Thermo-Optical Sensitivity Analysis of Highly Birefringent Polarimetric Sensing Photonic Crystal Fibers With Elliptically Elongated Veins

Nikolaos J. Florous, Member, IEEE, Shailendra K. Varsheney, Member, IEEE, Kunimasa Saitoh, Member, IEEE, and Masanori Koshiba, Fellow, IEEE

Abstract—The spectral and thermo-optical sensitivity responses of highly birefringent photonic crystal fibers (PCFs) with elliptically elongated veins integrated in their profile are being investigated using a novel sensitivity analysis based on an accurate semivectorial modal solver combined with temperature-dependent Sellmeier equations for pure silica and dry air. We demonstrate that by an appropriate selection of the design parameters it is possible to optimize the sensitivity of the modal birefringence or even to obtain null response at specific wavelengths. Thus, our investigation adds evidence to the potential use of highly birefringent PCFs as polarimetric sensors. Optimized overall temperature sensitivity could be obtained up to $7.5 \times 10^{-7}$ K$^{-1}$ at operational wavelength of 1.55 $\mu$m.

Index Terms—Photonic crystal fibers (PCFs), polarimetric sensors, sensitivity analysis, temperature-dependent Sellmeier equations, virtual boundary method.

I. INTRODUCTION

INDEX GUIDING photonic crystal fibers (PCFs), also known as holey fibers, are novel optical waveguides based on an artificially periodic microstructured profile that can enable light to be controlled in the fiber in ways not previously possible or even imaginable. They have attracted considerable attention in recent years [1], due to the unlimited possibilities in engineering their modal properties. Despite their great significance in various applications proposed so far, there are not yet scientific reports on the use of PCFs as polarimetric sensors [2]–[5], mainly for two reasons. First, a sensitivity analysis which permits the calculation of thermo-optical responses in PCFs is not known, and second, until now, temperature-independent Sellmeier equations were used so far to describe their material properties, thus prohibiting temperature-dependent phenomena to be studied in PCFs. In this letter, we report the first complete theoretical study of thermo-optical responses in PCFs with elliptical elongated veins integrated in their profile and we identify novel mechanisms that contribute to the overall thermo-optical response of PCF-based polarimetric sensors.

The response of classical Bragg grating sensors or polarimetric fiber sensors to external stress, temperature, and pressure primarily stems from a change in the refractive index of glasses induced by strain. In a more accurate consideration, one also needs to account for the dynamic rate of change in the refractive index caused by additional factors than strain as well as for the geometrical deformation of the cross profile of the fiber. For instance, the change of temperature induces strain due to the nonuniform expansion of the fiber’s cross profile, which in turn affects the distribution of refractive index in the fiber. Although this is the primary mechanism responsible for the change of measured parameters such as the modal index and birefringence in a classical fiber sensor, if a standard highly birefringent fiber sensor is replaced by a PCF, temperature no longer introduces strain. Now other secondary effects become dominant and can alter the thermo-optical response of PCF-based sensors, namely the temperature dependencies of the refractive indexes of silica and air as well as the cross profile’s thermal expansion.

II. MODELING THE THERMO-OPTICAL SENSITIVITY RESPONSE IN HIGHLY BIREFRINGENT PCFS

For PCFs, the thermal-induced strain is negligible, since the thermal expansion is considered uniform. The change of the fiber birefringence $B$ with temperature $T$ can be expressed using the contributions from the thermal refractive index change and from the thermal expansion as

$$\frac{dB}{dT} = \frac{\partial B}{\partial \lambda} \frac{\partial \lambda}{\partial T} + \frac{\partial B}{\partial n_s} \frac{\partial n_s}{\partial T} + \frac{\partial B}{\partial n_h} \frac{\partial n_h}{\partial T}$$

$$= \frac{\partial B}{\partial \lambda} \alpha_s + \frac{\partial B}{\partial n_s} \beta_s + \frac{\partial B}{\partial n_h} \beta_h$$

(1)

where in (1) we have accounted for the thermal expansion $\lambda$ as well as for the thermal change of the refractive indexes of silica $n_s$ and the material inserted in the holes $n_h$. The significance of effects related to thermal expansion and to the change of refractive indexes are governed by the respective coefficients, namely by the thermal expansion coefficient of silica $\alpha_s = 5.5 \times 10^{-7}$K$^{-1}$ and the thermal coefficients of both silica $\beta_s = 1.2 \times 10^{-5}$K$^{-1}$ and the dry-air $\beta_h = -0.9 \times 10^{-6}$K$^{-1}$. The above parameters related to (1) have been estimated during differentiation from the knowledge of temperature-dependent Sellmeier equations for both pure silica [6], [7] as well as for dry-air [8]. These equations can be summarized as follows:

$$n_s^2 = A + \frac{BX^2}{\lambda^2 - C} + \frac{DX^2}{\lambda^2 - E}$$

(2)
where the constants $A, B, C, D,$ and $E$ are linearly dependent on temperature-$T$ (in Celsius) in the following manner:

\[
\begin{align*}
A &= M_A T + Y_A; M_A = 3.1463 \times 10^{-8}; Y_A = 1.3155 \\
B &= M_B T + Y_B; M_B = 2.0427 \times 10^{-5}; Y_B = 0.7884 \\
C &= M_C T + Y_C; M_C = 2.8153 \times 10^{-6}; Y_C = 0.011029 \\
D &= M_D T + Y_D; M_D = -6.7886 \times 10^{-5}; Y_D = 0.91136 \\
E &= M_E T + Y_E; M_A = 100; Y_E = 10^{-10}.
\end{align*}
\]

For dry-air with standard volumetric composition of: 78.03% nitrogen (N), 20.99% oxygen (O2), 0.03% carbon dioxide (CO2), 0.01% hydrogen (H2), and 0.94% argon (Ar), the corresponding temperature-dependent Sellmeier equation takes the following form [8]:

\[
n_h(T) = 1 + 10^{-8} \left( 6432.8 + \frac{2049810 \lambda^2}{146 \lambda^2 - 1} + \frac{25540 \lambda^2}{41 \lambda^2 - 1} \right) \left( \frac{1 + a T_s}{1 + a T} \right) \frac{P}{P_s} \tag{3}
\]

where in the above equation $T$ is the temperature in Celsius, $T_s = 15 \, ^\circ C$ is a reference temperature, $\lambda$ is the wavelength in $\mu m$, $P$ is the pressure in mm-Hg, $P_s = 760$-mm-Hg is the reference standard pressure under normal conditions, and $a$ is a parameter slowly varying with temperature and can be depicted from [8] for different wavelength bands.

For PCF sensors, there are at least two novel sensing mechanisms that are not present in standard fiber sensors. First since the change of the refractive index of air holes with temperature is by an order of magnitude smaller than that of silica and has an opposite sign, the thermal response of PCF-sensors partly results from the direct nonuniform change of the refractive indexes from its cross profile. Second the large refractive index contrast between air and silica emphasizes the geometrical changes within the cross profile, as compared to the case of standard fibers. In our investigation, we combine a rigorous semivectorial technique of virtual boundary method [9] for the accurate prediction of the modal characteristics of PCFs with elliptically elongated air holes, with (1)–(3), to form an accurate algorithm for the thermo-optical sensitivity prediction in PCFs. As shown in Fig. 1, we consider PCFs with elliptical air holes arranged in a triangular configuration with lattice constant $\Delta$, and filling ratio $f$ (the ratio of the major semi axis over the pitch constant), while we particularly distinguish them in two types: type-A where the orientation of the major axis of the elliptical air holes is across the $x$-axis (horizontal axis), and type-B with corresponding orientation across the $y$-axis (vertical axis). In both cases the ellipticity is considered uniform across the profile of the PCFs and defined always as the ratio of the major semi axis over the minor semi axis. The choice of PCFs with elliptical air holes is considered here for mainly three reasons. At first it is well known that the use of elliptical deformations can significantly enhance the modal birefringence to very high values [9, 10]. The second reason is that their refractive index profile is much simpler to realize [11] in comparison to other highly birefringent PCFs with dissimilar air holes [12]. The third and most important reason is that the optimization of the sensitivity of the modal birefringence can be controlled using only one parameter, that is the ellipticity of the air holes as will be demonstrated later.

III. SELECTED NUMERICAL RESULTS AND DISCUSSION

Fig. 2 shows the contributions of silica (circles), air (stars), and the cross profile expansion of the geometry (squares), to the overall thermal sensitivity (solid curve) of the modal birefringence ($K^{-1}$), at $\lambda = 1550$ nm, as a function of the air-hole ellipticity-$\epsilon$ for (a) type-A PCF and (b) type-B PCF. For both cases, the maximization of the sensitivity function occurs for an air-hole ellipticity value of $\epsilon = 2.27$.

![Fig. 1. Schematic cross section of the highly birefringent PCFs considered as polarimetric sensors, (left panel) type-A PCF with horizontally oriented elliptical air holes, and (right panel) type-B PCF with vertically oriented elliptical air holes.](image1)

![Fig. 2. Contributions of silica (circles), air (stars), and the cross profile expansion of the geometry (squares), to the overall thermal sensitivity (solid curve) of the modal birefringence ($K^{-1}$), at $\lambda = 1550$ nm, as a function of the air-hole ellipticity-$\epsilon$ for (a) type-A PCF and (b) type-B PCF. For both cases, the maximization of the sensitivity function occurs for an air-hole ellipticity value of $\epsilon = 2.27$.](image2)
and for ．Near the region of zero-crossing, the main
150 nm, for type-A PCF (left panel) and type-B PCF (right
panel), while we consider a total number of six air-hole rings.
Although from the results in Fig. 4 we may drastically reduce it by increasing
the number of air-hole rings (around 12).

As a result of zero-crossing, it is evident that all these
mechanisms contributing to the overall sensitivity are not only
the change of the refractive index of silica but also that of air.

We can see that in the case of Fig. 3(b), the sensitivity of the
modal birefringence reaches a global maximum with a value
of about $7.5 \times 10^{-7}$ K$^{-1}$ around the telecommunication band.

According to the remarkable results is that for both cases the sensitivity
of the modal birefringence takes its maximum value at elliptic
icity of $\varepsilon = 0.27$. Near the region of zero-crossing, the main
mechanism contributing to the overall sensitivity is not only
the change of the refractive index of silica but also that of air.

At the exact point of zero-crossing it is evident that all these
continuations of silica (circles), air (stars), the cross pro-

Fig. 3. Thermal sensitivity of the modal birefringence $K_i$ (of silica/circles) at
the operational wavelength $\lambda = 1550$ nm and the cross profile expansion of the
geometry (squares) as a function of the operational wavelength $\lambda$. An (a) for
(type-A PCF) and (b) type-B PCF at fixed ellipticity of $\varepsilon = 0.27$.

Fig. 4. Normalized intensity distributions of the fundamental mode of
the remarkably high, we may drastically reduce it by increasing the
number of air-hole rings (around 12).

To summarize our work, the virtual boundary method was
used in combination with temperature-dependent Sellmeier
equations to form a rigorous computational technique for the
accurate estimation of thermal sensitivities in PCFs. We saw
that PCs can be potentially used for parametric sensors. The
type of PCs with infiltrated noble gases in the air holes are
currently under consideration.

REFERENCES

1. J. Brengue, D. Perier, S. E. Babin, and A. Butkus, "Photonic
crystal fibers: A new class of optical waveguides," J. Lightw.
2. K. Kuchkarsh, Y. Namikawa, and Y. Fujii, "Birefringence variation with
3. A. Philip and G. W. Mullin, "Temperature-sensitive fiber optic
5. W. Bock and T. Eftimov, "Temperature and intermodal birefringence
7. T. Eftimov, "Theoretical analysis of birefringence in elliptical hole
8. R. Penndorf, "Table of the refractive index of standard air and the
9. N. Florous and M. Koshiba, "Virtual boundary method for the anal-
ysis of elliptically cross-sectional photonic crystal fibers with elliptic
10. M. J. Steel and R. M. Osgood, "Optical Waveguides: A new class
11. A. Wang, G. Wang, K. Murphy, and R. Claus, "Polarization and