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Single-wavelength polarization-sensitive interrogation of a long-period grating (LPG) sensor

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Abstract

We propose a new scheme for the interrogation of long-period fiber gratings (LPGs) which traces the polarization trajectory on the Poincaré sphere. This method was applied to detect changes of the surrounding refractive index at a single wavelength. Sensitivities as high as 10^{-6} r.i.u. can be achieved for a broader range of refractive indices. This method can also be used in combination with WDM schemes.

Keywords: fiber optic sensors, polarization, LPG interrogation, polarization division multiplexing

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Long-period fiber gratings (LPGs) [1] have gained a lot of attention due to their sensitivity to a number of physical quantities and especially to changes in the surrounding refractive index (SRI) which makes them a good candidate for highly sensitive fiber optic refractometers with applications in chemical and biochemical sensing [2, 3].

Typically, the center wavelength shift of the LPG is tracked to measure the changes in the SRI. There are three particular issues related to this conventional interrogation scheme. First, a large wavelength shift, preferably greater than 20 nm, is desirable to achieve high sensitivity. Second, a broadband unpolarized source must be used to eliminate the effect of polarization-dependent loss (PDL) [4], which makes the use of a single-wavelength interrogation scheme inadequate. And third, for refractive index measurements, the high sensitivity is over a very narrow range of SRI values, close to the cladding refractive index, which is a serious limitation. Because of this a number of methods have been used to reduce

the PDL of LPGs [5–7] down to the more acceptable 0.21 dB level. However, since wavelength shifts as large as 60 nm are required for high sensitivity SRI measurements [2], this poses restrictions on the multiplexing of LPGs. Thus, having a high sensitivity and a reduced wavelength shift to allow for a greater number of multiplexed LPGs are contradictory requirements.

In a recent Müller–Stokes analysis [8], we have shown that when a highly polarized tunable laser is used in combination with a polarization analyzer, linearly birefringent LPGs exhibit a characteristic wavelength-dependent trajectory on the Poincaré sphere, each point P_i representing a polarization state at a separate wavelength λ_i .

In the present paper we show that when a linearly birefringent LPG is subjected to certain perturbations such as changes of the surrounding refractive index (SRI), strain, etc, these cause changes in the state of polarization that are observed as a unique trajectory on the Poincaré sphere. Each wavelength λ_i has its separate polarization trajectory with a specific sensitivity. Each point of the trajectory on the Poincaré sphere corresponds to a particular value of the measurand, which is the basis of a polarization-sensitive

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single-wavelength interrogation method. Thus, several LPGs tuned at different wavelengths can be interrogated simultaneously, which in essence is polarization-dependent wavelength division multiplexing.

2. Polarization-sensitive responses of LPG sensors

In our previous analysis [8], it has been assumed that in an LPG of pitch Λ , the mode coupling between the fundamental LP_{01} core mode and the LP_{0p} cladding mode is within the same polarization $LP_{01}^x-LP_{0p}^x$ and $LP_{01}^y-LP_{0p}^y$ pairs, characterized by propagation constants $\beta_x^0, \beta_x^p, \beta_y^0$ and β_y^p which define the core and the cladding birefringence $\delta\beta^0 = (\beta_x^0 - \beta_y^0)/2$ and $\delta\beta^p = (\beta_x^p - \beta_y^p)/2$. If an input polarization characterized by a Stokes vector $\mathbf{S}^0 = \{S_0^0, S_1^0, S_2^0, S_3^0\}$ is launched into the LPG, the output polarization will be given by the vector $\mathbf{S} = \{S_0, S_1, S_2, S_3\}$ such that

$$\mathbf{S} = \mathbf{M}(z) \cdot \mathbf{S}^0, \quad (1)$$

where

$$\mathbf{M}(z) = \begin{bmatrix} m_1^+ & m_1^- & 0 & 0 \\ m_1^- & m_1^+ & 0 & 0 \\ 0 & 0 & m_2^+ & m_2^- \\ 0 & 0 & -m_2^- & m_2^+ \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & C & -S \\ 0 & 0 & S & C \end{bmatrix}. \quad (2)$$

In the above matrices, $C = \cos(\delta\beta z)$, $S = \sin(\delta\beta z)$, $\delta\beta = \delta\beta^0 - \delta\beta^p$, $m_1^\pm = [C_x^2 \pm C_y^2 + \Delta_x^2 S_x^2 \pm \Delta_y^2 S_y^2]/2$, $m_2^\pm = C_x C_y \pm \Delta_x \Delta_y S_x S_y$, $C_i = \cos(\delta\beta_i z/2)$, $S_i = \sin(\delta\beta_i z/2)$, $\delta\beta_i = 2(\delta_i^2 + |\kappa_i|^2)^{1/2}$, $\Delta_i = 2\delta_i/\delta\beta_i$, $K_i = 2\kappa_i/\delta\beta_i$ with $\kappa_i = (\Delta\lambda_i \lambda_i/\lambda^2)/2\Lambda$ and $\delta_i = \pi(\lambda_i/\lambda - 1)/\Lambda$ being correspondingly the coupling coefficients and the detuning parameters, while the quantities λ_i and $\Delta\lambda_i$ are the center wavelength and the width (FWHM—full width at half maximum) of the LPG for each polarization ($i = x, y$) [1].

Knowledge of the output Stokes parameters S_0, S_1, S_2, S_3 allows the calculation of the degree of polarization (DOP) $P_i = (S_1^2 + S_2^2 + S_3^2)^{1/2}/S_0$, the PDL as well as to observe their spectral evolution on the Poincaré sphere.

3. Experimental results and comments

The experimental set-up used to measure the Stokes parameters S_0, S_1, S_2, S_3 and the degree of polarization is shown in figure 1. A highly polarized laser (Agilent 8164A), tunable in the range from 1525 nm to 1584 nm, served as a monochromatic source. A lightwave polarization analyzer (Agilent 8509C) was used to measure the total optical power I in dBm, the Stokes parameters $S_{1,i}, S_{2,i}, S_{3,i}$ and P_i at each wavelength λ_i . Simultaneously, each polarization state is represented in a three-dimensional Stokes space by a point with normalized coordinates $s_{1,i}, s_{2,i}$ and $s_{3,i}$ such that

$$s_{k,i} = S_{k,i}/P_i \quad (k = 1, 2, 3), \quad (3)$$

where S_0 is the total power, which if expressed in dBm, we note as I .

The three-dimensional Stokes space is defined by S_1, S_2 and S_3 . When light is completely polarized $P = 1$, all points lie on a sphere, known as the Poincaré sphere. For partially

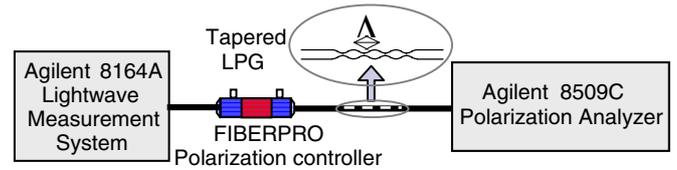


Figure 1. Experimental set-up used for measuring the wavelength dependence of the Stokes parameters and the DOP.

polarized light ($0 < P < 1$), the state of polarization can be represented either by a point inside the Poincaré sphere or by the normalized Stokes parameters, in which case the state is projected on the Poincaré sphere as in our experiments. Depolarized light with $P = 0$ is represented by a point in the origin, or by an infinite number of points evenly distributed on the Poincaré sphere.

Two groups of LPGs were fabricated using a standard Fitel S182K splicer. The first are made from SMF-28 communication fibers and the second from dispersion-shifted DS fiber. Glycerine solutions of varying concentrations as well as several types of oils of interest for the food industry with different values of the index of refraction were used to cover a wide range of SRI—from 1.33 to 1.48 r.i.u. (refractive index units), measured in the visible at 589 nm and correspondingly their values are lower around 1550 nm. During fabrication parasitic birefringence is introduced into the LPG, the magnitude of which unfortunately cannot be controlled.

Using the set-up from figure 1, and keeping constant temperature, we directly observe the polarization-dependent spectral response described by equations (1) and (2). The trajectory on the Poincaré sphere for SMF-based LPG-S immersed in pure water is shown in figure 2(a) while the spectral dependence of the DOP is shown in figure 2(b). This type of trajectory is strongly dependent on the input polarization as well as on the presence of external physical perturbations such as refractive index changes, elongation, temperature and twist. If such external fields are imposed on the LPGs, each point of the spectral trajectory in figure 2(a) corresponding to a given wavelength λ_i has its own trace on the Poincaré sphere as shown in figure 3 in which the dispersion-shifted fiber LPG-DS was subjected to elongation and the trace of greatest length at 1559 nm was recorded. As is seen for a given amount of strain, the initial Stokes vector \mathbf{S}^0 sweeps along an arc to a final Stokes vector \mathbf{S} and the total accumulated Stokes vector rotation angle is Ω . Each point on this trace corresponds to a unique value of the imposed strain. The trajectory's length is wavelength-dependent and at a certain specific wavelength λ_{\max} the trajectory reaches a maximum length that corresponds to the highest sensitivity. Similar behavior is observed for strain, temperature and other external perturbations imposed on the LPGs. Figure 3 shows the Poincaré sphere polarization trajectory at a single wavelength when the LPG is elongated. Irrespective of the perturbation imposed on the LPGs, the length of the polarization trajectory can be related to the total rotation angle on the Poincaré sphere.

Similar are the trajectories on twisting the grating, on changing the ambient temperature or surrounding refractive index. In all cases if the measurand x is changed by Δx ,

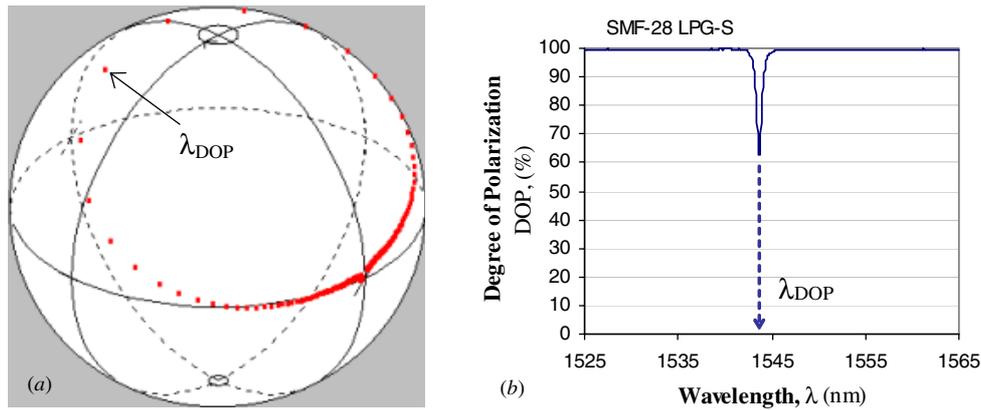


Figure 2. Polarization-dependent spectral response for LPG-S in water at constant temperature: (a) spectral trajectory on the Poincaré sphere; (b) spectral dependence of the DOP where λ_{DOP} is the wavelength of minimum DOP and coincides with the LPG center wavelength dip when both polarizations are excited.

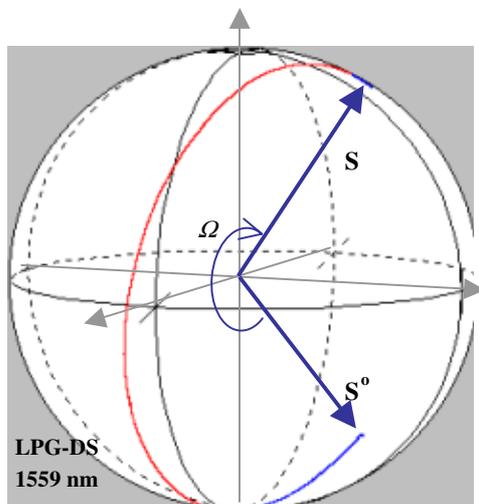


Figure 3. Polarization-dependent trajectory at a given wavelength λ_i (1559 nm) caused by strain, imposed on LPG-DS made from a dispersion shifted fiber at constant temperature.

then the initial Stokes vector rotates by $\Delta\Omega$ on the Poincaré sphere along an arc of length ΔL . Thus varying the measurand over a certain range, the total accumulated angle Ω and the corresponding arc length L will be

$$\Omega = \sum_i \Delta\Omega_i \quad \text{and} \quad L = \sum_i \Delta L_i. \quad (4)$$

Figure 4 shows the spectral polarization-dependent responses to strain, imposed on LPG-S grating, the initial state of polarization being right hand circular (RC). Figure 4(a) shows the center wavelength shifts of the minimum in the DOP, which generally coincides with center wavelength shifts of the transmission dip. More interesting are the results in figure 4(b) where we see that the plot of the total accumulated rotation angle Ω versus elongation is nonlinear and highly wavelength-dependent—a behavior that is typical for all polarization responses shown further.

Figure 5(a) gives the center wavelength shifts of the transmission minimum and of the DOP minimum, which practically coincide in all measurements, for temperature

variations between 15 °C and 60 °C. Also, the wavelength shifts of the central minimum of the PDL coincide with the DOP minimum wavelengths. Figure 5(b) represents the corresponding total accumulated Stokes vector rotation angle (Ω) at a particular wavelength of maximum sensitivity, namely 1561.2 nm. At other wavelengths, the dependences are similar, but shifted to the right or to the left.

As seen from figure 5(b) at certain wavelengths (as for example 1562 nm), the temperature dependence of the polarization-sensitive response is very weak at room temperature, which means that with an appropriate choice of gratings and wavelengths temperature dependence over certain ranges can be highly reduced.

Figure 6 shows the responses to torsion of LPG-3. We easily note that while the center wavelength shifts are quite small, about ± 1.2 nm for $\pm 13^\circ \text{ cm}^{-1}$ torsion rate, the total accumulated Stokes vector rotation angle Ω is quite large, reaching 500° at 1559.5 nm.

Because of PDL and depolarization, the dependences $\Omega(x)$ and $L(x)$ for a given measurand x are unique and trajectories like the one from figure 3 will not cross upon themselves to create ambiguity. Essentially, this means we can have a single-wavelength polarization-sensitive interrogation of an LPG. Since the trajectory depends on the input state of polarization, the lead-in and lead-out fiber sections have to be immobilized, which is a restriction. However, the possibility of interrogating several LPGs each at a different wavelength and with a specific affinity coating makes this approach attractive for building a measurement platform for biochemical sensing and simultaneous analysis of several analytes [3]. As multiple wavelength fiber lasers are becoming available [9], such polarization-sensitive spectrally multiplexed platforms become an interesting possibility. We therefore concentrate our attention on the responses of LPG to SRI changes as detected by this new polarization-sensitive interrogation method. Figure 7 shows the responses to SRI changes obtained with LPG-DS, while those from LPG S-2 are given in figure 8.

Results show that the center wavelength shifts in the total power, the PDL and the DOP are practically identical

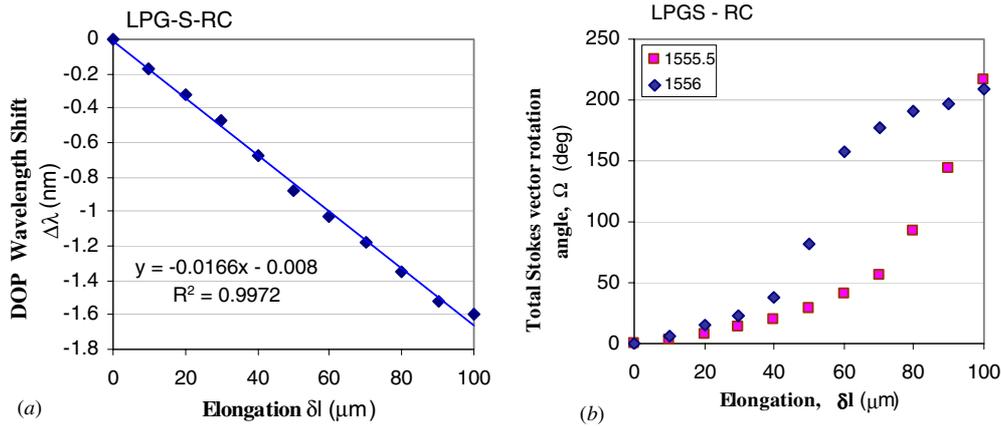


Figure 4. Strain dependence of (a) center wavelength shifts of the DOP minimum and (b) total accumulated Stokes vector rotation angle at two different wavelengths.

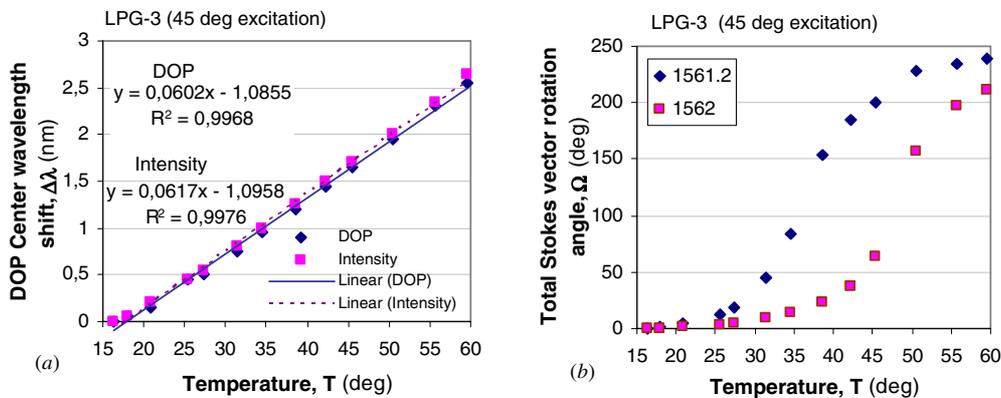


Figure 5. Temperature dependence of (a) center wavelength shifts of the transmission and the DOP minima, and (b) total accumulated Stokes vector rotation angle at the wavelength of maximum sensitivity λ_i (1561.2 nm).

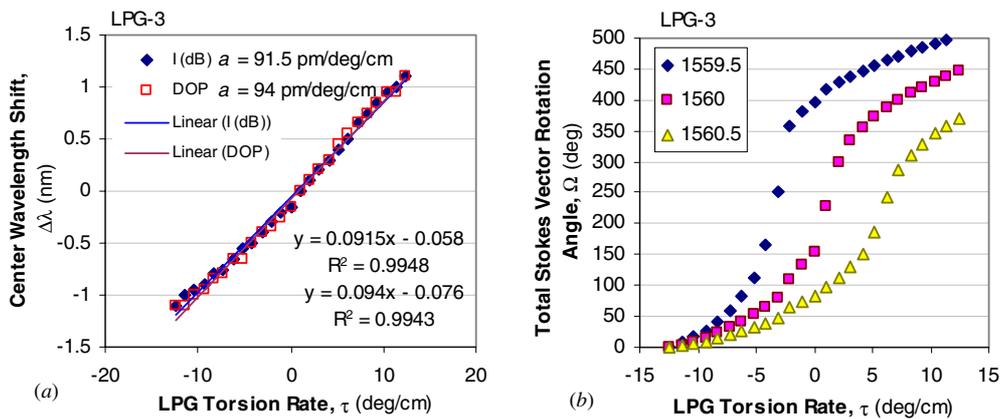


Figure 6. Responses to torsion of LPG-3: (a) center wavelength shift of the transmission and DOP minima; (b) dependence of the total accumulated Stokes vector rotation angle on the LPG torsion rate for three different wavelengths.

and for the particular gratings used are between 2.5 nm and 5 nm, which is rather a smaller shift compared to the width of the grating, which at 10 dB is 4.25 nm. With a resolution of 10 pm, the average sensitivity would be 6.10^{-4} r.i.u. for LPG-S. In contrast for a minimum detectable Stokes vector rotation angle of 0.2° and a total rotation angle of about 340° at 1543 nm, the average sensitivity would be 7.10^{-5} r.i.u., which is an order of magnitude better.

The results for LPG-DS are similar, namely 8.2×10^{-4} r.i.u. for the standard interrogation versus 5.7×10^{-5} r.i.u. for the present polarization-sensitive method. The sensitivities are much higher around the cladding refractive index reaching 5×10^{-5} r.i.u. This is about an order of magnitude better than the corresponding sensitivities for the standard method based on measurement of the resonance wavelength shift as

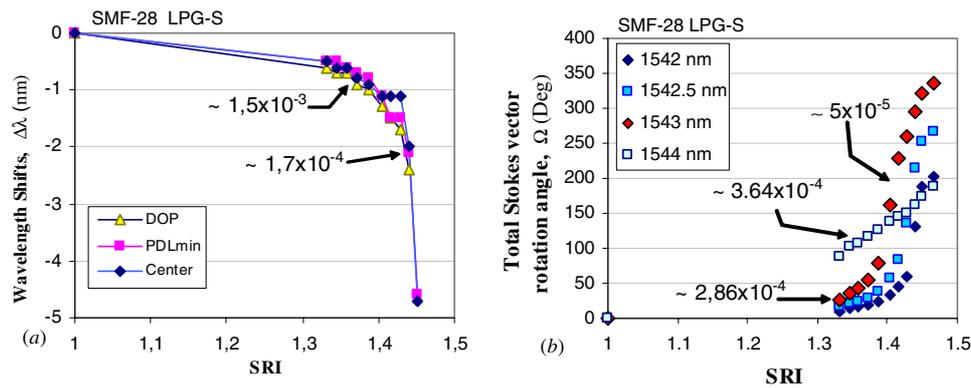


Figure 7. Responses to SRI of the LPG-S grating: (a) center wavelength shifts of the transmission, the DOP and the PDL minimum; (b) total Stokes vector rotation angles at four different wavelengths.

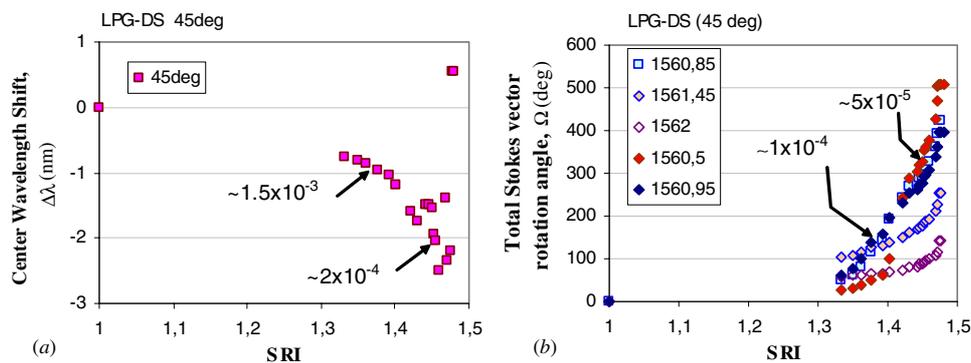


Figure 8. Response to SRI changes of the LPG-DS at 45° linear initial excitation: (a) center wavelength shifts and (b) total Stokes vector rotation angles at five different wavelengths.

is indicated in figure 8(a). We also note that at different wavelengths the sensitivities are different and a maximum sensitivity wavelength λ_{\max} exists, which is typically about 1.5 nm smaller than the LPG resonance wavelength. For the LPG S-2 $\lambda_{\max} = 1543$ nm while for the DS3 $\lambda_{\max} = 1560.5$ nm.

4. Conclusions

We have demonstrated a new interrogation method of LPGs that is based on the evolution of the Stokes vector of the transmitted light at a single wavelength. It has been found that maximum sensitivity is observed at a particular wavelength λ_{\max} . An advantage of the method is that different LPGs with small wavelength shifts can be multiplexed using standard communication laser diodes as sources. The method is applicable for a chemical and a biochemical measurement system based on multiplexed LPG refractometers detecting specific analytes. Also, at specific wavelengths, temperature dependence is very small.

Acknowledgments

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