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A novel surrounding refractive index sensor based on the polarization characteristics of thin-cladding long-period fiber grating

Yukun Bai [a,b,*], Yue Zhang [a], Xiurong Ma [a]

[a] *Engineering Research Center of Communication Devices and Technology, Ministry of Education, School of Computer and Communication Engineering, Tianjin University of Technology, Tianjin 300384, China*

[b] *Key Laboratory of Optoelectronic Information Science and Technology, Ministry of Education, Institute of Laser and Optoelectronics, College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China*

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ABSTRACT

In this paper, a new method to measure the surrounding refractive index (SRI) is proposed. It is based on the core-only photoinduced birefringence of long-period fiber grating (LPFG). The relationship between Stokes parameters of output light polarization states and SRI is analyzed using full-vector coupled mode equations. Compared to the conventional LPFG SRI sensors, this sensing method features a fairly good linearity performance and reasonably high resolution over a much broader SRI measurement range from 1 to 1.46 which may be applied to the humidity and vapor sensing.

1. Introduction

Long-period fiber grating (LPFG) couples light from the core mode to cladding modes of a single-mode fiber, which can produce a series of attenuation bands at various resonant wavelengths in the transmission spectrum [1]. The shift of resonance wavelength in response to certain external parameter forms the basis for the design of many types of optical LPFG sensors [2,3]. In respect to surrounding refractive index (SRI) sensors, Li et al. found that the resonant wavelength shift of the LPFG heated at 600 °C for more than 4 h was in good agreement with the theoretical calculation [4]. Fan et al. investigated the resonant wavelength of Mach–Zehnder interferometer formed by cascaded LPFGs with rotary refractive index (RI) modulation, and concluded that its sensitivity was 3.5 times higher than that of an MZI formed by two normal LPFGs [5].

Furthermore, as to the effect of cladding radius on the SRI sensitivity, several researchers have demonstrated that the etched LPFG had higher sensitivity than the original LPFG [6,7]. A. Iadicicco et al. showed that the resonance wavelength for a high order cladding mode, such as LP_{06}, of a thin-cladding LPFG exhibited higher sensitivity to SRI than that for the lower order cladding modes, such as LP_{05} and LP_{04} [8].

Recently, Eftimov et al. demonstrated a SRI measurement method based on the LPFG polarization characteristics [9]. By comparing the polarization states of single-wavelength output light at a SRI value of 1 and other SRI values on the Poincare sphere, a SRI sensor based on birefringent LPFGs was constructed.

In this paper, we propose a novel SRI sensor based on the Stokes parameters characteristics of the output light from a thin-cladding UV-induced birefringent LPFG. In practice, UV-induced LPFGs fabricated on low-intrinsic birefringence photosensitive optical fiber belong to the core-only photoinduced birefringence category [10]. Photoinduced birefringence can be attributed to one-sided exposure, which creates a larger RI change on the side of the core where the UV beam is impinged on [11], and the polarization of the writing beam [12]. Because for both core-mode and cladding-mode analyses the three-layer fiber model is more accurate than the two-layer counterpart [13–15], especially for the thin-cladding case, the effective RIs of the core mode and cladding modes are calculated using the three-layer fiber model. To demonstrate the sensing principle, the LPFG with core-only photoinduced birefringence is analyzed using full-vector coupled mode equations and the Stokes parameters. Then, a practical design

* Corresponding author at: Tianjin University of Technology, Engineering Research Center of Communication Devices and TechnologyMinistry of Education, School of Computer and Communication Engineering, Tianjin 300384, China.
E-mail address: tjutbai_1@163.com (Y. Bai).

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example is presented. Lastly, the effects of LPFG parameters and incident light parameters on the sensing properties are analyzed, respectively.

2. SRI sensing based on a LPFG with core-only photoinduced birefringence

For a uniform LPFG fabricated on a germanium-doped single-mode fiber through UV irradiation, the internal birefringence which includes the shape birefringence and stress birefringence can be neglected. However, in the presence of uneven UV-exposure in the LPFG fabrication process, different "dc" index changes along the two principal axes of the optical fiber, namely the core-only photoinduced birefringence, should be taken into account. Generally, the photoinduced birefringence is on the order of 10^{-6}. Assuming the permittivity perturbation $\Delta\varepsilon$ is a function of z dependence, therefore, in the analysis of mode coupling, the coupling between LP_{01}^{x} and LP_{01}^{y} is neglected, and only the couplings between the core mode and cladding modes of the same polarization are taken into account. The permittivity perturbation including the photoinduced birefringence in the fiber core can be written as

$$\Delta\varepsilon^{i}(z) \approx 2\varepsilon_0 n_1 \Delta n_1^{i}(z) \approx 2\varepsilon_0 n_1[(n_1\sigma(z) \pm \Delta n)(1+\cos(2\pi z/\Lambda))]\ (i = x, y) \tag{1}$$

where "+" for $i = x$, "−" for $i = y$, n_1 is the material RI of the fiber core. ε_0 is the dielectric constant of vacuum. Λ is the grating period. $\sigma(z)$ is the slowly varying envelope of grating on the order of 10^{-4}. $n_1\sigma(z)$ is the "dc" index change without photoinduced birefringence. Δn is the "dc" index change difference induced by uneven UV-exposure between the two principal axes, i.e., the x and y axes, which, on the order of 10^{-6}, represents the photoinduced birefringence.

In the presence of the fiber core birefringence, the originally degenerated core modes LP_{01}^{x} and LP_{01}^{y} acquire a propagation constant difference $\Delta\beta = \beta_1^{x} - \beta_1^{y}$, which can be calculated from $\Delta\beta = \kappa_{co-co}^{x} - \kappa_{co-co}^{y}$[16], with κ_{co-co}^{x} and κ_{co-co}^{y} being the self-coupling coefficients of the core modes LP_{01}^{x} and LP_{01}^{y}, respectively. Since the "dc" index changes for both x and y polarizations are fairly small, the average propagation constant $\bar{\beta} = (\beta_1^{x} + \beta_1^{y})/2$ is approximately equal to $\beta = 2\pi neff_{co}/\lambda$, with $neff_{co}$ denoting the effective RI of the degenerated core mode. Therefore, the propagation constants for the x- and y-polarization core modes can be calculated from.

$$\beta_1^{x} = \beta + \Delta\beta/2$$

$$\beta_1^{y} = \beta - \Delta\beta/2 \tag{2}$$

The full-vector coupled mode equations of LPFG are [17].

$$\begin{cases} dA_1^{i}/dz = jA_1^{i}(z)\kappa_{co-co}^{i} + jA_2^{i}(z)\kappa^{i}\exp(-2j\delta^{i}z) \\ dA_2^{i}/dz = jA_1^{i}(z)\kappa^{i*}\exp(2j\delta^{i}z) + jA_2^{i}(z)\kappa_{cl-cl}^{i} \end{cases} (i = x, y) \tag{3}$$

where A_1^{x} and A_1^{y} are the electrical field amplitudes of the core modes LP_{01}^{x} and LP_{01}^{y}, respectively; $0 \le z \le L$, L is the grating length; $\delta^{i} = 0.5(\beta_1^{i} - \beta_2 - 2\pi/\Lambda)$, β_2 is the propagation constant of the coupled cladding mode, here the effective RIs or the propagation constants of the core mode and cladding modes are calculated using the three-layer fiber model; κ_{co-co}^{i} is the self-coupling coefficient of the core mode, while κ_{cl-cl}^{i} is that of the cladding mode, which is small enough to be neglected, $\kappa^{i} = \kappa_{cl-co}^{i}/2$, κ_{cl-co}^{i} is the cross-coupling coefficient between the core mode and the cladding mode. The self-coupling coefficients of the core modes LP_{01}^{x} and LP_{01}^{y} are written as:

$$\kappa_{co-co}^{x}(z) = 0.5\omega\varepsilon_0 n_1(n_1\sigma(z) + \Delta n)\int_0^{2\pi} d\phi \int_0^{r_1} rdr(\left|\mathbf{E}_r^{co}\right|^2\cos^2\phi + \left|\mathbf{E}_\phi^{co}\right|^2\sin^2\phi) \tag{4}$$

$$\kappa_{co-co}^{y}(z) = 0.5\omega\varepsilon_0 n_1(n_1\sigma(z) - \Delta n)\int_0^{2\pi} d\phi \int_0^{r_1} \mathrm{rdr}(\left|\mathbf{E}_r^{co}\right|\sin^2\phi + \left|\mathbf{E}_\phi^{co}\right|\cos^2\phi) \tag{5}$$

in which ω is the angular frequency, and r_1 is the fiber core radius.

The cross-coupling coefficient between LP_{01}^{x} and the cladding mode is

$$\kappa_{cl-co}^{x}(z) = 0.5\omega\varepsilon_0 n_1(n_1\sigma(z) + \Delta n)\int_0^{2\pi} d\phi \int_0^{r_1} \mathrm{rdr}(\mathbf{E}_r^{cl}\mathbf{E}_r^{co*}\cos^2\phi + \mathbf{E}_\phi^{cl}\mathbf{E}_\phi^{co*}\sin^2\phi) \tag{6}$$

and that for LP_{01}^{y} is

$$\kappa_{cl-co}^{y}(z) = 0.5\omega\varepsilon_0 n_1(n_1\sigma(z) - \Delta n)\int_0^{2\pi} d\phi \int_0^{r_1} \mathrm{rdr}(\mathbf{E}_r^{cl}\mathbf{E}_r^{co*}\sin^2\phi + \mathbf{E}_\phi^{cl}\mathbf{E}_\phi^{co*}\cos^2\phi) \tag{7}$$

with the input conditions $A_1^{i}(0) = 1$ and $A_2^{i}(0) = 0$, the core mode amplitudes are derived from Eq. (3)

$$A_1^{i}(z) = [\cos((\sqrt{\kappa^{i}\kappa^{i*} + (\bar{\sigma}^{i})^2})z) + j\bar{\sigma}^{i}(1/\sqrt{\kappa^{i}\kappa^{i*} + (\bar{\sigma}^{i})^2})\sin((\sqrt{\kappa^{i}\kappa^{i*} + (\bar{\sigma}^{i})^2})z)]\exp(j\kappa_{co-co}^{i}z/2)\exp(-j\delta^{i}z)\ (i = x, y) \tag{8}$$

where $\bar{\sigma}^{i} = \delta^{i} + \kappa_{co-co}^{i}/2$

The electric fields of the core modes LP_{01}^{x} and LP_{01}^{y} along a LPFG can be written as

$$\begin{cases} E_x = A_1^{x}(z)\exp(-j\beta_1^{x}z + j\delta_x) \\ E_y = A_1^{y}(z)\exp(-j\beta_1^{y}z + j\delta_y) \end{cases} \tag{9}$$

with the initial phases δ_x,δ_y being constant.

Assuming that the incident light is a completely-polarized light, its Stokes parameters are defined as [18]

$$\begin{cases} s_0 = E_xE_x^* + E_yE_y^* \\ s_1 = E_xE_x^* - E_yE_y^* \\ s_2 = E_x^*E_y + E_xE_y^* \\ s_3 = -j(E_x^*E_y - E_xE_y^*) \end{cases} \tag{10}$$

which can be normalized against s_0 by letting $s_0 = 1$. These parameters $s_i (i = 1, 2, 3)$ are three-dimensional coordinates, and can be described by a point on the surface of the Poincare sphere. To calculate the spherical distance, the three-dimensional coordinates $s_i (i = 1, 2, 3)$ are converted into latitude and longitude coordinates as follows:

$$\begin{cases} 2\chi = \arctan(s_3/\sqrt{s_1^2 + s_2^2}) \\ 2\varphi = \begin{cases} \arctan(s_2/s_1) & ,s_1 > 0 \\ \pi + \arctan(s_2/s_1) & ,s_1 < 0,\ s_2 > 0 \\ \arctan(s_2/s_1) - \pi & ,s_1 < 0,\ s_2 < 0 \end{cases} \end{cases} \tag{11}$$

where 2χ is latitude (unit: radian),2φ is longitude (unit: radian), and the radius of the Poincare sphere is $r = 1$ (dimensionless).

Assuming that on the Poincare sphere the latitude and longitude of point A are $2\chi_1$ and $2\varphi_1$, respectively, and that of point B are $2\chi_2$ and $2\varphi_2$, the spherical distance, namely the minor arc length, between A and B is