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# Determination of group and phase birefringence dispersion of Hi-Bi optical fiber using a broadband light source

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## ABSTRACT

The paper deals with the determination of group and phase birefringence of an experimental highly birefringent (Hi-Bi) optical fiber across a wide wavelength span ranging from 1200 nm to 1700 nm. Several approaches for birefringence determination are used and the results are discussed. For the investigation, a set of two plane polarizers, a broadband light source, and an optical spectrum analyzer are used. The front face of the Hi-Bi fiber is illuminated by a linearly polarized light from a broadband light source and the end face of the fiber is connected to a fiber plane polarizer. At the output of the fiber plane polarizer, a typical spectrum – an interference pattern consisting of a quasi-periodic distribution of maxima and minima is measured by an optical spectrum analyzer. From the positions of subsequent minima of the interference pattern measured by the optical spectrum analyzer, the group birefringence dispersion is determined. The mean value obtained is in good agreement with that calculated from a differential group delay. The phase birefringence dispersion is determined by finding the appropriate dispersion functions representing the phase birefringence by fitting the measured spectrum to a calculated one, as the character of the spectrum depends on the phase birefringence.

**Keywords:** Birefringence, Hi-Bi optical fiber, birefringence dispersion, group birefringence, phase birefringence

## 1. INTRODUCTION

In a Hi-Bi optical fiber, a linearly polarized light wave entering the fiber is decomposed into two linearly polarized eigenmodes that propagate through the fiber with different velocities, resulting in a change of polarization state of the wave after traveled distance  $L$ . This change is well defined and stable along the whole fiber, enabling the fiber's utilization in many applications requiring that the output state of polarization (SOP) must remain unchanged or, at least, well under the control. In reality, external conditions such as temperature, fiber bending, or micro bending due to applied forces or change of pressure induce stress or strain inside the fiber, resulting in the change of SOP. The change of SOP is described by a quantity called birefringence, which is the difference between refractive indices of linearly polarized eigenmodes propagating through the fiber. The measurable impact of the external physical quantities such as temperature, atmospheric pressure, ultrasound, magnetic field, electric current, force, etc. on the fiber's birefringence can be used for their sensing<sup>1-8</sup>. Recently, also various birefringent photonic crystal fibers (PCF) have emerged, and possible sensing applications have been discussed stemming from their unique mechanical and optical properties<sup>9-13</sup>.

Since the Hi-Bi fiber, in general, can be used with any source of light, it is important to possess knowledge on the birefringence dispersion in a wavelength band as broad as possible. Moreover, in the case of an application utilizing the broadband source of light we have to be careful to distinguish between phase ( $B$ ) and group ( $B_g$ ) birefringence of the fiber in general, as well. Therefore, in the paper, we focus on investigation leading to the determination of the group and phase birefringence of the fabricated Hi-Bi fiber. Recently, we have investigated group birefringence of the Hi-Bi fiber in the rather narrow wavelength range around 1550 nm using several approaches<sup>14</sup>. Since the results showed the appropriateness of the investigation and evaluation methods, we decided to determine the group birefringence in a wider wavelength range and extend our investigations also to the phase birefringence in such a wide range of wavelengths.

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## 2. EXPERIMENT

The investigated experimental Hi-Bi fiber was prepared at Xlim Research Institute. The cross-section of the fiber is shown in Fig. 1. The radius  $b$  of the cladding is  $70.015\ \mu\text{m}$  and the diameter of the germanium doped core equals  $8.5\ \mu\text{m}$ . There are two Stress Applied Parts (SAPs) with diameters  $2R = 24.15\ \mu\text{m}$  composed of a silica-based glass called SAL ( $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-La}_2\text{O}_3$ ) with 70 % mol  $\text{SiO}_2 + 20\ \%$  mol  $\text{Al}_2\text{O}_3 + 10\ \%$  mol  $\text{La}_2\text{O}_3$  located aside the core. The distance  $d$  from the center of SAP to the center of the core is  $38.36\ \mu\text{m}$ .

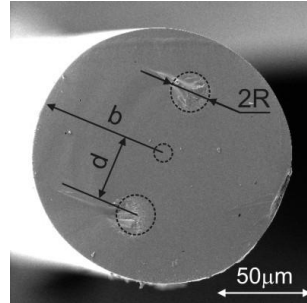


Figure 1. Hi-Bi fiber cross-section. The radius of the cladding  $b = 70.015\ \mu\text{m}$ , the radius of the SAP  $R = 12.075\ \mu\text{m}$ , and the distance between the fiber core and the SAP's center  $d = 38.36\ \mu\text{m}$ .

The birefringence of the fiber was investigated by the experimental setup based on the arrangement of the polarizing elements as known in polarimetry (Fig. 2). Light from a supercontinuum laser light source Leukos (wavelength range  $550 - 1900\ \text{nm}$ , average power  $200\ \text{mW}$ ) was coupled to an optical fiber plane polarizer via the coupling optics and standard single-mode optical fiber SMF28. For polarizing light entering the Hi-Bi fiber and analyzing the polarization state of light emerging from the fiber, we used a set of two plane polarizers (OZ Optics Ltd.) integrated with single-mode fiber and designed for the central wavelength  $1550\ \text{nm}$  with a possibility to change the polarization state of light by rotating the polarizer in  $360^\circ$  in the plane perpendicular to the fiber axis. The investigated fiber was placed between two single-mode fibers and for their alignment, Hi-Bi fiber's ends were fixed on the 3-axis stages with sub-micron resolution, NanoMax 300 (Thorlabs). Due to the sensitivity of the Hi-Bi fiber to the temperature changes, the fiber and both stages were isolated from the ambient environment. The spectrum at the output optical fiber polarizer (denoted as A in Fig. 2) was measured by an optical spectrum analyzer (Anritsu MS9710B) with  $0.07\ \text{nm}$  resolution. The measurements were performed at room temperature and normal atmospheric pressure for two lengths of the tested fiber samples  $L_1 = 50\ \text{cm}$  and  $L_2 = 254\ \text{cm}$ .

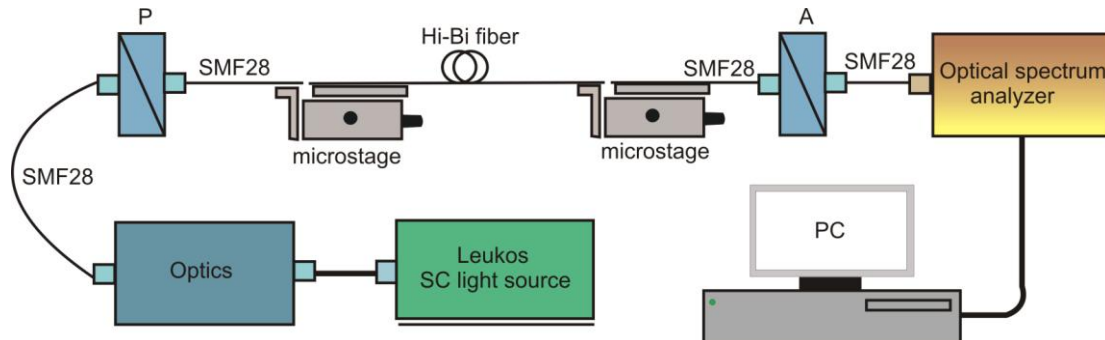


Figure 2. The experimental setup for investigation of a Hi-Bi fiber's group and phase birefringence.

The mutual positions of the planes of polarization of the input and output polarizers were set appropriately to observe the typical spectral distribution of intensity, i.e. interference pattern at the output of the single-mode fiber with an integrated polarizer. Figures 3a and 3c show the spectra measured for Hi-Bi fiber samples with lengths  $50\ \text{cm}$  and  $254\ \text{cm}$ , respectively. The measured spectra were normalized (Fig. 3b, 3d) and used for the evaluation of group and phase birefringence dispersions, after that. The group birefringence was determined from the positions of minima and maxima in the normalized spectra and the phase birefringence function was found according to fitting the calculated spectrum to the measured one. A slightly noisy character of the spectrum is due to a two-mode regime below  $1300\ \text{nm}$  and OH-ion absorption around  $1400\ \text{nm}$ .

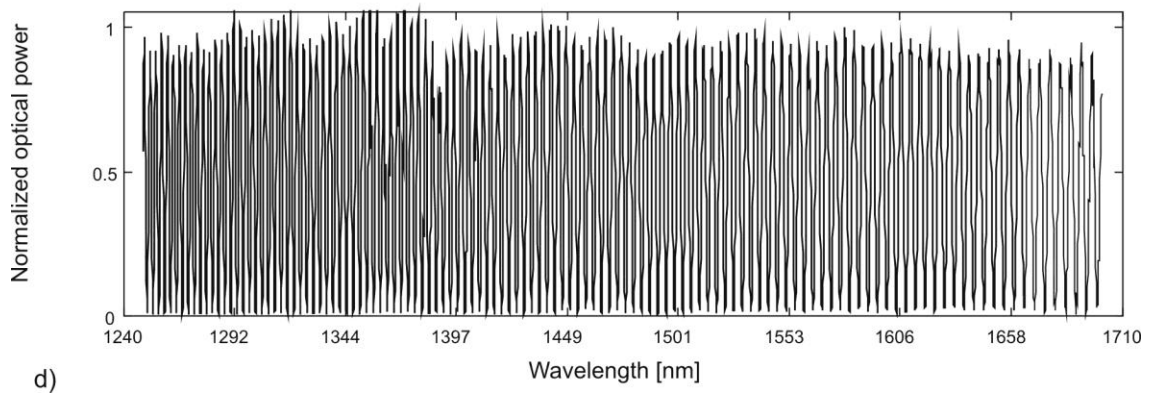
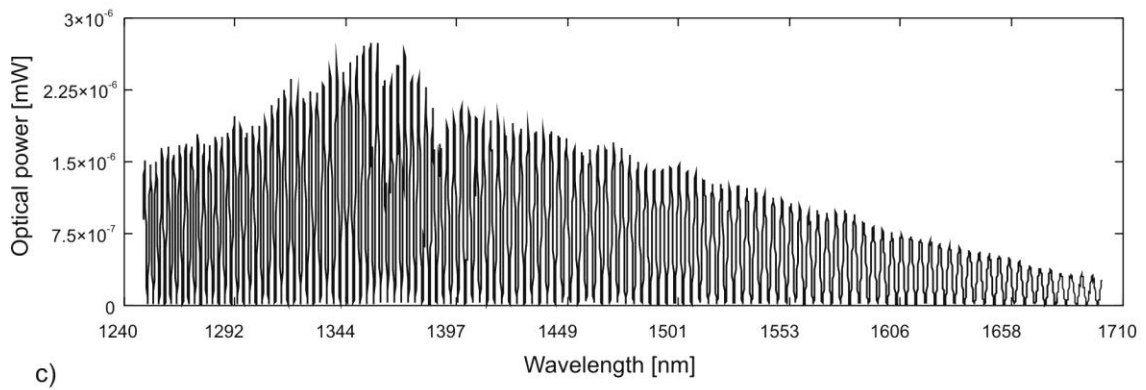
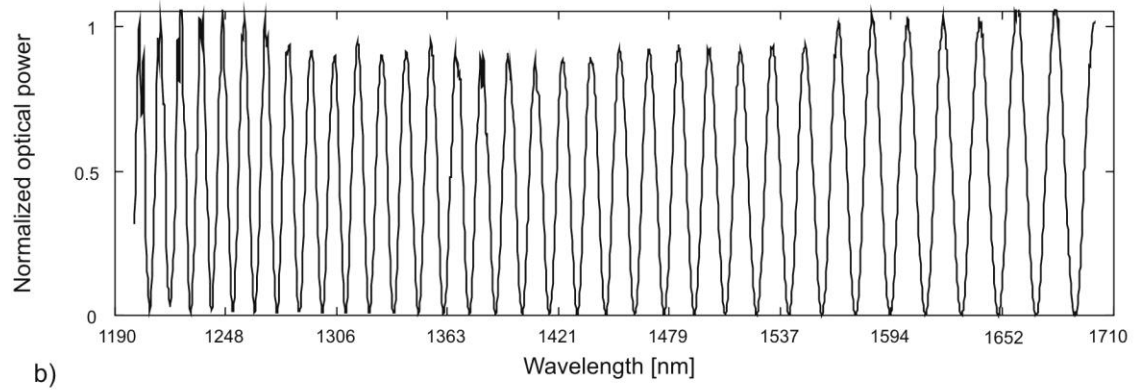
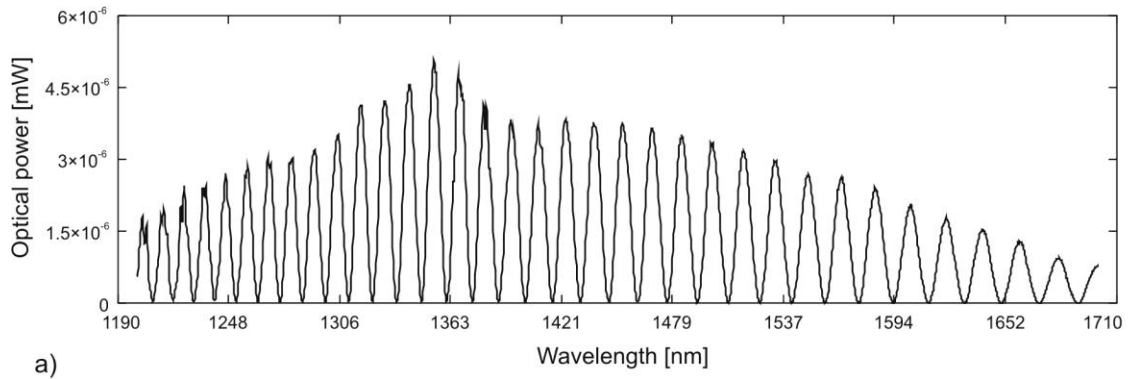


Figure 3. Measured and normalized optical spectra detected at the output of the single-mode fiber with an integrated polarizer for lengths of the fiber sample 50 cm (a, b) and 254 cm (c, d).

### 3. RESULTS AND DISCUSSION

The optical wave traveling through the Hi-Bi optical fiber is decomposed into two eigenmodes with assigned refractive indices different from each other. At the plane polarizer placed behind the investigated optical fiber, the eigenmodes recombine however, the polarizer transmits only the components parallel to the polarizer's plane of polarization. These transmitted parallel components with mutual phase difference interfere with each other, and the optical spectrum containing interference minima and maxima can be observed.

#### 3.1 Group birefringence dispersion

The group birefringence dispersion  $B_g$  can be evaluated from the measured spectrum by determining the positions of minima or maxima observed within the spectrum according to a relationship stemming from a condition for observing minima or maxima of two waves' interference<sup>15</sup>

$$B_g = \frac{\lambda_i \cdot \lambda_j}{(\lambda_i - \lambda_j) \cdot L}, \quad (1)$$

where  $L$  is the fiber length and  $\lambda_i$  and  $\lambda_j$  are the wavelengths corresponding to two successive minima or maxima in the spectrum. In the spectra, we identified the wavelengths corresponding to minima and calculated the group birefringence of the fibers according to Eq. (1). The resulted values of group birefringence for fiber lengths 50 cm and 254 cm are shown in Fig. 4a and 4b, respectively.

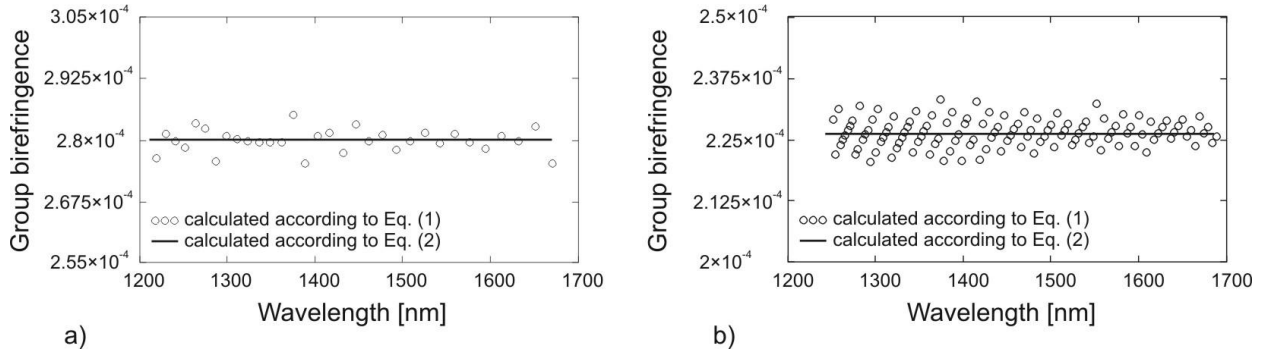


Figure 4. Group birefringence of the experimental Hi-Bi optical fiber determined from positions of minima of the optical spectrum (blank circles) according to Eq. (1) and calculated from the optical spectrum using differential group delay approach according to Eq. (2) for fibers with lengths 50 cm (a) and 254 cm (b).

The group birefringence can be determined from the measured spectrum also using the differential group delay approach based on the relationship between differential group delay  $\Delta\tau$  and the optical path difference, i.e.  $\Delta\tau \cdot c = B_g \cdot L$ , where  $c$  is the speed of light in vacuum<sup>16</sup>. Thus, for the group birefringence of the fiber, we can write

$$B_g = \frac{k \cdot N \cdot \lambda_b \cdot \lambda_e}{(\lambda_b - \lambda_e) \cdot 2L}, \quad (2)$$

where  $k$  stands for a dimensionless mode-coupling factor statistically accounting for the wavelength dependence of the polarization states<sup>16</sup>,  $N$  is the number of extrema observed between the beginning and the end of the chosen wavelength span ( $\lambda_b$ ,  $\lambda_e$ ) and  $L$  is the length of the fiber. The value of group birefringence calculated according to Eq. (2) is plotted as a solid line in Fig. 4. It can be seen that the value obtained from Eq. (2) can be considered a mean value of the group birefringence in the investigated wavelength range.

#### 3.2 Phase birefringence dispersion

When a uniaxially birefringent medium is placed between two plane polarizers with mutually crossed polarization planes and illuminated by polychromatic light, the spectral distribution of intensity observed behind the output polarizer will be a function of wavelength, the thickness of the medium, and the phase birefringence<sup>17</sup>. The investigated highly birefringent optical fiber can be considered such a uniaxially birefringent medium with the phase birefringence  $B$  and the

thickness corresponding to the fiber length  $L$ . For the spectral distribution of intensity,  $I(\lambda)$  detected at the output plane polarizer we can write<sup>17</sup>

$$I(\lambda) \propto \left\{ \sin \left[ \frac{\pi \cdot L}{\lambda} \cdot B(\lambda) \right] \right\}^2. \quad (3)$$

In Eq. (3) the phase birefringence  $B$  is written as a function of wavelength as the material of the fiber is, in general, a dispersive medium. The phase birefringence of the fiber can be obtained by putting an appropriate form of function  $B(\lambda)$  into Eq. (3) to find the best fit of the calculated normalized spectral distribution of intensity to the normalized measured spectrum.

One of the simplest dispersion functions describing refractive indices of nonabsorbing (very low absorbing) materials is the two-term Cauchy dispersion formula. Describing the refractive indices of eigenmodes propagating through the fiber by these formulae and using the definition of birefringence we get the Cauchy dispersion formula for the birefringence in the form

$$B(\lambda) = A_1 + \frac{10^4 \cdot B_1}{\lambda^2}, \quad (4)$$

where  $\lambda$  is given in nanometers. It follows from Eq. (3) that minima in the spectrum will be observed when condition  $\pi \cdot L \cdot B(\lambda) / \lambda = m\pi$  is fulfilled, where  $m$  is an integer denoting the order of the minimum in the spectrum<sup>18,19</sup>. Using Eq. (4) the condition leads to

$$A_1 \cdot \frac{L}{\lambda} + \frac{10^4 \cdot B_1}{\lambda^3} \cdot L = m + k, \quad (5)$$

where  $k$  is the number of distinguished minima in the observed spectrum<sup>18,19</sup>. Parameters  $A_1$ ,  $B_1$ , and  $m$  can be determined by fitting the dependence of the minimum order on its position in the spectrum by Eq. (5). The result of fitting the dependence of the minimum order on wavelength for two fiber lengths is shown in Fig. 5

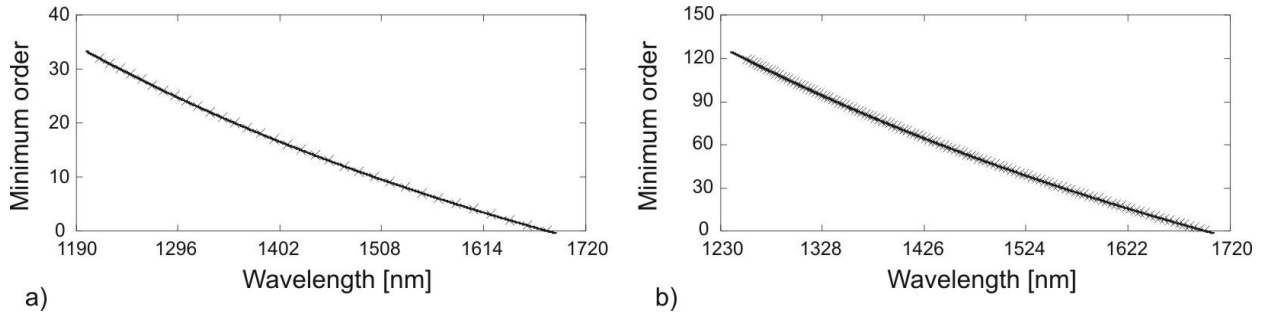
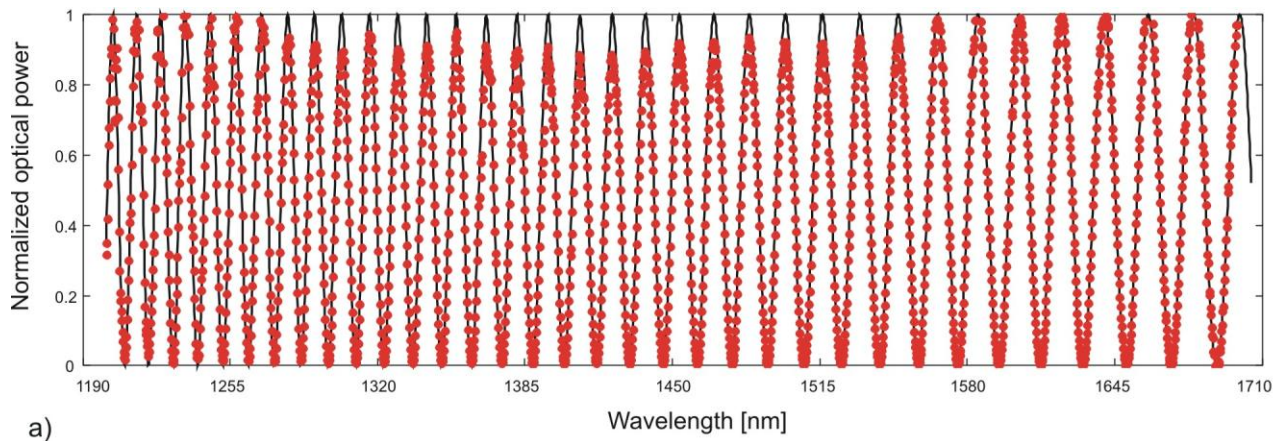


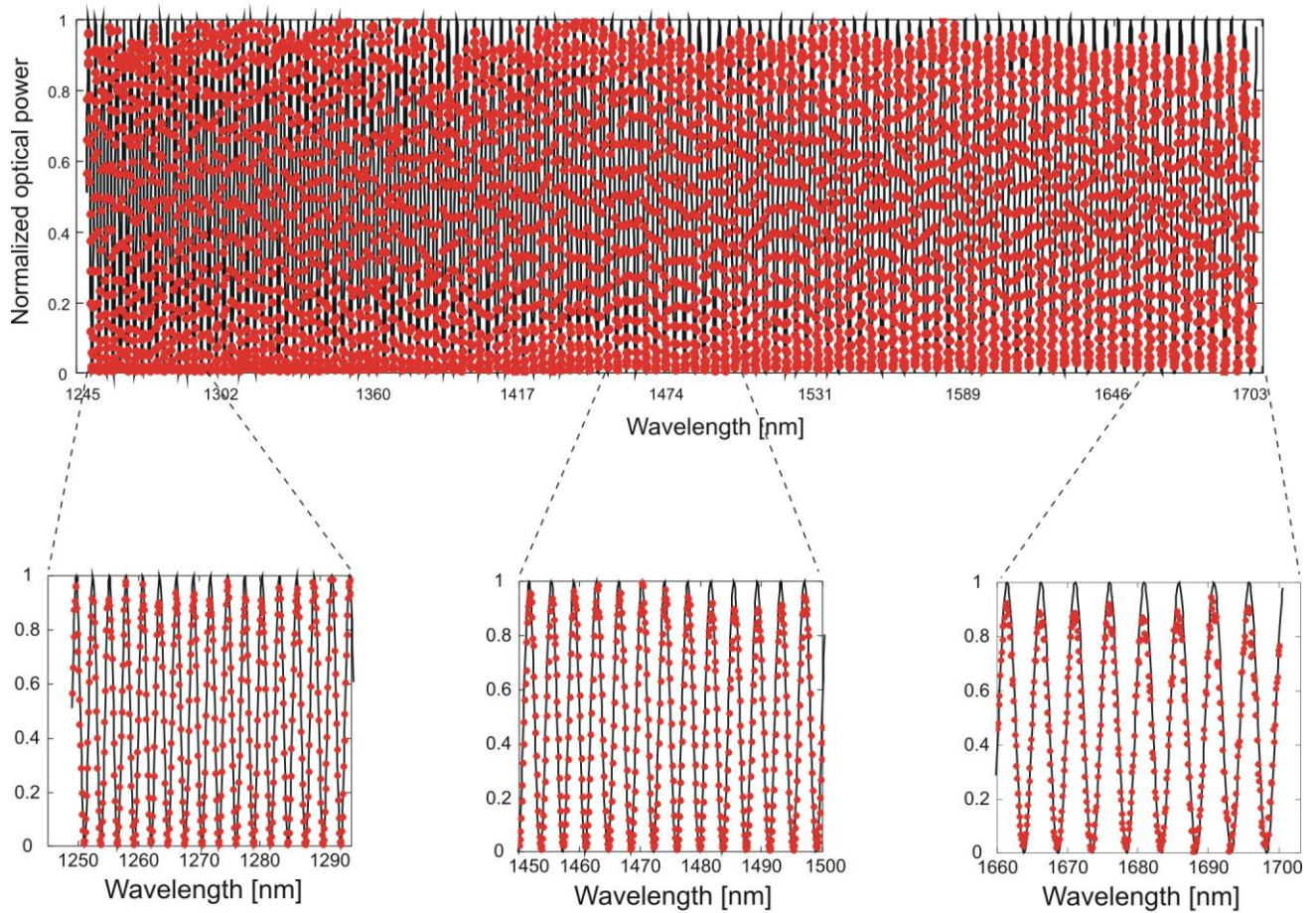
Figure 5. Dependence of the minimum order on wavelength obtained from the optical spectra measured for fiber lengths 50 cm (a) and 254cm (b). Crosses represent measured data and the solid line represents the fitting curve.

Once the parameters  $A_1$  and  $B_1$  are known, the phase birefringence dispersion can be calculated according to Eq. (4). However, the values of the parameters were determined using the number of distinguished minima within the spectrum, only. The whole spectrum contains many more measured points so it is expected to get a bit precise values of the parameters  $A_1$  and  $B_1$  by fitting the Eq. (3) to the whole measured spectrum. In that case, the values  $A_1$  and  $B_1$  determined by the preceding step can be considered the initial values for the next fitting process. The result of fitting the normalized measured spectrum by that calculated according to Eq. (3) containing the phase birefringence  $B(\lambda)$  according to Eq. (4) is shown in Fig. 6. As can be seen, there is an excellent match between measured and calculated dependence for the considered phase birefringence function in the form of the Cauchy formula with determined parameters  $A_1$  and  $B_1$ . This holds also for the spectrum measured for the fiber with the length of 254 cm. As the number of extrema within the spectrum is much higher here and plotted curves are too close to each other, we show selected parts of the spectrum by zooming in to see that an excellent match between calculated and measured dependences is obtained in this case, too.





a)



b)

Figure 6. Spectral dependences of the normalized optical powers calculated from the measured spectra (red dots) versus those obtained by fitting (solid line) according to Eq. (3) for fiber lengths 50cm (a) and 254cm (b).

Since the investigated Hi-Bi fiber possesses the geometry of the birefringent PANDA fiber, the phase birefringence of the fiber can be expressed employing the physical properties of the materials the fiber consists of and the geometrical parameters of the produced fiber<sup>20</sup>

$$B = \frac{2CE\Delta\alpha\Delta T}{1-\nu} \cdot \left(\frac{R}{d}\right)^2 \cdot \left[1 - 3\left(\frac{d}{b}\right)^4\right] = K \cdot \left(\frac{R}{d}\right)^2 \cdot \left[1 - 3\left(\frac{d}{b}\right)^4\right], \quad (6)$$

where the parameters  $C$ ,  $E$ ,  $\nu$  are the stress-optic coefficient, Young's modulus, and the Poisson's ratio, respectively,  $\Delta\alpha$  is the difference of the thermal expansion coefficients between the cladding and the SAP's, and  $\Delta T$  is the temperature difference between the room temperature and softening temperature of the pure silica glass<sup>20</sup>. The geometrical parameters  $R$ ,  $b$ ,  $d$  are the radius of SAP, the radius of cladding, and the distance from the center of SAP to the core, as already introduced in Fig. 1. The parameters in Eq. (6) representing physical properties can be expressed by a constant  $K$ , the order of which can be estimated using the typical values of these parameters that can be found elsewhere<sup>21-24</sup>. After putting Eq. (6) into Eq. (3) we tried to find the best fit with the measured spectrum. As the geometrical parameters were known, the  $K$  was the only parameter undergoing the fitting process. However, no reasonable agreement between measured and calculated spectrum was achieved. We did not succeed even if we let the length of the fiber be fitted, as well.

When looking at the phase birefringence expressed by Eq. (6), it is clear that the wavelength dependence is not included. The term expressing the wavelength dependence can be introduced when we consider there are nonzero fiber initial inelastic twist<sup>25</sup> and/or twist of the fiber present at its placing, leading to birefringence that can be expressed by the term  $B_c(\lambda) = B_{c0} + (\lambda/\pi L)\alpha$ , where  $\alpha$  is the initial twist angle. After incorporating this additional term into Eq. (6) and running the fitting process again, with  $K$ ,  $L$ ,  $B_{c0}$  and  $\alpha$  being the parameters to be fitted, we achieved an excellent agreement between the measured and calculated spectrum for reasonable values of the fitting parameters. The match is so good that after plotting, the situation cannot be distinguished from that shown in Fig. 6. When phase birefringence is calculated according to Eq. (6) amended with the term  $B_c(\lambda)$  using values of the parameters obtained by fitting, we get phase birefringence dispersion which is plotted in Fig. 7.

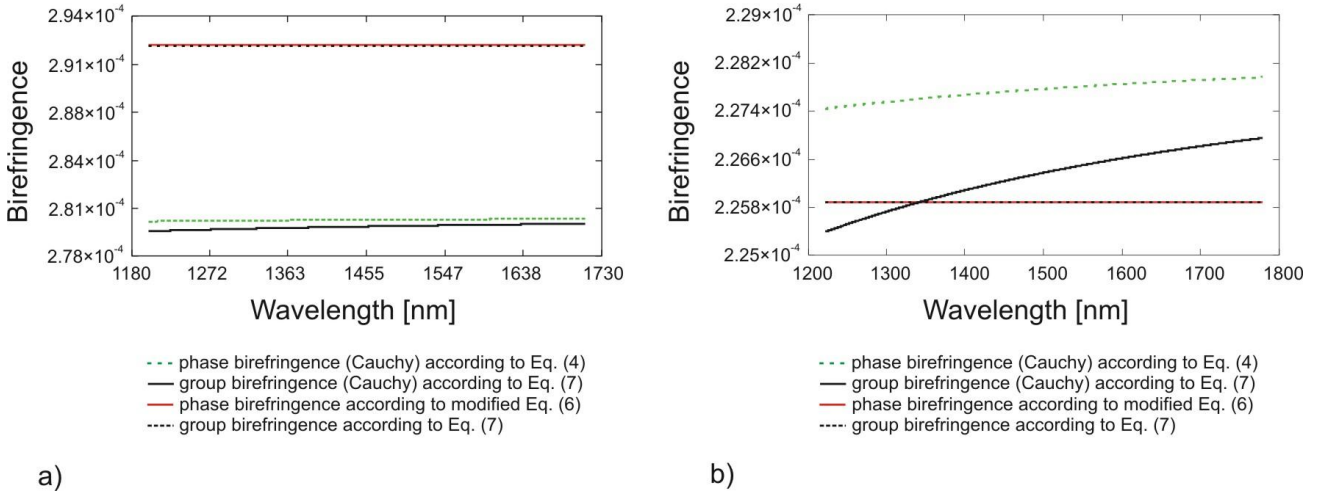


Figure 7. Group and phase birefringence of the Hi-Bi fiber with length 50 cm (a) and 254 cm (b) calculated according to Eqs. (4), (6), and (7).

In Fig. 7 there is plotted also the group birefringence dispersion which is calculated from obtained phase birefringence dispersion according to well-known relationship<sup>25</sup>

$$B_g(\lambda) = B - \lambda \cdot \frac{dB}{d\lambda}. \quad (7)$$

For comparison, Fig. 7 also shows the phase birefringence dispersion calculated according to the Cauchy dispersion formula (Eq. (4)) and group birefringence dispersion calculated from it according to Eq. (7). It can be seen that the difference between phase and group birefringence dispersions of the investigated fiber is quite low in the whole investigated spectral region. It is of the order of  $10^{-6}$  in case the phase birefringence dispersion is determined using the Cauchy dispersion formula and  $10^{-9}$  when phase birefringence dispersion is described by the Eq. (6) amended with the



wavelength-dependent term  $B_c(\lambda)$ . Values of the birefringences correspond very well with those obtained in our previous work for different fiber lengths<sup>14</sup>.

#### 4. CONCLUSION

In the paper, we investigated the group and phase birefringence of the highly birefringent optical fiber fabricated at Xlim Research Institute, France, and in a wide spectral range. The birefringence was determined by analyzing the spectrum measured at the output of the birefringent fiber placed between two plane polarizers with mutually crossed planes of polarizations. For the determination of birefringence dispersion the polychromatic source of light was employed. The group birefringence dispersion was determined from found positions of minima within the spectrum and the known length of the fiber, and the known number of extrema observed within the investigated spectral range using the relationship between the differential group delay and the group birefringence, as well. The phase birefringence dispersion was determined by fitting the normalized measured spectrum by a calculated one. For calculation of the spectrum, we used the phase birefringence in form of the two-term Cauchy dispersion formula and form containing physical parameters of the material of the fiber and the geometrical parameters of the fiber, as well. An excellent match between the measured and calculated spectra was achieved, however, in the latter case we had to introduce a wavelength-dependent term into phase birefringence expression. Nevertheless, the result shows that the wavelength dependence of the phase and group birefringence is rather weak in the whole investigated spectral range. Also, the difference between the values of the phase and group birefringence is very small. So, for this fiber, the need for distinguishing between them is not critical. The investigation was performed for two different fiber lengths and showed that the value of the birefringence determined for longer fiber is, in general, lower than that for shorter fiber. This is probably due to different conditions at placing the shorter and longer fiber samples in the space between optical fiber plane polarizers.

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