a standard SMF, a Teflon-cannula, and the medium pending to test. The long-period grating is induced by imposing a periodical pressure on the waveguide. The sensor proposed in this paper needs neither a special fiber nor an expensive writing device to fabricate long-period grating in the waveguide.

2. Operation Principle

To use a MI-LPFG in refractive index sensing, a composite optical waveguide based on a SMF is designed, whose configuration is shown in Fig. 1. It can be seen that a bare SMF is placed in a Teflon-cannula whose diameter is larger than that of the fiber, and the medium pending to test is injected into the area between the fiber and the cannula. When a pressure is applied on the composite optical waveguide, it is deformed into an elliptical one without changing the shape in the cross section of the fiber inside the cannula, as shown in Fig. 1. The propagation characteristic and the field distribution of the fundamental core mode in the elliptical composite waveguide do not change because the field of the core mode is concentrated in and near the fiber core. However, the propagation coefficients of the cladding modes depend on the ellipticity of the elliptical composite waveguide and the polarization direction of the input light.

The elliptical composite waveguide can be regarded as a perturbation to the cylindrical waveguide with four layers. The propagation coefficients of a cladding mode polarizing along x- and y-axis in the elliptical composite waveguide have a small difference, both of which are near the propagation coefficient of the cladding mode in the cylindrical waveguide with four layers before it is deformed into an elliptical one. The field distributions of the cladding modes range into the area where the medium exists, and hence, the resonant wavelengths of the grating based on the elliptical composite waveguide shift when the refractive index of the medium changes.

If a periodical pressure is applied on the waveguide, a long-period grating is formed in the elliptical composite waveguide owing to the photoelastic effect and the microbending effect. Like in an ordinary LPFG, the energy of the core mode LP_{01} is coupled into that of the cladding modes $LP_{1m}^{x,y}$ if the phase-matching condition as follows is satisfied:

$$\beta_{co}\left(\lambda_{res}^{x,y}\right) - \beta_{cl}^{x,y}\left(\lambda_{res}^{x,y}\right) = \frac{2\pi}{\Lambda} \tag{1}$$

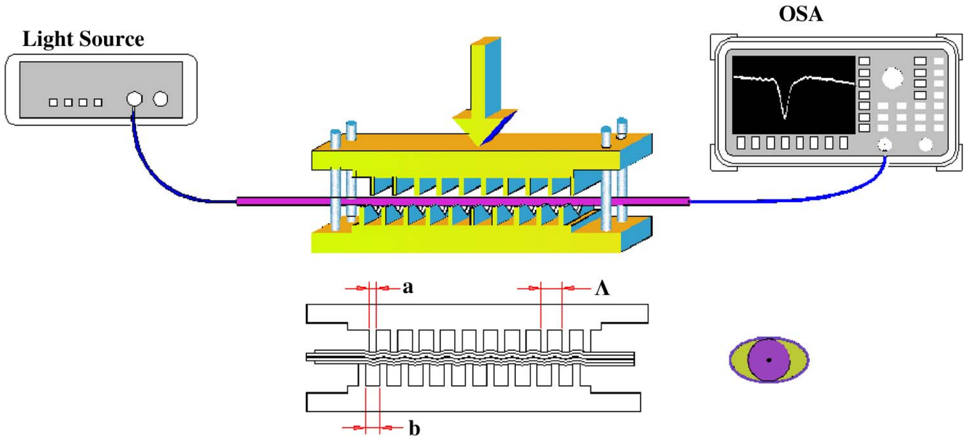

Fig. 2. Schematic of the experimental setup.

where β_{co} and $\beta_{cl}^{x,y}$ are the propagation coefficients of the fundamental core mode and the cladding modes with polarization direction along x- or y-axis, respectively, and Λ is the pitch of the long-period grating. The resonant wavelength is given by

$$\lambda_{res}^{x,y} = \left(N_{co} - N_{cl}^{x,y}\right)\Lambda \tag{2}$$

where $N_{co} = \beta_{co}/k_0$, $N_{cl}^{x,y} = \beta_{cl}^{x,y}/k_0$ are the effective refractive indices of the fundamental core mode and the cladding modes with x- or y-polarization directions, respectively.

The propagation coefficient of the cladding mode with x-polarization is different from that of the one with y-polarization. Therefore, their resonant wavelengths are not identical, and both of them will change as the refractive index of the medium varies. The mount of the resonant wavelength shift depends on the refractive index of the medium injected in the Teflon-cannula.

3. Experimental Setup and Results

The experimental setup of the SRI sensing based on the composite waveguide MI-LPFG is given in Fig. 2. The MI-LPFG is generated by pressing the waveguide with the periodically grooved plates which have a small offset between them (half a grating pitch), as shown in the cross section in Fig. 2. It can be seen that the composite waveguide is placed between two periodically grooved plates, where the plate below has a V-shape groove to fix the waveguide. The grooved plate in the setup consists of 200 periods having grating pitch $\Lambda = 580$ μm, groove width $b = 380$ μm, and bulge width $a = 200$ μm.

In the SRI sensing based on the composite waveguide, the long-period grating mainly originates from the modulation of the refraction index of the fiber under the effect of the pressure. When a pressure is applied on the plates of the setup, long-period grating is produced inside the fiber through the photoelastic effect and the microbending effect. The photoelastic effect comes from the periodical pressure perpendicularly applied on the fiber whose refractive index is periodically changed along the fiber length by pressing the experimental setup. Because of the small offset between periodically grooved plates, the experimental setup also leads to periodical bending in the fiber where it suffers a perpendicularly periodical pressure. From [15], we can know that a bending fiber with a uniform refractive index may equal to a straight fiber with an increased refractive index distribution on the cross section of the fiber. A larger pressure on the setup makes a smaller bending radius of the fiber and induces a deeper refractive index periodical modulation in the fiber through the microbending effect. Thus, the larger the pressure applied on the composite wave-guide, the deeper the refractive index periodical modulation in the MI-LPFG becomes. When the periodical pressure on the composite waveguide increases, mode couplings from fundamental core mode to the cladding modes will enhance through the photoelastic effect and the microbending

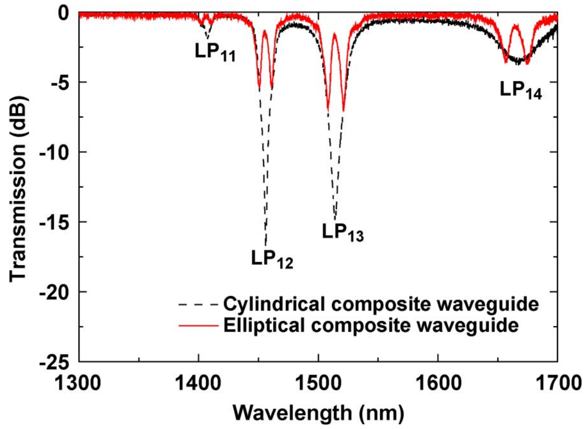

Fig. 3. Transmission spectra of cylindrical and elliptical composite waveguide-based MI-LPFG.

effect. If a larger pressure is applied on the waveguide, a transmission spectrum of the MI-LPFG with a deeper modulation of the refractive index in the fiber will be observed.

The fiber used in the composite waveguide is the SMF (Corning SMF-28). A supercontinuum source (Koheras: Superk Compact), from which an unpolarized light is launched, is connected to the input end of the fiber, as shown in Fig. 2. Then, the transmission spectra are measured by an optical spectrum analyzer (Yokogawa: AQ6370B). Since the supercontinuum light source is unpolarized, there is no polarization-dependent element used in the sensor system.

At first, the transmission spectra of the composite waveguide-based MI-LPFGs with air in the cannula are investigated. Using the setup shown in Fig. 1, an LPFG is mechanically induced in a cylindrical composite waveguide in which the cannula diameter is about 125 μm (the diameter of the fiber) and the cannula thickness is 70 μm. Its transmission spectrum is given in Fig. 3 with a black dashed line. We can see that there are four resonant notches in the spectrum corresponding to the couplings from the fundamental core mode to the cladding modes LP_{11}, LP_{12}, LP_{13}, and LP_{14} where x- or y-polarization cladding modes have the same propagation coefficients, i.e., $(\beta_{cl}^{x})_{1m} = (\beta_{cl}^{y})_{1m}$ (where $m = 1, 2, 3, 4$).

Using a cannula with a diameter of 250 μm (larger than the diameter of the fiber), the elliptical composite waveguide-based MI-LPFG is obtained with a waveguide ellipticity of 0.611 when a pressure is applied on the composite waveguide in the experimental setup. Its transmission spectrum is shown in Fig. 3 with the red solid line. It can be seen that couplings occur from the fundamental core mode to the cladding modes LP_{1m} $(m = 1, 2, 3, 4)$, each of which has two notches in the transmission spectrum. The reason is that the propagation coefficients of the cladding modes with x- and y-polarization are a little different, i.e., $(\beta_{cl}^{x})_{1m} \neq (\beta_{cl}^{y})_{1m}$. From (1) and (2), we can know that every mode coupling corresponds to two resonant notches in the transmission spectrum of the elliptical waveguide-based MI-LPFG, which is different from that of the cylindrical waveguide-based MI-LPFG (black dashed line).

Next, the spectra of the elliptical composite waveguide-based MI-LPFG under different pressures are measured, and the results are given in Fig. 4. Under a large pressure, the periodical refractive index modulation induced by the photoelastic effect and the microbending effect in the cladding layer is deeper than that in the fiber core. The field distribution of the LP_{11} mode is mainly in and near the fiber core. Thus, the depth of the notch for LP_{11} mode is small for all the pressures, as shown in Fig. 4. By contrary, the couplings are greatly enhanced for LP_{12}, LP_{13}, and LP_{14} modes when the pressure is increased from P_1 to P_4, where the mode couplings should be in an undercoupling condition ($\kappa L < \pi/2$, κ is the coupling coefficient and L is the length of the grating). The couplings to these cladding modes decrease under the maximal pressure P_5, where the resonant couplings correspond to an over-coupling condition $(\kappa L > \pi/2)$. The experimental results show that the resonant wavelengths almost do not change in the undercoupling condition for

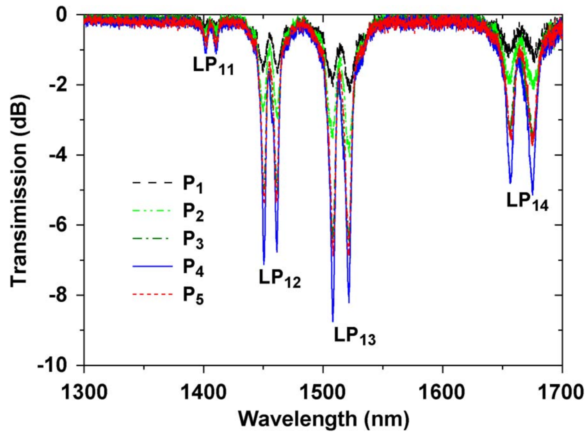

Fig. 4. Transmission spectra of the elliptical composite waveguide-based MI-LPFG under different pressures.

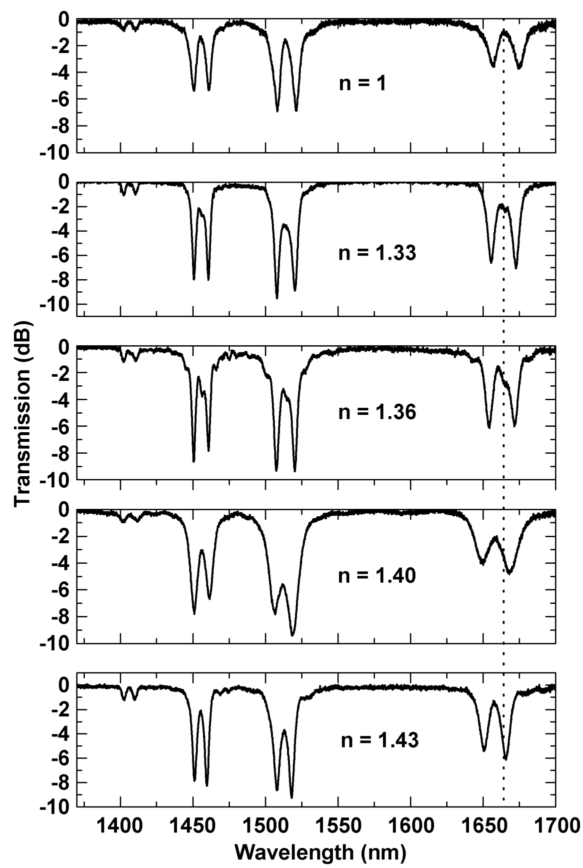

Fig. 5. Transmission spectra of several media with different refractive indices.

different pressures. Consequently, when the medium in the Teflon-cannula is replaced, the pressure on the composite waveguide should keep constant, and the resonant coupling should be in the undercoupling condition.

It should be pointed out that the variation of the refractive index induced by the photoelastic effect and the microbending effect is slowly changed in every grating period, unlike the ultraviolet

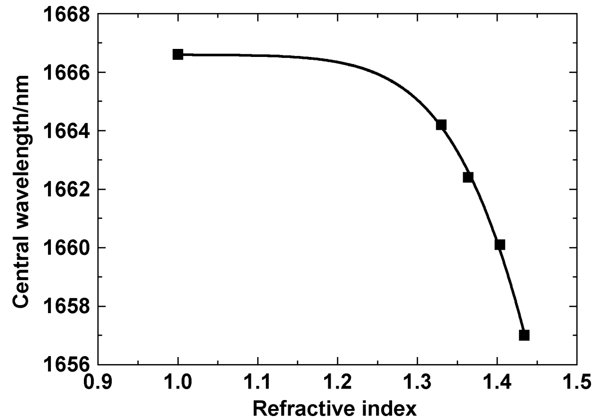

Fig. 6. Variation of central resonant wavelength of LP_{14} mode with refractive index.

exposure or infrared laser written ones whose refractive index variation at the two edges is very abrupt. Therefore, the ripples, which are induced by reflecting at grating edges, disappear between adjacent mode-related resonant notches in the transmission spectra at different pressures in our experiment (see Fig. 4).

Then, several media with different refractive indices are separately injected into the composite waveguide, and the transmission spectra are investigated by imposing the same pressure on the experimental setup. As shown in Fig. 5, the resonant coupling to the LP_{14} mode with either x-polarization or y-polarization is the most sensitive to the variation of the medium refractive index. The variation of the resonant wavelengths with the refractive index for the couplings to LP_{11}, LP_{12}, and LP_{13} modes in both polarizations is small, because most of the field distribution for these low-order cladding modes is at the area out of medium pending to test. Therefore, resonant coupling to the high-order cladding mode should be chosen in the refractive index sensing to obtain a high sensitivity to the refractive index.

Finally, it should be mentioned that the shift of the resonant wavelengths for couplings to x-polarized, y-polarized cladding modes or both of them can be used in the refractive index sensing. The central resonant-wavelength $\lambda_{\text{center}} = (\lambda^y_{res} + \lambda^x_{res})/2$ of the LP_{14} mode against the refractive index is measured, and the results are shown in Fig. 6. As the expectation in the analysis, the resonant wavelength shift for high-order cladding mode coupling is greater than that for low-order ones. Moreover, the index sensitivity is maximal as the medium refractive index is a little smaller than the refractive index of the fiber cladding. In our experiment, the refractive index sensitivity for LP_{14} mode resonance is 2.78×10^{-4} RIU when the medium refractive index varies from 1.33 to 1.43.

4. Conclusion

A refractive index sensor using a MI-LPFG is proposed and demonstrated. The sensing element is based on a composite waveguide made of an SMF, a Teflon-cannula, and the medium pending to test. The research shows that the high-order mode coupling should be used to denote the variation of the refractive index to obtain high sensitivity. The pressure applied on the setup should make the mode coupling in the undercoupling state and keep constant when the medium in the cannula is replaced, to avoid the error from self-coupling coefficient increase. Experimental results show that the sensitivity for the resonance of LP_{14} mode is 2.78×10^{-4} RIU when the medium refractive index varies from 1.33 to 1.43. The measurable refractive index range will be extended once a specially designed overlay is coated on the fiber in the composite waveguide. The method proposed in this paper needs neither a special fiber nor an expensive LPFG-writing device, which is reconstructable, simple, and convenient in refractive index sensing.

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