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Characterization of Temperature-Induced Changes in Polarization-Maintaining Nonlinear Optical Fibers

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Abstract. We theoretically characterize the temperature-induced chan-ges in polarization-maintaining (PM) nonlinear optical fibers. Based on a linear model of the temperature-dependent birefringence, we compute the change of the output polarization state (PS) of light through the calculation of the Stokes parameters. Our treatment provides an important analysis for the implementation in nonlinear temperature sensors.

Keywords: Polarization-maintaining nonlinear optical fibers, temperature-dependent birefringence, nonlinear polarization conversion, optical fiber sensors.

1 Introduction

The theory for describing and controlling the nonlinear polarization conversion of circularly polarized (CP) light in nonlinear birefringent optical fibers (BOFs) (Low- and High-BOFs) is given in Ref. [4]. Through a nonlinear model, it was provided the conditions to obtain the most common continuous wave (CW) polarization states (PSs) at the BOF output. In that regard, all-optical nonlinear control of CP light was demonstrated by tailoring the nonlinear and birefringence fiber parameters.

Such results are very important because open new perspectives for all-optical fiber sensors and provide considerable physical insight on the all-optical polarization control with nonlinear BOFs. In this work, we characterize the temperature-induced changes in PM nonlinear optical fibers through the computing of the change of the output PS of light. For this purpose, we develop a theoretical model to show how the birefringence is affected by the temperature changes.

2 Temperature Sensing Mechanism

We begin by considering a CW CP light beam launched into a lossless PM fiber such that it excites the two orthogonally polarized modes.

The coupled-mode equations that describe the evolution of the two orthogonally polarized components are given by [1]:

$$\frac{\mathrm{d}U_x}{\mathrm{d}z} = i\frac{1}{L_{NL}}\left(|U_x|^2 + \frac{2}{3}|U_y|^2\right)U_x + i\frac{1}{3L_{NL}}U_x^* U_y^2 \mathrm{e}^{-i2\Delta\beta z}, \tag{1}$$

$$\frac{\mathrm{d}U_y}{\mathrm{d}z} = i\frac{1}{L_{NL}}\left(|U_y|^2 + \frac{2}{3}|U_x|^2)\right)U_y + i\frac{1}{3L_{NL}}U_y^* U_x^2 \mathrm{e}^{+i2\Delta\beta z}, \tag{2}$$

where $U_x(z)$ and $U_y(z)$ are the normalized slowly varying amplitudes of such orthogonal polarization components of the optical field. Here the factor $i = \sqrt{-1}$ represents the imaginary unit, z is the standard notation for the propagation distance, $L_{NL} = (\gamma P_0)^{-1}$ is the nonlinear length, P_0 is the input peak power, and γ is the nonlinear parameter.

The linear birefringence parameter is $\Delta\beta = 2\pi/L_B$, where $L_B = \lambda/B$ is the beat length, $B = |n_x - n_y|$ is the degree of modal birefringence, and λ is the wavelength of light. n_x and n_y are the effective refractive indices along the x- and y-polarization axes of the PM fiber, respectively. It is usually assumed that n_x along the x-polarization or slow axis is greater than n_y along the y-polarization or fast axis.

Solutions of Eqs. (1) and (2) can be given by the following matrix form representation which describes the evolution of the two normalized slowly varying amplitudes, $U_x(z)$ and $U_y(z)$, along a PM fiber [4]:

$$\begin{bmatrix} U_x(z) \\ U_y(z) \end{bmatrix} = \mathbf{M}(z) \begin{bmatrix} U_x(0) \\ U_y(0) \end{bmatrix}, \tag{3}$$

where $U_x(0)$ and $U_y(0)$ represent the normalized slowly varying amplitudes of the two orthogonally polarized modes of the input signal field. The propagation matrix $\mathbf{M}(z)$ given by:

$$\mathbf{M}(z) = \begin{bmatrix} t\, e^{i(\phi_{NL\pm} - \Delta\,\beta z/2)} & \pm\, i\, r\, e^{i(\phi_{NL\mp} - \Delta\,\beta z/2)} \\ \pm i\, r\, e^{i(\phi_{NL\mp} + \Delta\,\beta z/2)} & t\, e^{i(\phi_{NL\pm} + \Delta\,\beta z/2)} \end{bmatrix}. \tag{4}$$

Is satisfied when either right hand circular polarization (RHCP) or left hand circular polarization (LHCP) light is launched into the PM fiber. Here $\phi_{NL+}(z)$ and $\phi_{NL-}(z)$ are two nonlinear phase shifts, and $t(z) = \sqrt{1 + u(z)}/\sqrt{2}$ and $r(z) = i\sqrt{1 - u(z)}/\sqrt{2}$ are defined as the transmittance and reflectance, respectively. In general, before relations satisfy the conservation of energy conditions: $|t(z)|^2 + |r(z)|^2 = 1$ and $r(z)t^*(z) + t(z)r^*(z) = 0$. In Eq. (4), the upper and lower signs in $\pm$ and $\mp$ are considered to be associated with the RHCP and LHCP input light, respectively.

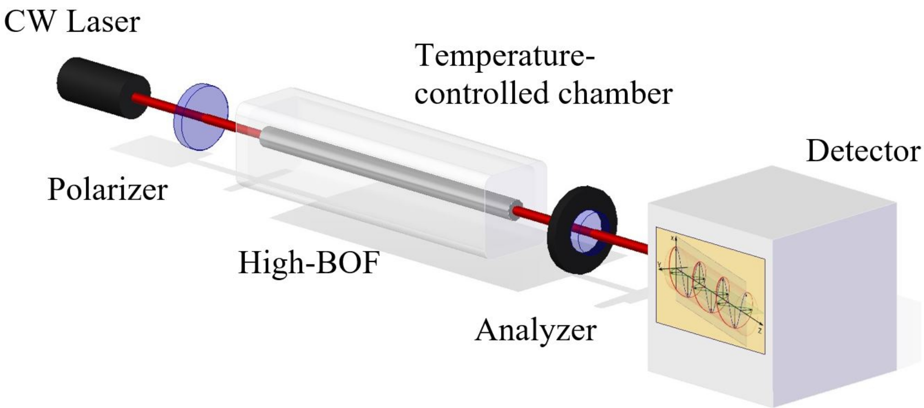

Fig. 1. A light beam traveling through a High-BOF (polarization-maintaining fiber) affected by a specific temperature, changing its physical proprieties and the polarization of light.

The $u(z)$, $\phi_{NL+}(z)$ and $\phi_{NL-}(z)$ functions are given by:

$$u = \text{cn}(\Delta\beta z|m), \tag{5}$$

$$\phi_{NL+}(z) = \frac{5}{6}z \mp \frac{1}{2}\arccos[\text{dn}(\Delta\beta z|m)], \tag{6}$$

$$\phi_{NL-}(z) = \frac{5}{6}z \pm \frac{1}{2}\arccos[\text{dn}(\Delta\beta z|m)], \tag{7}$$

where $\text{cn}(x|m)$ and $\text{dn}(x|m)$ are two Jacobi elliptic functions with argument x and modulus $m = k^2$. For any elliptic function, its modulus must lie between 0 and 1. In our case, the modulus $m = [\gamma P_0/(3\Delta\beta)]^2$; and therefore, $k = \gamma P_0/(3\Delta\beta)$.

2.1 Methodological Strategy

Power variations of the propagating light and physical parameters, such as temperature, stress, magnetic field, and torsion affect the birefringence of an optical fiber. Thereby some analytical models that relate such physical parameters with the birefringence of optical fibers have been developed [2, 3, 5].

In that regard, such intuitive relations can be used to implement such theoretical model [4] and develop high-sensitivity all-optical fiber sensors and new sensing methods that allow obtaining magnitudes of parameters more accurately. For our purposes, we implement the following approach given by [2, 5]:

$$B = B_0 + \gamma_b(T + T_0), \tag{8}$$

where T is the temperature of the fiber under test, T_0 is the room temperature, B_0 is the birefringence at room temperature, and γ_b is the thermal coefficient, which relates the birefringence with temperature in High-BOFs. Therefore, we can use such relation and introduce it in the developed theoretical model through the definition of the beat length given by $l_B = \lambda/B$.

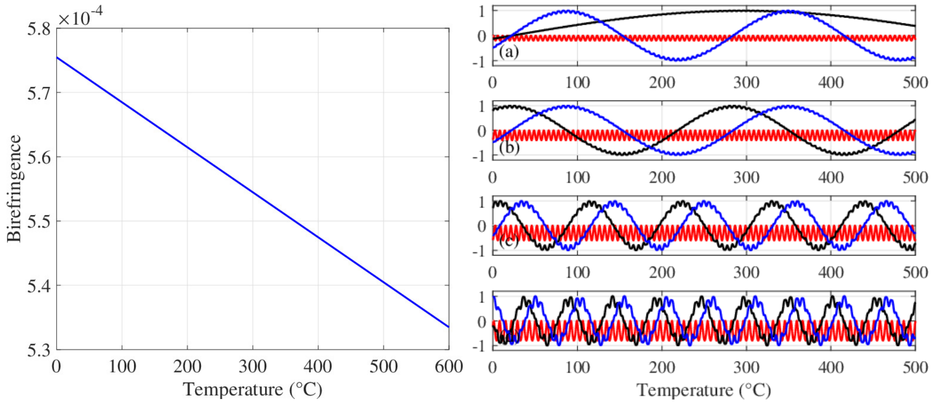

Fig. 2. The graph on the left shows the behavior of fiber's birefringence with increasing temperature, and the graph on the right shows how the Stokes parameters change as the temperature increases. S_1 (red solid line), S_2 (black solid line,) and S_3 (blue solid line). Output Stokes parameters for a High-BOF length $L = 2\,\mathrm{m}$, $\lambda = 1550\,\mathrm{nm}$, $\gamma_b = -7x10^{-8}$ °C^{-1}, $T_0 = 20$ °C, and $B_0 = 5.74x10^{-4}$ [3, 5]. Normalized input power for (a) $P_0/P_c = 0.2$, (b) $P_0/P_c = 0.4$, (c) $P_0/P_c = 0.6$ and (d) $P_0/P_c = 0.8$, when a right-handed circularly polarized light is launched into the PM fiber.

In this way, we can apply the theoretical model to analyze how the temperature affects the output polarization in optical fibers. For this purpose, the change of the output PS of initially CW CP light must be monitored after its transmission through a PM fiber.

3 Results

Using Eq. (8), it is possible to calculate the birefringence changes of the High-BOF due to the temperature increments or decrements. Therefore, applying the theory given in [4] and using Eq. (8), we obtain theoretically how the temperature changes affect the Stokes parameters of the output polarized light.

4 Conclusions

We have described and characterize theoretically the temperature-induced chan-ges in PM nonlinear optical fibers through the computing of the change of the output PS of light. We have developed a theoretical model to show how the birefringence is affected by the temperature changes. Our study creates a new possible way to measure temperature utilizing this kind of fibers that we know they are a good option because their properties.

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