Birefringent photonic crystal fiber as a multi-parameter sensor

T. Nasilowski[a], P. Lesiak[a,c], R. Kotynski[a], M. Antkowiak[a,b], A. Fernandez Fernandez[b], F. Berghmans[a,b] and H. Thienpont[a]

[a]Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium,
[b]SCK.CEN, Boeretang 200, B-2400 Mol, Belgium
[c]WUT, Faculty of Physics, Koszykowa 75, Warsaw, Poland

Polarizations maintaining photonic crystal fibers (PCF) constitute a new class of birefringent optical fibers with strong separation of polarization modes and large possibilities of tailoring different parameters. These advantages appear to be perfect for designing optical fiber sensor, so we decided to test this type of fiber. A plane-wave method was used to numerically calculate the effective refractive indices and the field distribution of the propagation modes. The simulation results were compared with experimental measurements of the birefringence and finally the fiber was experienced as a sensor with fully automated set-up.

Introduction

Holey fibers (HF) as a subgroup of photonic crystal fibers (PCF) constitute a new class of optical fibers which has revealed many interesting phenomena paving the way for a large number of novel applications either in the telecom or in the sensing domain. The typical HF [1] consists of pure silica with a periodic distribution of air holes in the cladding. In PCF light can be guided either by effective index mechanism related to total internal reflection [2] or through bandgap effect [3] caused by periodically spaced air holes. HF can potentially be made highly birefringent, because the large index contrast facilitates high form geometrical birefringence. Various methods of introducing birefringence into HFs have been presented. PCF with elliptical air holes [4,5] or/and with asymmetric core or asymmetric distribution of holes [6-8] in the fiber have been applied to exhibit strong birefringence. Compared with elliptical-hole PCF, the later two designs are more suitable for the implementation of birefringent PCF. This is due to the fact that the shape of elliptical holes is very difficult to be controlled in the fabrication process. We have adopted the asymmetric core design similar to the one proposed in [7], but instead two rods in the center of the structure we have used three ones (Fig. 1). In that way we have created highly elliptical core. In this paper we demonstrate that by creating two fold rotational symmetry the PCFs with high birefringence is obtained. Based on elasto-optical measurements of the polarization state on the output of the fiber [9], we measure the fiber birefringence (beat length) for different wavelengths and compare it with numerical simulations based on plane wave method [10]. Also temperature and strain sensitivities were evaluated. Finally, the propagation losses measurements have shown the polarizing phenomena for longer wavelengths.

Propagation losses

The PCF used for the experiments was fabricated by modification of conventional optical fiber drawing process. The fiber has 7 layers of air holes and distance between the holes (pitch) of Λ=1.16 μm and hole diameter $\boldsymbol{d}$=0.52 μm.

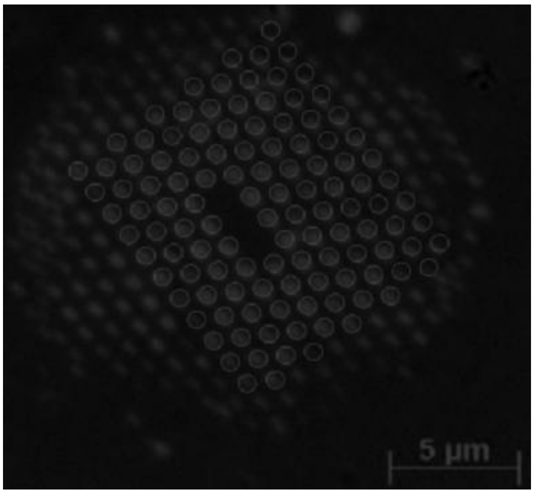

Figure 1: High resolution optical microscope picture of highly birefringent PCF cross-section with the drawing of triangular lattice air holes.

The transmission losses were measured with standard cut-back method for wavelengths range approximately from 1250 nm to 1650 nm and the results are presented on Fig. 2. Strong attenuation of longer wavelengths provokes more careful investigation of the wavelength depended losses. Since in birefringent fiber polarization plays an important role, the transmission losses of different polarization modes should be verified. Polarization dependent loss, which is a difference between attenuation of two polarization modes expressed in dB, is presented on Fig. 3. One can clearly notice that for longer wavelengths investigated PCF becomes polarizing one – only one polarization mode is maintain.

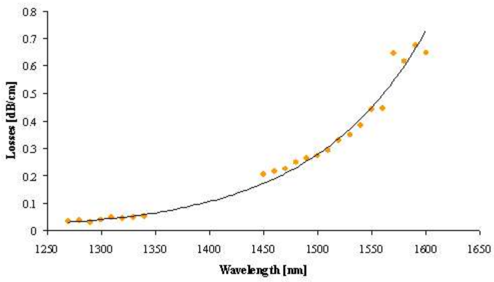

Figure 2: Propagation losses characteristic in function of wavelength.

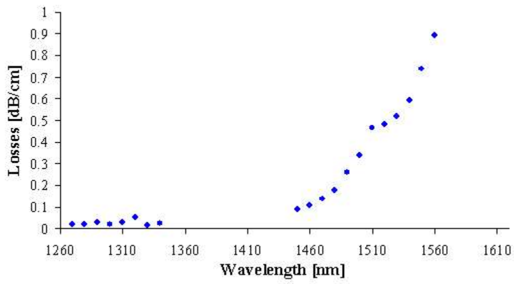

Figure 3: Polarization dependent losses in function of wavelength. Fiber maintain only one polarization mode for wavelength higher than 1500 nm.

Birefringence characteristics

Birefringence is defined as a difference between effective refractive indices of two fundamental polarization modes. From experimental point of view it is more practical to use beat length (L_B) define as follows:

$$L_B = \frac{2\pi}{\beta_x - \beta_y} = \frac{\lambda}{n_x - n_y} = \frac{\lambda}{B}, \qquad (1)$$

where β_x, β_y are the propagation constants of two orthogonal polarization modes, n_x, n_y are the effective refractive indices of each mode, λ is a wavelength and B – birefringence.

Numerical simulations of birefringence (and beat length) with plane wave method and their experimental verification with elasto-optic method is presented on fig. 4. Generally the experimental and numerical results follow similar trends. The discrepancies between simulations and experiments can be explained either by numerical errors, non precise estimation of fiber dimensions (pitch, hole diameter) or internal stresses in the fiber core not included in calculations. Nevertheless we proved that designed PCF exhibits much higher birefringence (approx. one order of magnitude) comparing with standard highly birefringent fibers like Panda or Bow-Tie fibers for longer wavelengths.

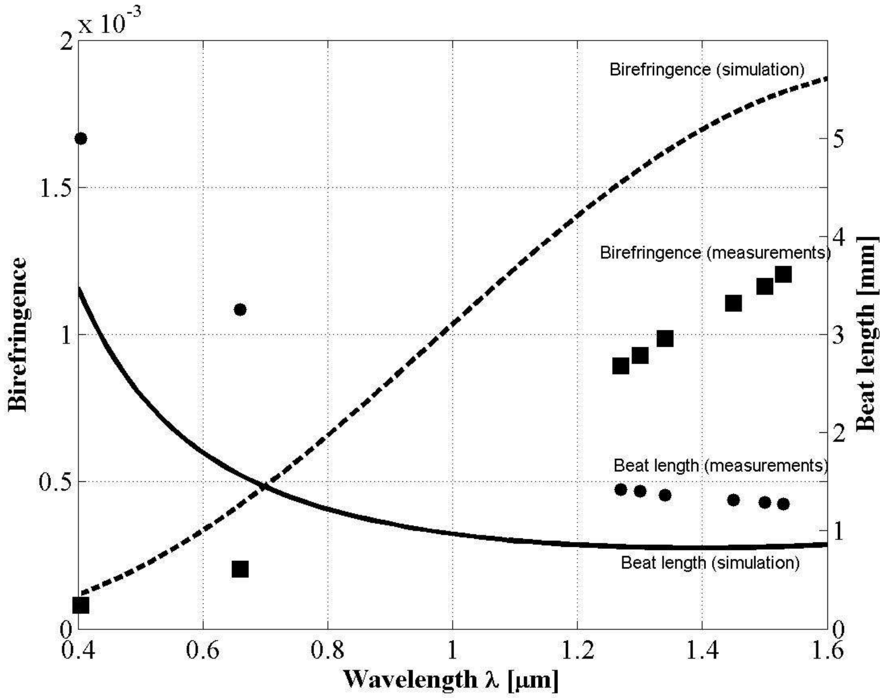

Figure 4: Birefringence and beat length vs. wavelength: calculated numerically (solid line – beat length, dashed line - birefringence), and measured experimentally (circles – beat length, squares - birefringence).

Temperature and strain sensitivities

Very high birefringence of PCF gives rights to expect also high sensitivities (changes of birefringence with a measured value) of this type of fiber used as a sensor. On the other hand lack of doped glass in the fiber core allows us to suspect very low temperature sensitivity due to zero difference of thermal expansion coefficients between core and cladding. In that case our PCF would be used as a mechanical sensor without temperature compensation mechanisms. Experiment and comparison with standard birefringent fibers presented in table 1 confirm the expectations.

Fiber type	**Temperature sensitivity [rad/m·K] (λ=633nm)**
HB 600 (bow-tie)	-8,0
Andrew E-type	-1,05
HB PCF	**~0,1**

Table 1: Comparison of temperature sensitivities for highly birefringent standard fibers and PCF.

Consecutively strain sensitivity (Fig. 5) appears to be relatively high and comparable with standard fibers (Table 2). Strain is defined as a ratio between a fiber elongation δL and its original length L:

$$\varepsilon = \frac{\delta L}{L} \quad (2)$$

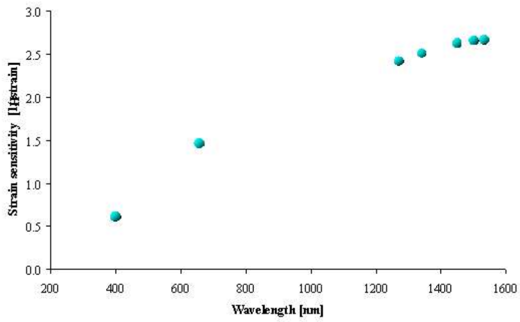

Figure 5: Strain sensitivity vs. wavelength.

Fiber type	Strain sensitivity [rad/m·mstrain] (λ=633nm)
Andrew E-type	5.7
Andrew D-type	7.0
HB 600 (bow-tie)	98.2
HB 800 (bow-tie)	118.6
PANDA SM 63	125.7
PANDA SM 85	165.3
HB PCF	**14**

Table 2: Comparison of strain sensitivities for highly birefringent standard fibers and PCF.

Conclusions

It was demonstrated, based on elasto-optical measurements, that very high birefringence ($>10^{-3}$ for longer λ) PCF was obtained by implementing two fold rotational symmetry of the cross section of the fiber. Trends of experimental characteristics confirm numerical simulations based on plane wave method. Very low temperature sensitivity proves to be negligible correction to relatively high strain sensor, i.e. temperature compensation would not be necessary. Finally, investigated PCF proved its polarizing ability for wavelengths larger than 1500 nm.

References

[1] J.C. Knight at. al., Opt. Lett. 21, 1547 (1996), 22, 484 (1997).

[2] J. Broeng, D. Mogilevstev, S.E. Barkou and A. Bjarklev, "Photonic Crystal Fibers: A New Class of Optical Waveguides", Optical Fiber Technology **5,** 305-330 (1999).

[3] J. Broeng, S.E. Barkou, T. Søndergaard, A. Bjarklev, "Analysis of air-guiding photonic bandgap fibers", *Opt Lett.* 25, 96-98 (2000)

[4] M. J. Steel and R. M. Osgood, Jr., "Elliptical-hole photonic crystal fibers", *Opt Lett.* 26, 229-231 (2001).

[5] M. J. Steel and R. M. Osgood, Jr., "Polarization and dispersive properties of elliptical-hole photonic crystal fibers", *J. Lightwave Technol.* 19, 495-503 (2001).

[6] A. Ortigosa-Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. St. J. Russell, "Highly birefringent photonic crystal fibers", *Opt Lett.* 25, 1325-1327 (2000).

[7] T. P. Hansen, J. Broeng, S. E. B. Libori, E. Knudsen, A. Bjarklev, J. R. Jensen, and H. Simonsen, "Highly birifringent index-guiding photonic crystal fibers", *IEEE Photonics Technol Lett* 13, 588-590 (2001).

[8] K. Suzuki, H. Kubota, S. Kawanishi, M. Tanaka, and M. Fujita, "Optical properties of a low-loss polarization-maintaining photonic crystal fiber", *Opt Express* 9, 676-680 (2001).

[9] W. J. Bock and W. Urbanczyk, "Measurements of polarization mode dispersion and modal birefringence in highly birefringent fibers by means of electronically scanned shearing type interferometry," Appl. Opt. **32,** 5841–5848 (1993).

[10] R. Kotynski et. al., Proc. of the Annual Symposium of the IEEE/LEOS Benelux Chapter, pp. 187-190, 2002.