Long period grating based refractometer with polarization-sensitive interrogation

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Abstract. We propose a new scheme for the interrogation of long-period fiber gratings (LPGs) which makes use of their polarization properties. Polarization-sensitive interrogation was applied to detect changes due to changes of the external refractive index by using three wavelengths on the International Telecommunication Union (ITU) grid. We show that the new approach can allow for a greater sensitivity and can be used in combination with spectral multiplexing schemes.

1. Introduction

The polarization properties of long-period fibre gratings (LPGs) have caused considerable interest mainly because of the unwanted polarization-dependent losses (PDL) and their wavelength dependence [1]. The causes and magnitude of PDL have been studied for CO₂-written [2], arc-induced [3], and photonic-crystal-based LPGs [4,5] and several methods have been suggested for their reduction [6,7] or compensation [8]. Knowledge of PDL is essential in LPG-based components for communication as well as for sensor applications [9]. In the latter case, the existence of PDL can be made inessential only if a non-polarized broadband source is used. This condition, in turn, eliminates the possibilities to use single-wavelength sources such as standard communication lasers for LPG interrogation schemes.

The polarization properties of LPGs, however, are not restricted to the PDL. Recently [4,5] we have shown that linearly birefringent LPGs have a characteristic wavelength-dependent trajectory in the form of a circle on the Poincaré sphere when a highly polarized tunable laser is used. Consequently introducing external perturbations on an LPG the state of polarization at a given wavelength follows a unique trajectory [10].

In the present paper we show that when a linearly birefringent LPG is subjected to external perturbations such as torsion and change of the surrounding refractive index (SRI), the spectrally-dependent polarization trajectory on the Poincaré sphere, which lies approximately on a plane, changes orientation. The orientation of this plane can be determined by a single vector normal to it.
External perturbation causes the end of this vector to follow a unique trajectory in the three-dimensional Stokes space.

We show that by measuring the Stokes parameters of an LPG at three different wavelengths we can determine the orientation of the polarization trajectory for a given value of the external perturbation. This in fact represents a polarization-sensitive method for interrogating LPGs which is compatible with multiwavelength lasers [11] emitting on the standard International Telecommunication Union (ITU) grid.

2. Spectrally-dependent polarization evolution of an LPG

The experimental set-up used to measure the Stokes parameters $S_0, S_1, S_2, S_3$ and the degree of polarization (DOP) $P$, as well as to observe their spectral evolution on the Poincaré sphere, is shown in figure 1. A highly polarized laser (Agilent 8164A), tunable in the range from 1525 nm to 1584 nm, was used 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 $\lambda_i$. 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

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

$$P_i = \left( S_1^2 + S_2^2 + S_3^2 \right)^{1/2} S_0^{-1}$$  \hspace{1cm} (2)

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

The three-dimensional Stokes space is defined by $S_1, S_2, S_3$. When light is completely polarized $P = 1$, all points lie on a sphere, known as the Poincaré sphere. For partially 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 [1], in which case the state is projected to the Poincaré sphere as in our experiments. Depolarized light with $P = 0$ is represented by a point in the origin, or by infinite number of points evenly distributed on the Poincaré sphere.

Several tapered LPGs were fabricated from an SMF-28 Corning optical fiber using a standard splicer (FITEL S182K). In the experiment the SRI around the LPG was varied from that of air $n_a = 1$ and distilled water $n_d = 1.3323$ to that of 100% glycerine $n = 1.4714$. For each value of the SRI, the Stokes parameters $s_{k,i}$ ($k = 1, 2, 3$) were measured at wavelengths $\lambda_i (i = 1, ... n)$ and the polarization states were automatically plotted on the Poincaré sphere. Figure 2 shows the spectral evolution of the state of polarization of LPG-2 for two different ambient media, air and distilled water. We see that the spectral trajectory on the Poincaré sphere can be considered to lie on a plane, which we shall refer to as ‘Stokes plane’. In reality, the trajectory lies on a slightly curved surface. However, for all practical purposes we assume that the error is negligible. Comparison between the two trajectories $T_1$ and $T_2$ reveals that $T_2$ is rotated with respect to $T_1$ through an angle $\Delta \Theta$, which we define as the angle between the vectors $N_1$ and $N_2$, normal to the plane of each trajectory as illustrated in figure 2c.

To describe the orientation of these vectors we need to find the equation for each plane [11], which in the Stokes space can be expressed as a linear equation with respect to the variables $s_1, s_2$, and $s_3$.
where $N_1$, $N_2$ and $N_3$ are the coordinates of the vector $N$, normal to the Stokes plane, namely:

$$N = (N_1, N_2, N_3)$$

and $D$ is a constant. If we use the Hessian normal form, then we can introduce the orthonormal unit vector $n = N/|N| \ [11]$. To determine the coefficients $N_1$, $N_2$, $N_3$ and $D$ we need to know the Stokes parameters at three different wavelengths $\lambda_1$, $\lambda_2$ and $\lambda_3$, namely $S_{1,1}$, $S_{2,1}$ and $S_{3,1}$ for $\lambda_1$; $S_{1,2}$, $S_{2,2}$ and $S_{3,2}$ for $\lambda_2$ and $S_{1,3}$, $S_{2,3}$ and $S_{3,3}$ for $\lambda_3$. Then, using well-known relations [11], we can calculate the coefficients $N_1$, $N_2$ and $N_3$.

Figure 2. Spectral trajectories of the state of polarization at the output of LPG-2 at two different ambient refractive indices where each point represents a state of polarization at a separate wavelength: a) trajectories $T_1$ and $T_2$, the vectors $N_1$ and $N_2$ normal to them and the angle between them $\Delta \Theta$.

Figure 2 b) $T_1$ - in air; Figure 2 c) $T_2$ – in distilled water;

Figure 3 shows the rotation of the Stokes plane due to successive twists through different angles applied to LPG-3. If the external perturbation changes by equal increments then the ends of the vectors $N_i$ change orientation and define a polarization trajectory (figure 3b). If we denote by $\Delta \Theta_i$ the angles between $N_i$ and $N_{i-1}$, then the total rotation angle accumulated is given by $\Theta = \sum \Delta \Theta_i$. For infinitesimal Stokes plane rotation angles $d\Theta$, summation will be replaced by an integral.

There are several ways of defining a line trajectory associated with the angular movement of the Stokes plane. One is to use the end of the normal $N$, another is to use the unit vector $n$ to indicate a point on the trajectory and the elementary arcs will accordingly be $dS$ and $ds$ (Table 1) while $S$ and $s$
will be the lengths of the corresponding trajectories. A second way is to multiply the distance \( d \) from the plane to the point of origin by \( n \) and define the vector \( \nu = dn \) which uniquely describes the orientation of the Stokes plane by tracing a trajectory inside the Stokes phase space as shown in figure 3b). The length of the trajectory will then be \( \delta \). A fourth way is to use the degree of polarization \( P \) from equation (2), which was shown to vary depending on the phase detuning between the coupled polarization modes [4]. The elementary arc \( dp \) and the total trajectory \( P_{DOP} \) are also given in Table 1.

![Figure 3. Rotation of the Stokes planes: a) spectral trajectories of the state of polarization at the output of LPG-3 for three different twist angles \( \theta_1 = -180^\circ, \theta_2 = -90^\circ, \theta_3 = 0^\circ \)

b) evolution of the normal vectors \( N_i \)](image)

**Table 1.** Elementary arcs and lengths of trajectories for each of the four cases.

| Elementary arc | \( dS = |N| \, d\Theta \) | \( ds = |n| \, d\Theta \) | \( d\delta = |n| \, d\Theta \) | \( dp = Pn \, d\Theta \) |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Length of trajectory | \( S = \int |N| \, d\Theta \) | \( s = \int |n| \, d\Theta \) | \( \delta = \int |n| \, d\Theta \) | \( P_{DOP} = \int Pn \, d\Theta \) |

Ultimately, because the orientations of the vectors \( N \) and \( n \) depend on the value \( x \) of the external perturbation, then \( S(x), s(x), \delta(x) \) and \( P_{DOP}(x) \) are functions of \( x \) as well. More importantly, each point on any of the plane polarization trajectories is uniquely related to a particular value \( x \) of the measurand. Thus identifying the position on the plane polarization trajectory is equivalent to measuring the value of the particular external perturbation. In practice, a sensor based on this type of interrogation would be using the mapping of the trajectory vs. values of the external perturbation. In this case, to avoid ambiguity, it is important that the polarization trajectory does not cross itself. While this may happen to the trajectory defined by the normal unit vector \( n \), it will not happen to the other trajectories.

### 3. Experimental results and analysis

We investigated two tapered LPGs made from standard SMF-28 Corning fiber by introducing periodic microtapering of pitch \( \Lambda \) and a total number of \( k \). Fusion-induced LPGs have been known to exhibit linear birefringence and hence, polarization-dependent properties. The gratings studied were labeled as LPG-2 (\( \lambda_c = 1544 \) nm) and LPG-3 (\( \Lambda = 770 \) \( \mu \)m, \( k = 67, \lambda_c = 1559 \) nm). The whole grating region was
submerged in different concentrations of water solutions of glycerine to obtain a total of eleven different values for the SRI ranging from 1.3327 to 1.4653. These refractive indices were measured in the visible range (\(\lambda = 589 \text{ nm}\)) using a standard Abbe refractometer.

Using the set-up shown in figure 1 we measured the spectral evolution of the Stokes parameters for the different refractive indices. The wavelength of the tunable laser was changed by increments of \(\delta \lambda = 0.1 \text{ nm}\). The results obtained are summarized in the plots in figure 4. Before taking the measurements, we set the state of polarization of the light close to right circular state (figure 2a,b) and figure 3a) at wavelengths away from the LPG resonance. This ensures that both polarizations are almost equally excited at the LPG input.

We found that changes of the SRI lead to changes in the spectral dependencies of the Stokes parameters, to wavelength shifts of their extrema (minima and maxima) and, consequently, to shifts of the PDL and DOP minima. We compared these polarization-dependent wavelength shifts with the standard centre wavelength shifts of the resonance wavelengths as shown in figure 4a,b. The results showed that, with the exception of the shifts of some extrema of Stokes parameters, the responses to changes in the SRI are practically identical. Fig. 4a shows that the wavelength shift of the maximum of the \(S_3\) parameter is twice as large as the wavelength shifts of the central resonance wavelength and the minima of the DOP and PDL. Also, the sensitivity for SRIs from 1.38 and 1.45 is much higher than the standard response. In the 1.33 to 1.43 range, the averaged sensitivity for these center wavelength shifts is 0.087 r.i.u./nm which with a 10 pm spectral resolution would yield a sensitivity 8.7 \(\times 10^{-4}\) r.i.u., where r.i.u. stands for “refractive index unit”. Results for LPG-3 were similar.

To determine the orientation of the Stokes plane we took the values of the Stokes parameters at three different wavelengths, each of them coinciding with or very close to an ITU 100 GHz grid channel used in DWDM. These three wavelengths used to calculate the angular increments \(\Delta \Theta\), are referred to as a “trio”. For LPG-2 the central wavelength of the middle channel coincides with ITU channel #44. The channel combinations were as follows: trio #1 - ITU channels 43, 44, and 45; trio #2 - 42, 44, and 46, and trio #3 - 41, 44, and 47. If the spectral trajectories \(T_i\) on the Poincaré sphere were ideal circles, all trios would yield identical responses. However, as was indicated earlier, the trajectories do not lie on a plane but on a slightly curved surface which results in different responses for each of the trios, as is clearly seen in figure 4b.

**Figure 4.** Responses of SRI changes in LPG-2 : a) wavelength shifts of the transmission minimum of the total power \(I\) and of chosen extrema (minimum or maximum) of each of the Stokes parameters; b) total Stokes plane rotation angle for three different trios of ITU channel wavelengths
The curves for the total Stokes plane rotation angle are quite similar in that they are essentially characterized by two regions of different sensitivity $\Delta n/\Delta \Theta$. The sensitivities for trio #1 are correspondingly $\Delta n/\Delta \Theta = 9.28 \times 10^{-4}$ r.i.u./deg for the 1.33 to 1.43 range and $\Delta n/\Delta \Theta = 1.06 \times 10^{-4}$ r.i.u./deg above 1.43. The orientation of the trajectories has been found to be stable and repeatable within about $\delta \Theta = 0.2$ deg, so the resolution of SRI measurements would be correspondingly $\Delta n = 1.86 \times 10^{-4}$ r.i.u. ($n = 1.33$ to 1.43) and $\Delta n = 2.12 \times 10^{-5}$ r.i.u. ($n > 1.43$) which is comparable to or better than the sensitivity obtained from the wavelength shifts.

4. Conclusions
We observed a rotation of the spectrally-dependent polarization trajectory of an LPG on the Poincaré sphere when the grating was subjected to changes in the SRI. Based on this finding, we have proposed a polarization-sensitive method for the interrogation of LPGs which makes use of their birefringence. The method uses three wavelengths on the ITU grid and offers a higher sensitivity than conventional methods based on centre wavelength shifts. It can also allow polarization-sensitive wavelength division multiplexing.

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