Birefringent optical fiber with dispersive orientation of polarization axes

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Abstract: We demonstrate for the first time in optical fibers the “dispersion of the axes” phenomenon, which relies upon spectral dependence of polarization planes of the guided modes. This feature was achieved in a specially designed side-hole fiber by combining linear birefringence induced by a pair of holes located in the cladding and the elliptical core tilted with respect to the symmetry plane of the holes. We performed numerical simulations of this design properties. The side-hole fiber with a tilted core was fabricated and experimentally studied. The orientation of the principal polarization planes of the fundamental modes varied by 14.5° in the analyzed spectral range. This value is in a good agreement with the simulation results.

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1. Introduction

In this work we present for the first time in optical fibers the effect known in crystal optics as “dispersion of the axes” [1]. In crystals this effect is observed for monoclinic and triclinic symmetries. It relies on spectral dependence of principal axes orientation which results in variation of optical axes orientations against wavelength [1,2]. For example, in monoclinic Li$_2$SO$_4$·H$_2$O crystal, the orientation of the optical axes changes a few times in the infrared region from 2.6 to 40 $\mu$m [3] because of the interaction of an electromagnetic wave with phonons. “Dispersion of the axes” has been also reported in smectic liquid crystals [4], in which a rotation of the principal axes is about 1° over the visible spectral range and leads to contrast deterioration of liquid crystal light intensity modulators.

In optical fibers, the effect of “dispersion of the axes” manifests itself in spectral dependence of the principal polarization planes orientation. Fibers possessing such a new feature could be of interest for applications in nonlinear optics and distributed sensing. For example, one may expect new phenomena related to nonlinear vector frequency conversion processes in the fibers with polarization axes dispersion. Moreover, as the orientation of principal polarization axes can be tuned by external factors, new applications of such fibers can be also expected in distributed sensing based on polarization OTDR.

To achieve dispersion of the principal polarization axes in an optical fiber, we propose a special design of the side-hole fiber with birefringence induced simultaneously by the holes located in the vicinity of the elliptical core, which is tilted with respect to the symmetry plane of the cladding. We confirmed that fabrication of such fiber is feasible and experimentally demonstrated a rotation of the principal polarization axes by 14.5° over the spectral range from 500 to 1100 nm.

Highly birefringent (HB) fibers are used since the 1980’ for sensing applications. In conventional HB fibers, a phase modal birefringence exceeding $10^{-4}$ may be induced by elliptical shape of the core [5] or stress applying elements located symmetrically with respect to the core [6]. It is already well known that fibers with stress induced birefringence show little dependence of modal birefringence $B$ upon wavelength, while in elliptical core fibers $B$ reaches maximum at certain wavelength and gradually decreases for increasing wavelength. In both types of fibers, orientation of the principal polarization axes is defined by the symmetry planes of the fiber cross sections and is therefore wavelength independent.

The side-hole fiber with cylindrical core has been reported for the first time in [7] for application to hydrostatic pressure sensing. Since that time several variations of the initial design of the side-hole fiber were reported in literature, including addition of elliptical core to obtain greater birefringence [8], enlargement of the holes size to obtain greater polarimetric sensitivity to hydrostatic pressure and narrowing the glass bridge between the holes to induce unusual birefringence dispersion [9]. In the last case, thanks to stronger interaction of the fundamental mode with the boundaries of the holes, the phase modal birefringence increases against wavelength in the long wavelength range thus causing a sign change of the group modal birefringence at certain wavelength [10].

2. Birefringent fiber design and numerical analysis

In the proposed fiber design, schematically shown in Fig. 1, a germanium doped core of an elliptical shape is placed between two air holes, however, the symmetry axes of the elliptical core $(x', y')$ are rotated with respect to the symmetry axes of the fiber cladding $(x, y)$ by the angle $\theta$. As a result, principal polarization axes rotates against wavelength. In the short wavelength range at which the fundamental mode is well confined in the elliptical core and does not interact with the holes, the polarization axes are defined by the symmetry axes of the core ellipse $(x', y')$. For increasing wavelength the mode spreads deeper into the cladding and starts to interact stronger with the holes boundaries. As a result, an increase in the phase
modal birefringence is observed against wavelength as well as a gradual rotation of the principal polarization axes towards the symmetry axes of the cladding (x, y).

In order to evaluate the influence of the core tilt on dispersion of the polarization axes and modal birefringence, the numerical simulations were performed using the finite element method (FEM). It has been shown in [11] that significant part of modal birefringence in the elliptical core fiber is induced by

stress arising thanks to different thermal expansion coefficients of the pure silica cladding ($\alpha_{cl} = 5.3 \times 10^{-7} \text{K}^{-1}$ [12, 13]) and the GeO$_2$ doped core ($\alpha_{co} = 12.8 \times 10^{-7} \text{K}^{-1}$ for 6.5 mol% concentration of GeO$_2$ [12, 13]). When the fiber is cooled down below glass transition temperature ($T_g = 1100 ^\circ \text{C}$ [12]) during a drawing process, the difference in thermal expansion leads to appearance of stress, which gives rise to material birefringence in the core region. To account for this effect, we first calculated the thermal stress distribution arising during the drawing process. Knowing the local principal stress components $\sigma_i(x,y)$, $i = 1, 2, 3$, we were able to determine the stress-induced change in material refractive index $\Delta n_i = C_1 \sigma_i + C_2 (\sigma_j + \sigma_k)$, where $C_1 = -6.9 \times 10^{-13} \text{Pa}^{-1}$ and $C_2 = -41.9 \times 10^{-13} \text{Pa}^{-1}$ [11, 12], while $i, j, k$ denotes principal stress directions. Those directions are varying over the fiber cross-section and they define the local coordinate system in which the electric permittivity tensor $\varepsilon_{123}$ is diagonal. The stress corrections of the refractive index were used to determine electric permittivity tensor in the principal coordinate system. In order to obtain the electric permittivity tensor in x, y, z coordinates, we used the following transformation $\varepsilon_{xyz} = A^{-1} \varepsilon_{123} A$, where $A$ is a transformation matrix built of unit vectors of the local principal stress directions. In the second step, we calculated a field distribution in the fundamental polarization modes, effective refractive indices and orientation of the polarization axes accounting for the material birefringence induced by thermal stress. Both mechanical and optical calculations were performed for the set of geometrical parameters presented in Table 1 using the finite element method.

![Figure 1](image-url)

**Figure 1.** Cross-section of the side-hole fiber with tilted elliptical core. (a) Parameters defining the fiber geometry: $a$ and $b$ – major and minor axes of the elliptical core, $d$ – bridge thickness, $R$ – air hole radius, $\theta$ – angle between the symmetry plane of the cladding and the core. (b) Blue and red arrows indicate an orientation of the polarization axis of slow mode for short and long wavelength range, respectively, $\phi_b$ and $\phi_r$ denote angles between the polarization axis and the symmetry axis of the cladding for the corresponding wavelength range.

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<th>Table 1. Geometrical Parameters of the Side-hole Fiber with the Tilted Elliptical Core Used in Numerical Simulations</th>
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For sake of consistency, we define a phase birefringence as the difference in effective refractive indices of slow and fast polarization modes, namely $B = n_{\text{slow}} - n_{\text{fast}}$. Such definition does not depend on orientation of the polarization axes of the guided modes. We also calculated the spectral dependence of a group modal birefringence defined as $G = B - \lambda \frac{dB}{d\lambda}$ and the spectral dependence of the polarization azimuth $\phi$ of the slow mode with respect to the $x$ symmetry axis of the cladding. In order to evaluate the effect of stress on modal birefringence, we made two series of calculations. In the first one, we disregarded the material birefringence induced by thermal stress, so in this case the calculated birefringence is a result of only geometrical effects. In the second series of simulations, we took into account the corrections to the electric permittivity tensor related to thermal stress.

The results of simulations are presented in Fig. 2. For $\theta = 0^\circ$, the polarization plane of the slow mode is aligned in parallel to the core major axis and its orientation is wavelength independent. For $\theta = 90^\circ$, we observed a switching of the polarization axes at certain wavelength ($\lambda_B = 0$). Due to its definition, the phase birefringence is not a differentiable function of wavelength for $\theta = 90^\circ$ and consequently the group birefringence is discontinuous at $\lambda_B = 0$. In this case, however, the fiber polarization axes are wavelength independent and overlap with symmetry axes of the fiber cross-section ($x, y$). In this case the phase modal birefringence can be defined as a difference in effective indices of $x$- and $y$-polarized modes, namely $B = n_x - n_y$. Applying such definition of $B$ one obtains the dashed purple curves in Figs. 2(a)-2(d), which are continuous and smooth.

For the tilted core ($0^\circ < \theta < 90^\circ$), the gradual rotation of the fiber polarization axes against wavelength was observed, Figs. 2(e) and 2(f). In general the value of $\theta$ limits a rotation range of the fiber polarization axes, since in the short wavelength limit $\phi \rightarrow \theta$ and in the long wavelength limit $\phi \rightarrow 0^\circ$. In the analyzed spectral range from 500 to 1100 nm, the rotation of the polarization axes is 78.9$^\circ$ for $\theta = 85^\circ$ (from 83.2 @ 500 nm to 4.3 @ 1100 nm) and 5.1$^\circ$ (from 12.6 @ 500 nm to 7.5 @1100 nm) for $\theta = 15^\circ$, when the stress is taken into account in the simulations.
Moreover, accounting for the thermal stress results in the increase of the modal birefringence and the shift of \( \lambda_{B=0} \) from 695 nm to 855 nm. The reasons for the two effects are as follows. The principal directions of the stress birefringence in the core region overlap with the ellipse symmetry axes \((x', y')\) and as a result, the phase modal birefringence increases when the thermal stress is taken into account in the simulations. Yet stronger interaction of the fundamental modes with the holes boundaries is needed to compensate for this increase, which pushes \( \lambda_{B=0} \) towards longer wavelengths.

3. Experimental results

In order to confirm experimentally the effect of dispersion of polarization axes, we fabricated by the stack and draw method the side-hole fiber with a tilted core doped with GeO\(_2\) (doping level of 6.5 mol\%). The cladding was stacked from Heralux F300 silica rods. The holes were obtained by leaving the empty spaces during the preform stacking and then by applying pressure during the fiber drawing process. To make the elliptical core, we used Ge doped rods fabricated by MCVD method. The undoped external layers of these rods were removed by etching in fluoric acid. Because doped silica glass has lower viscosity and lower softening temperature than pure silica, the germanium doped glass penetrated free spaces between pure silica rods during the drawing process. As a result, the core boundary in the fabricated fiber is rigged. In Fig. 3, we show an image of the fiber cross-section obtained in the scanning electron microscope and the post-processed picture showing the edges of the fiber core and the holes. This picture was then used to reproduce the real geometry of the fiber in the finite element model. In Figs. 3(c) and 3(d) we show the calculated field distributions in the fundamental slow mode at \( \lambda = 500 \) nm (c) and \( \lambda = 900 \) nm (d).

![Fig. 3](image1.jpg)

Fig. 3. (a) SEM image of the fabricated fiber, (b) subdomains of numerical model: white – air, grey – silica, dark grey – doped core, (c, d) normalized field distributions in slow mode; arrows indicate orientation of polarization planes at \( \lambda = 500 \) nm (c) and \( \lambda = 900 \) nm (d).

![Fig. 4](image2.jpg)

Fig. 4. Schematic diagram of the experimental setup for measuring dispersion of polarization axes; SC – supercontinuum source, P – rotatable polarizer, O – microscope objective, A – rotatable analyzer with transmission azimuth perpendicular to the polarizer; length of the fiber used in the experiment was \( L = 1072 \) mm.

silica glass has lower viscosity and lower softening temperature than pure silica, the germanium doped glass penetrated free spaces between pure silica rods during the drawing process. As a result, the core boundary in the fabricated fiber is rigged. In Fig. 3, we show an image of the fiber cross-section obtained in the scanning electron microscope and the post-processed picture showing the edges of the fiber core and the holes. This picture was then used to reproduce the real geometry of the fiber in the finite element model. In Figs. 3(c) and 3(d) we show the calculated field distributions in the fundamental slow mode at \( \lambda = 500 \) nm and \( \lambda = 900 \) nm with arrows indicating the polarization planes.

The fiber properties were examined in the setup shown in Fig. 4. The output signal was registered using a spectrometer or an optical spectrum analyzer in the spectral range from 500 to 1100 nm. In the first step, using the inspection scope, we aligned the holes vertically at both fibers ends. Then a rotatable polarizer and analyzer were placed respectively at the fiber input and output to measure the dispersion of the fiber polarization axes. One should note that when the crossed polarizer and analyzer are rotated with respect to the fiber polarization axes, the contrast of spectral interference fringes drops to zero at wavelength, at which the orientation of the fiber axes matches the transmission directions of the polarizer and the analyzer. As it is shown in Fig. 5, by rotating the crossed polarizer and analyzer, one can extinguish the interference fringes at successive wavelengths and determine the angular
position of the fiber polarization axes with a precision of ± 1°. Using such a procedure, we measured the spectral dependence of the fiber polarization axes in the spectral range from 500 nm to 1050 nm. We also determined the polarization extinction ration, which is 30 dB in the range from 800 nm to 1100 nm for the fiber of length \( L = 1072 \text{ mm} \).

On the other hand, it is also possible to set the transmission azimuth of the analyzer in such a way that both polarization modes are excited in the whole wavelength range, Fig. 5. In this case, the spectral interference fringes of good contrast are observed at the fiber output in the whole spectral range. This allows to apply a well-known spectral interferometry method [14] to measure the group birefringence in the investigated fiber. The spectral dependence of the phase birefringence was measured by combining the spectral interferometry method and the lateral force method as described in [15].

A comparison of the measured and the calculated birefringence and azimuth of the polarization axis of the slow mode is presented in Fig. 6. The numerical simulations taking into account the stress effect were conducted for the spectral range, in which the confinement losses are lower than 1 dB/m, as illustrated in Fig. 7. The losses were estimated using impedance boundary conditions (IBC) for the stressed fiber. For phase and group birefringence the agreement between the measured and the calculated values is relatively good. The observed discrepancies are most probably caused by random changes in core geometry along the fiber length and uncertainties in SEM image post-processing. The conducted experiment confirms the effect of polarization axes dispersion predicted by numerical simulations. The measured average value of the axes dispersion is \( 2.6°/100 \text{ nm} \) in the spectral range of 500 nm – 1050 nm, while the numerical value is about \( 1.6°/100 \text{ nm} \).

Fig. 5. (a) Orientation of the polarizer (\( P_{\phi} \)) and the analyzer (\( A_{\phi=90°} \)) during measurement of the polarization planes dispersion; \( \lambda \) arrow indicates rotation of the polarization plane against wavelength; \( P_G \) and \( A_G \) indicate orientation of the polarization cross during group birefringence measurements. (b) Spectrograms registered at the fiber output using OSA; top (black) line was obtained for the polarizer and the analyzer set respectively at \( P_G \) and \( A_G \) (dashed line indicates position of zero group birefringence, \( \lambda_G = 0 \)), the middle (blue) and bottom (red) spectrograms were obtained for \( P_{\phi} \) and \( A_{\phi=90°} \); the minimum in fringe contrast is observed for \( \phi = 7.5° \) at 845 nm and for \( \phi = 4.5° \) at 1040 nm (minimum contrast wavelength indicated with dashed line).

Fig. 6. Comparison of experimental and numerical results for the fabricated fiber: (a) phase and group birefringence, (b) spectral dependence of the polarization plane of the slow mode.
4. Conclusions

By combining two different mechanisms of birefringence generation, we demonstrated for the first time the effect of polarization axes dispersion in optical fibers. This unusual property of the proposed fiber may lead to new physical phenomena and applications. The orientation of the polarization axes in the proposed fiber can be varied by external physical parameters (especially by hydrostatic pressure), which in turn may induce local coupling between the polarization modes easily detectable using the polarization OTDR technique. Therefore, it seems possible to apply the proposed fiber to distributed pressure sensing by exciting at the fiber input one polarization mode and monitoring the polarization state of the back reflected signal.

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