Group birefringence cancellation in highly birefringent photonic crystal fibre at telecommunication wavelengths

P. Morin, B. Kibler, J. Fatome, C. Finot and G. Millot

The spectral dependence of the group modal birefringence in a highly birefringent nonlinear photonic crystal fibre is studied both numerically and experimentally. The sign inversion and the cancellation of the group modal birefringence in the telecommunication window is demonstrated. Two simple experimental techniques are used to evaluate the wavelength of zero polarisation mode dispersion. The experimental results are in excellent agreement with numerical calculations based on vectorial beam propagation method simulations.

Introduction: Since their emergence in the past decade, photonic crystal fibres (PCFs) have stimulated major progress in linear and nonlinear guided optics by offering outstanding flexibility in the design of the group-velocity dispersion and nonlinear characteristics [1]. Birefringence properties can also be precisely tailored and extremely high built-in birefringence has been reported by breaking the standard perfect sixfold symmetric core and cladding structure [1]. Such polarisation-maintaining (PM) PCFs have been decisive for several fibre-based applications such as lasers, interferometers and supercontinuum sources [2–4]. However, several researchers have stressed that the induced form birefringence characteristics in such PCFs may exhibit a strong wavelength dependence [5], leading to significant variations of the group modal birefringence over a short wavelength range. Recently, Martynkien *et al.* have also demonstrated that group birefringence can cross zero value near 880 nm in highly birefringent (HiBi) microstructured fibre with elliptical GeO_2 doped inclusion in the core [6]. In addition, numerical investigations have shown that complex PCFs with composite form and stress birefringence are convenient to manage the wavelength dependence of both phase and group birefringences [7].

In this Letter, we describe for the first time the inversion of the sign of the group modal birefringence in the telecommunication window by using a commercially available standard HiBi-PCF. With the help of two simple experimental techniques, we demonstrate a zero value of group modal birefringence (zero polarisation mode dispersion) near 1570 nm, i.e. across this wavelength the sign of group birefringence changes. From comparison with numerical simulations, we are able to validate these experimental results, thus having important consequences for the design of PCF-based devices that rely on polarisation-dependent nonlinear effects.

Experiments: The basic parameters required to investigate light propagation in HiBi-PCF, are the phase birefringence $B = (n_{eff,x} - n_{eff,y})$, and the group birefringence $G = (n_{g,x} - n_{g,y})$, where $n_{eff,x}$, $n_{eff,y}$ and $n_{g,x}$, $n_{g,y}$ are the effective refractive indices and the group indices of both orthogonal polarisation modes, respectively. B and G are related through $G = B - \lambda\, dB/d\lambda$, where λ is the input wavelength. In our experiments, measurements of group modal birefringence G at telecommunication wavelengths have been achieved using two different methods, shown in Fig. 1. The first setup is based on a frequency-domain interferometer using a broadband source. In this case, two polarisation modes are first excited at the fibre input and then interfere at the output of the tested fibre owing to the polariser-analyser device aligned at 45° with respect to the fibre polarisation axes. Spectral interference is recorded using an optical spectrum analyser (OSA), as shown in Figs. 2*a* and *b*. The second setup relies on the direct analysis of the output state of polarisation (SOP) using a commercial polarisation analyser. In this case, we observe the polarisation state evolution on the Poincaré sphere with the scanned input wavelength from a tunable continuous-wave (CW) laser, as shown in Figs. 2*e*–*g*. As a result, the group birefringence was measured by using the so-called wavelength scanning method in both interferometric and polarimetric techniques [8]. The phase difference introduced on the one hand between two successive maxima spaced by $\Delta\lambda$ on the interference spectrum, and on the other hand by a full circular path on the Poincaré sphere is exactly equal to 2π, i.e. the SOP is restored. Consequently, the absolute value of G is directly calculated from the following relation: $|G| = \lambda^2/(L\,\Delta\lambda)$, where λ is an average wavelength between two successive interference fringes and L is the fibre length. Note that the sign of G cannot be determined by means of our setups.

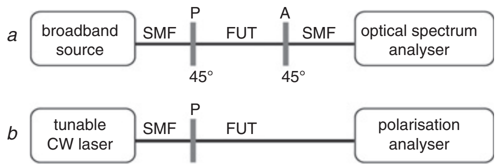

Fig. 1 *Experimental setups based on interferometric and polarimetric methods for group modal birefringence measurements*

P: polariser; A: analyser; SMF: singlemode fibre; FUT: fibre under test
a Interferometric method
b Polarimetric method

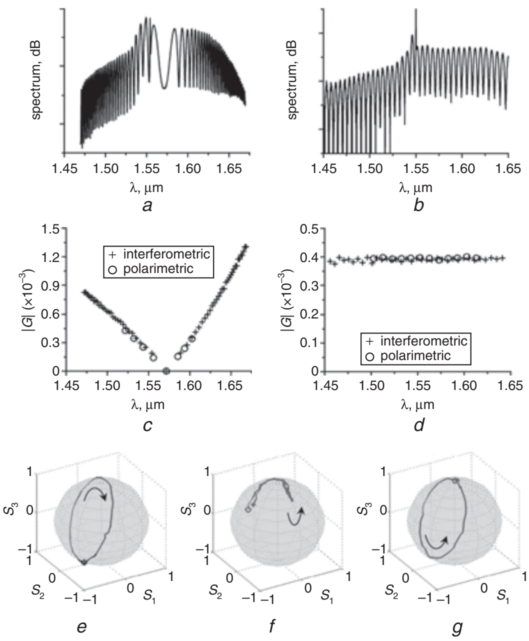

Fig. 2 *Experimental spectral interferences obtained with first setup for presented HiBi-PCF (Fig. 2a) and standard PM fibre (Fig. 2b); comparison of group birefringence measurements obtained with both methods for presented HiBi-PCF (Fig. 2c) and standard PM fibre (Fig. 2d); evolution of Stokes vectors on Poincaré sphere of SOP obtained at HiBi-PCF output with second experimental setup and by scanning over the following wavelength ranges: 1540–1546.6 nm, (Fig. 2e), 1560–1581.8 nm (Fig. 2f), and 1590–1597.4 nm (Fig. 2g)*

Initial and final wavelengths of each scanning are indicated by cross and circle, respectively. Trajectory direction indicated by arrow

The investigated fibre is a commercially available polarisation-maintaining highly nonlinear PCF (Crystal Fibre NL-PM-750), which is generally aimed at near-infrared supercontinuum generation. The fibre length used was 1.42 m. The experimental measurements of the group birefringence are summarised in Fig. 2*c*. A remarkable agreement between both techniques is observed (the comparison was limited to the operating range of the tunable CW laser). The wavelength dependence of G is significant, as readily assessed by the rapidly varying period of the spectral interference shown in Fig. 2*a*. The most striking feature is, however, that the absolute value of G cancels at a specific wavelength near 1570 nm. In other words, at 1571.5 nm, the PCF under investigation exhibits a zero group birefringence. We underline that this zero polarisation mode dispersion does not involve a zero phase birefringence. Note also that this zero group birefringence wavelength can be directly retrieved from the symmetry wavelength of the spectral interferences (Fig. 2*a*).

Such a zero value could be linked to a change of sign of the group birefringence. To obtain further insights, we show the wavelength scanning around 1570 nm for the polarimetric method in Fig. 2*f*. In this case, the polarisation trajectory on the Poincaré sphere does not follow a standard rotation such as the one illustrated in Fig. 2*e*; it undergoes an unusual direction inversion during the wavelength scanning. Indeed, we note that the clockwise circular path (Fig. 2*e*) becomes anticlockwise (Fig. 2*g*) when the wavelength scanning is carried out beyond the wavelength of the zero group birefringence. This feature definitively confirms our hypothesis: across a particular wavelength the sign of group birefringence changes.

To emphasise the remarkable specificity of birefringence characteristics of this HiBi-PCF, we show in Figs. 2*b* and *d* the measurements of G for a standard PM fibre based on stress elements (1.12 m-long commercial patch cord). As expected, the group birefringence remains constant at all wavelengths (i.e. the period of spectral interferences does not depend on the wavelength) since both phase and group birefringence parameters coincide ($G \simeq B$) [5].

We now present the numerical results of birefringence characteristics obtained by using vectorial beam propagation method simulations. The microstructure parameters used for the numerical simulations were extracted from the data sheet of the PCF and slightly adapted from the SEM image of the fibre cross-section shown in the inset of Fig. 3*a*. In particular, this PCF exhibits two large holes on either side of the core. This core asymmetry then involves distinct propagation parameters for the fundamental linearly polarised modes. Our fibre microstructure modelling allows us to calculate the group velocity dispersion (GVD) for both polarisation axes of our HiBi-PCF. These numerical results are in good agreement with those provided by the manufacturer, as shown in Fig. 3*a*. The numerical calculations of phase and group birefringence are then given in Figs. 3*b* and *c*, respectively. Here, the axis along which the mode index is smaller, i.e. the fast axis, corresponds to the x-axis where one finds both large holes. The phase birefringence B increases as the wavelength increases, since the mode field diameter becomes larger, resulting in a modal asymmetry growth. Contrary to the phase birefringence, the group birefringence G follows a completely different evolution with wavelength. From our simulations, we can first notice that B and G have opposite signs at low wavelengths, which is simply because B/λ is smaller than $dB/d\lambda$. Then, since the phase birefringence increases with wavelength, one can reach a specific wavelength at which the previous terms compensate for each other, i.e. $G = 0$. The numerical zero group birefringence is given at 1570 nm. For longer wavelengths, B and G have now the same signs; B/λ became larger than $dB/d\lambda$. We also compare in Fig. 3*c* the numerical values of G with the previous experimental results, and we clearly observe an excellent agreement, which confirms the sign inversion and the cancellation of the group modal birefringence in the telecommunication window.

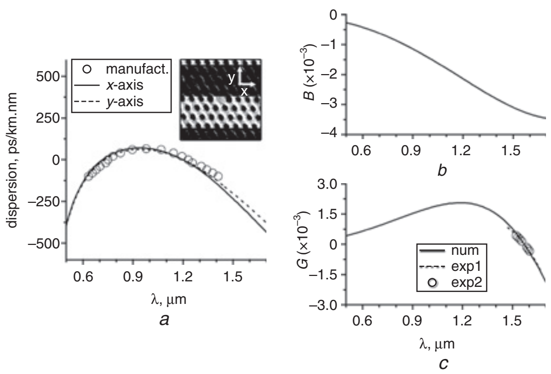

Fig. 3 *Numerical dispersion calculations of both fundamental orthogonal polarised modes of HiBi-PCF performed from SEM image of fibre cross-section (inset) compared to manufacturer data, numerical calculation of phase modal birefringence B, and numerical calculation of group modal birefringence G compared to experimental results obtained in telecommunication window*

a Numerical dispersion calculations of fundamental orthogonal polarised modes of HiBi-PCF
b Numerical calculation of phase modal birefringence
c Numerical calculation of modal birefringence

Conclusions: These results demonstrate that high phase birefringence PCF can exhibit both zero polarisation mode dispersion and group birefringence inversion at telecommunication wavelengths by using a carefully controlled core design. This observation is clearly of interest in the applicability of a novel class of controlled birefringence PCF for nonlinear optics applications. Moreover, it will also be advantageous when the suppression of polarisation-dependent nonlinearities is desirable.

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