Development of highly nonlinear polarization-maintaining fibers with normal dispersion across entire transmission window

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Abstract
A determined polarization state of light is required in nonlinear optics applications related to ultrashort and single-cycle light pulse generation. Such short timescales require up to one full octave of the spectral width of light. A fiber-based, pulse-preserving and linearly polarized supercontinuum can meet these requirements. We report on the development—from linear simulations of the fiber structure, through fabrication of physical fibers to their versatile characterization—of polarization-maintaining, highly nonlinear photonic crystal fibers, intended for femtosecond pumping at a wavelength of 1560 nm. A full octave of linearly polarized light around this wavelength would enable the covering of amplification bandwidths of the three major fiber amplifiers, from ytterbium-doped systems up to thulium- and holmium-doped fiber amplifiers, with a coherent, linearly polarized seed signal. At the same time, an all-normal chromatic dispersion profile over an entire transmission window, and a small dispersion of nonlinearity in the developed fibers, would facilitate use of commercially available femtosecond fiber lasers as pump sources for the developed fibers.

Keywords: fibers, birefringence, normal dispersion, nonlinear optics

(Some figures may appear in colour only in the online journal)

1. Introduction

The coherence time of a light source is determined by the reciprocal of the spectral bandwidth. In the simplest view, the narrower the spectral line, the more coherent the light source is. Broad bandwidth light is usually incoherent. Mode-locked lasers, having bandwidths of tens of nanometers, are nevertheless characterized by long coherence times. A femtosecond laser output pulse in the frequency domain consists of an equally spaced comb-like structure, pertaining to the coherent superposition of its resonator longitudinal modes [1]. The coherence time in this case stems from the width of the ‘comb’ lines (e.g. tens to hundreds of kHz) and not from the width of the envelope typically recorded as the laser spectrum [2].

Ti:sapphire lasers have octave-spanning amplification bands, which facilitate the obtaining of few-cycle pulses directly from the oscillator. Mode-locked rare earth-doped fiber lasers offer far superior robustness, but their amplification bands span typically 50–250 nm in the near-infrared region. The related limitations of few-cycle pulse generation with fiber lasers can be overcome by taking advantage of all-normal dispersion fiber-based supercontinuum generation. Octave-spanning spectra in these conditions can be readily
obtained under 50–100 fs pumping [3–5] and similar performance has also been reported with commercially available, mode-locked fiber lasers operating at 1560 nm [6]. The output supercontinuum pulses preserve the temporal profile and the comb-like structure of the driving lasers (albeit the pulses are dispersively stretched). In the case of 780 nm or 1030 nm femtosecond pumping from optical parametric chirped pulse amplification laser systems, these characteristics have been shown to enable temporal recompression to below two optical cycles, using active phase compensation [7]. A light pulse with a duration of single optical cycles has been demonstrated, using erbium-doped fiber amplifiers and advanced synthesis of spectrally broadened pulses due to dispersive wave generation and soliton self-frequency shift [8].

The better of the two approaches: preservation of the output pulse’s temporal profile and fiber-based realization can be combined when a fiber amplifier is coherently seeded over its whole amplification band from a pulse-preserving supercontinuum source. The power scaling of such a system with a 1030 nm femtosecond laser front-end has been demonstrated up to a level compatible with an attosecond pulse regime [9]. Coherent, full-bandwidth seeding of a thulium and holmium co-doped fiber amplifier has been discussed recently [6]. Importantly, the use of standard polarization-maintaining (PM) active fibers and fiber-optics components (pump-signal combiners or wavelength-division multiplexing (WDM) elements) facilitates phase coherence and intensity stability during power (pulse energy) scaling, because beating among randomly polarized fiber modes is not present. This, however, requires that the supercontinuum signal be linearly polarized. In-line fiber polarizers can be used, albeit spectral filtration of the seed is difficult to avoid. It is particularly important in the case of Tm$^{3+}$ + Ho$^{3+}$ doped fiber amplifiers, which possess the broadest bandwidth of the three major fiber amplifiers.

A polarized and pulse-preserving supercontinuum can be obtained at around 1030 nm with the use of commercially available fibers [10, 11]. The available spectral width of the supercontinuum in such a case does not cover the Tm$^{3+}$ + Ho$^{3+}$ amplification band. A PM microstructured silica fiber with a highly Ge-doped core has been demonstrated recently, in which the dispersion at normal wavelengths has been engineered flat over near-infrared wavelengths up to around 2500 nm [12]. At this wavelength, a zero dispersion point was estimated with numerical simulations. Also, the effective area at around a 2 μm wavelength was already reaching 40 μm$^2$, which is almost half of the area of commercial large mode area fibers [11].

We report that it is possible to achieve birefringence of the weakly PM microstructured fibers in the order of 10$^{-4}$ reported earlier for silica all-normal dispersion (ANDi) photonic crystal fibers (PCFs) compatible with 1030 nm pumping [10], using relatively sturdy silicate soft glasses, to arrive at a PM ANDi fiber compatible with 1560 nm femtosecond lasers. A non-PM ANDi soft glass fiber reported recently in a successful coherent supercontinuum amplification [6] is taken as a starting point in the designing of two different PCF structures with intentional birefringence, an all-normal dispersion profile across the fibers’ transmission window, and just over 10 μm$^2$ of effective area over the Tm$^{3+}$ + Ho$^{3+}$ fiber amplification band.

The presented discussion of results of numerical simulations of the fibers’ properties is supported with a detailed description and characterization of physically developed test fibers.

2. Structure design and material properties

We begin by revisiting the starting structure, which was successfully demonstrated in coherent supercontinuum generation [4, 13] and more recently in application in the coherent seeding of ultrafast, Tm$^{3+}$ + Ho$^{3+}$ fiber amplifier seeding [6]. The fiber structure is shown in a scanning electron microscope (SEM) image in figure 1. It has a hexagonal lattice, in which the air-holes are filled with a different type of glass rods at the preform assembly stage, to form glass inclusions in the final fibers.

The structure in figure 1, earlier reported in [6, 13] and recently also in [14], is specifically composed of Schott glasses labeled SF6 (core, lattice) and F2 (lattice filling, and surrounding tube). The material dispersions of both glasses are shown in figure 2.

The refractive index of the core glass is higher than that of the core surrounding; therefore, the structure supports index-guided propagation. Material dispersion was directly included in the simulation (initial values of the material refractive index were wavelength-dependent, according to figure 2). This all-solid glass photonic crystal fiber approach facilitates the engineering of flattened normal dispersion profiles, because chromatic dispersion of the fiber is then manipulated by the contributions of both the waveguide (lattice topology) and the material (two glass types). One of these structures is taken as the starting point in the design and fabrication of a polarization-maintaining variant.

A PCF with this type of lattice can be fabricated using the common stack-and-draw procedure. Two ways of introducing birefringence to a hexagonal PCF lattice are possible. Stress elements can be introduced in the fiber structure like in the

Figure 1. SEM image of the fabricated fiber structure, here referred to as the ‘base structure’.
The built-in stress, a change of the refractive index in the structure, is introduced in such PCFs compatible with 1030 nm femtosecond pumping [10]. As a result of the built-in stress, a change of the refractive index in the structure’s transverse plane is introduced. High birefringence of the fiber can also be achieved using the side-hole approach, where the mode confined in the core experiences defined optical axes with dramatically different refractive indices, due to the presence of air holes at two opposite sides of the core [15]. This approach is impractical with the type of structure shown in figure 1, because of the intricate role of the hexagonal lattice in shaping the dispersion and mode confinement properties [16]. An elliptical deformation of the fiber structure, i.e. its squeezing along one of the axes, has therefore been investigated as a possible alternative means of inducing birefringence.

The proposed bow-tie modification of the original base fiber design is shown in figure 3(a). Compared to the base structure in figure 1, this design has the number of photonic lattice rings decreased by one (to six, instead of seven). The lattice constant is \( A = 1.73 \, \mu m \), the width of the hexagonal inclusion is \( d = 1.35 \, \mu m \), and \( d/A = 0.77 \). The outer diameter of the whole designed structure is \( 125 \, \mu m \). The structure consists of three types of glasses, differing in refractive index values and mechanical properties. Two of them are again Schott SF6 and F2 glasses, and the third is a modified F2 glass, labeled F2/05, with a slightly changed refractive index \( (n_0 = 1.617) \) and a significantly increased thermal expansion coefficient (table 1). The composition of the glass was as following (compound, mol.%): \( \text{SiO}_2 \) 70.17, \( \text{PBO} \) 15.55, \( \text{Na}_2\text{O} \) 8.08, \( \text{K}_2\text{O} \) 6.07, and \( \text{As}_2\text{O}_3 \) 0.13. Other parameters of the glasses, necessary for mechanical simulation, were considered as temperature-dependent and are equal to: Young’s modulus \( 5.547 \times 10^{10} \) and \( 5.763 \times 10^{10} \) Pa, Poisson’s ratio \( 0.238 \) and \( 0.236 \), and densities \( 5180 \) and \( 3610 \, \text{kg m}^{-3} \) at room temperature (293.15 K) for the SF6 and F2 glasses, respectively.

In order to take into account the contribution made by stress to the change of the refractive index in the structure, an approach similar to that reported in [17] was applied. Numerical simulations were performed using the finite element method, operationalized in COMSOL Multiphysics software. The simulation process comprised two steps. In the first, the structural mechanics module was used and the simulation involved induced stress calculations, while the second step was an optical-domain simulation with the use of the wave optics module.

The chosen mesh density was adapted to the size of the structure’s element, starting from \( 8.38 \, \mu m \) of the maximal element size and \( 0.0375 \, \mu m \) for the minimal one (the fiber’s cladding), to \( 0.15/0.05 \, \mu m \) (microstructure). The boundary condition was a perfectly matched layer, having a thickness of \( 3 \, \mu m \), located at the external boundary of the cladding.

The main assumption, considering the stress induced in the fiber structure, is that the stress builds into the structure at temperatures below the glass transition temperature \( T_g \) [17]. The \( T_g \) values, as well as the thermal expansion coefficients for each of the glasses used for the design of the fiber, are summarized in table 1.

It is then assumed that under the built-in stress, the \( x \) and \( y \) components of a refractive index tensor are changed. The refractive index tensor is defined as:

\[
\mathbf{n} = \begin{bmatrix}
    n_x & 0 & 0 \\
    0 & n_y & 0 \\
    0 & 0 & n_z
\end{bmatrix}
\]

The changes of its components are calculated according to a formula:

\[
n_i = n_0 - C \cdot \sigma_j
\]

where \( i \) and \( j \) denote \( x \) and \( y \) components, \( C \) is the stress-optical coefficient, \( \sigma \) is the appropriate stress vector component, and \( n_0 \) is the value of the refractive index without the influence of mechanical stress.

It is further assumed that the \( z \) component of the refractive index tensor does not change. The value of the stress-optical coefficient depends on the material. In the simulation, they are assumed equal to \( 0.65 \times 10^{-12} \, \text{m}^2 \, \text{N}^{-1} \) for SF6 glass [18] and \( 2.81 \times 10^{-12} \, \text{m}^2 \, \text{N}^{-1} \) for F2 [18] and F2/05 glasses. The calculated \( x \) component of the stress tensor and birefringence induced in the fiber structure (the difference between \( y \) and \( x \) components of the refractive index tensor) are presented in figure 4.
The obtained difference between the two components of the stress tensor has a moderate value, of the order of $10^{-5}$. This can be assigned to the fact that the stress reaching the core area is largely diminished by the photonic lattice, which in turn is crucial for dispersion shaping and mode confinement. The effective mode area ($A_{\text{eff}}$) of the fundamental mode was also calculated in the simulations and is within the range of 2.5 to 15 $\mu$m$^2$ over a wavelength span of 900 to 2750 nm, as shown in figure 5. In particular, the wavelength dependence of the effective area, which translates into dispersion of nonlinearity [19], is desirable when weak. In such a case, a nonlinear response similar to that at the pump wavelength would facilitate efficient spectral broadening at the red-shifted edge of the propagating pulse’s spectrum.

### 3. Fabricated structures and dispersion characterization

The preform for a test structure of the ANDi PCF with stress-inducing rods, discussed in the previous section, was stacked with the use of rods and capillaries by the standard stack-and-draw technique. The physically developed test structure has a slight ellipticity, as shown in the SEM image in figure 6. This ellipticity was caused by the different softening temperatures of the two glasses of the fiber cladding (the one of the stress rods and of the glass filling). The difference in temperatures results from the modified thermal expansion coefficients of the stress rod material (table 1).

The second proposed method of introducing birefringence to the hexagonal photonic crystal base structure is to make the lattice elliptical. The number of lattice rings in the photonic cladding of the physically developed fiber was reduced to five, and air holes of a diameter comparable to the size of the photonic lattice structure were placed on each side of the lattice at the preform stacking stage. The air holes were collapsed during drawing in order to introduce ellipticity in the fiber microstructure. The fabricated elliptically-deformed fiber is shown in figure 7.

The dimensions of the structure’s core were equal to $2.68 \times 1.91 \mu$m, which means that the structure was more squeezed than the discussed ‘bow-tie’ fiber. The lattice widths

| Glass     | Glass transition temperature ($T_g$) (°C) | Thermal expansion coefficient ($\alpha_{20, 300}$°C) (1/K) | Reference |
|-----------|-----------------------------------------|---------------------------------------------------|-----------|
| Schott SF6| 423                                     | $9 \cdot 10^{-6}$                                  | [18]      |
| Schott F2 | 431                                     | $9.092 \cdot 10^{-6}$                              | This work |
| F2/05     | 417.6                                   | $10.55 \cdot 10^{-6}$                              | This work |

![Figure 4](image-url)  
(a) $x$ component of tensor of stress. (b) Stress-induced birefringence in the fiber with stress rods.

![Figure 5](image-url)  
Calculated effective mode area of a fundamental mode of the simulated fiber with stress rods.

![Figure 6](image-url)  
SEM image of the fabricated fiber structure with stress-inducing components (‘bow-tie’ structure).
The fabricated test fibers were then characterized experimentally, and specifically chromatic dispersion and birefringence measurements were performed. The developed test fibers were intended to validate the technological feasibility of fabricating ANDi PM fibers with a reasonable value of birefringence, simultaneously maintaining an all-normal dispersion profile across the transmission window. The fibers were not optimized with respect to loss, and broadband attenuation measurements were not performed. Based on typical coupling efficiencies achievable with similar fibers, e.g. [4, 13, 14, 16], and mean power output from the fibers reported in this work, we estimated a loss level of around 6 dB m⁻¹. This is improvable in further iterations of the technological process of their fabrication. We note that this unoptimized and considerable attenuation level did not preclude the recording of clear interferograms in dispersion and birefringence measurements with the use of fiber sample lengths typical for femtosecond supercontinuum generation. Chromatic dispersion in the developed fiber was measured for each of the polarization axes, using an unbalanced Mach-Zehnder interferometer set-up, schematically shown in figure 8. The method was explained in detail in [20].

A collimated supercontinuum (450–2400 nm, Leukos SM-30-450) was used as the light source. The light is divided into the two arms of the interferometer with a beam splitter with a 1–6 μm anti-reflection coating (BS₁). Neatly cleaved test fiber is placed in the test arm of the interferometer. A 60 × microscope objective (L₁) was used to couple the supercontinuum light into the test fiber, and an aspheric lens (L₂) at the other end of the fiber collimated the output light. The coupling of light into the fiber was monitored by imaging the output end of the fiber onto an InGaAs camera, which also confirmed excitation of the fundamental mode in the investigated fiber in all measurements. The reference arm has a gradient filter (G) to match the equal intensity in both arms. The two mirrors (M₁ and M₂) on a linear translation stage in the reference arm allow compensation of the optical path length in the measurement arm. A broadband linear polarizer was placed in the measurement arm before and after the fiber, as shown in figure 8. The polarizer and analyzer are rotated carefully to excite only one axis at a time; either the fast or the slow axis. The geometry of the set-up and length of the linear stages facilitates working with fibers of lengths from 10 to 20 cm. The fiber length typically used in our measurement was around 14 cm. Light from both arms is combined in a beam splitter (BS₂) and collimated. Lenses (L₃) and coupler (C) are used to collect the light from the interferometer, which is then transferred through a single-mode fiber (SMF) to an optical spectrum analyzer (OSA), which records from 1200 nm to 2400 nm (Yokogawa AQ6375). The length of the reference arm is adjusted to determine an optical path difference between the test and reference arms. The characteristic wide interference fringes over a wide spectral range are recorded to determine the chromatic dispersion of the fiber. From this the relative compensation, lengths Δx(λ) of the reference arm were collected for different equalization wavelength positions. This data was used to obtain the relative group index \( N_{rel}(\lambda) \):

\[
N_{rel}(\lambda) = \frac{2 \cdot \Delta x(\lambda)}{L} + 1
\]

where \( L \) is the length of the fiber.

The measured \( N_{rel}(\lambda) \) was fitted with a 5th order polynomial that is the Cauchy dispersion equation, as follows:

\[
N_{rel}(\lambda) = A_1 \lambda^4 + A_2 \lambda^2 + A_3 + A_4 \lambda^2 + A_5 \lambda^4.
\]

From this, we can obtain parameters A₁–A₅ to further calculate the chromatic dispersion as:

\[
D(\lambda) = \frac{1}{c} \frac{dN_{rel}(\lambda)}{d\lambda} = \frac{1}{c} (-4A_1 \lambda^4 - 2A_2 \lambda^2 + 2A_4 \lambda^2 + 4A_5 \lambda^4).
\]

The data obtained during measurements are fitted with equation \( N_{rel}(\lambda) \) as mentioned in (4). \( N_X \) and \( N_Y \) represent the relative group index for X and Y polarizations respectively for the ‘bow-tie’ as shown in figure 9 and for elliptical fiber as shown in figure 10. The gap between the measurements in figure 9 is due to water absorption, and noise structure made it difficult to measure the equalization wavelength precisely.

The fitting parameters of \( N_{rel}(\lambda) \) obtained for both polarization modes in the elliptical and ‘bow-tie’ fibers are presented in table 2. From these, the parameter chromatic dispersion \( D(\lambda) \) is calculated from equation (5).

Numerical simulation was carried out so that the structure would resemble the physically developed one. The fabricated structures were simulated with the assumption that the squeeze is in only one direction. The geometrical parameters of the ‘bow-tie’ fiber were taken from the real structure: the core size was equal to 2.56 × 1.94 μm, lattice widths were 24.5/18.7 μm, the average lattice constant was 1.68 μm and the stress-applying zones were 38.6 × 21.5 μm in size. The measured dispersion profiles of the fiber with stress-inducing components, compared with numerical results, are presented in figure 11.
Figure 8. Mach-Zehnder interferometer setup for dispersion measurement. M: silver mirrors. P: polarizer. BS: beam splitter. G: gradient neutral-density filter. L: lenses. A: polarization analyzer. C: coupler. SMF: single-mode fiber.

Figure 9. Relative group index obtained from measurements for ‘bow-tie’ fiber: (a) X polarization and (b) Y polarization. The solid dots are measured points and the red curve was obtained by fitting.

Figure 10. Relative group index obtained from measurements for elliptical fiber: (a) X polarization and (b) Y polarization. The solid dots are measured points and the red curve was obtained by fitting.

Table 2. Fitting parameters for reproducing the measured dispersion parameter $D$.

| Fiber          | $A_1$   | $A_2$   | $A_3$   | $A_4$   | $A_5$   |
|----------------|---------|---------|---------|---------|---------|
| Bow-tie (E_x pol) | 4.83E-02 | -5.21E-02 | 1.58   | -0.010 09 | 2.81E-05 |
| Bow-tie (E_y pol) | 3.39E-02 | -2.71E-02 | 1.57   | -0.0053 | -4.07E-04 |
| Elliptical (E_x pol) | 8.19E-03 | 2.34E-02 | 1.51   | 0.0058 | -1.20E-03 |
| Elliptical (E_y pol) | -2.36E-03 | 3.54E-02 | 1.50   | 0.00574 | -1.16E-03 |

To obtain $D$ in ps nm$^{-1}$ km$^{-1}$, express the speed of light $c$ in km ps$^{-1}$ and the wavelength $\lambda$ in $\mu$m.

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Dispersion remains at normal values for the whole considered wavelength range and is in very good agreement with the dispersion profiles obtained numerically. A small difference between the numerical simulation and the measurement can be explained by diffusion during drawing not being taken into account in the simulations.

Dispersion of the elliptical structure was calculated using the same numerical approach as for the other considered lattice layouts. The results of these calculations, performed for both polarization axes of the fiber, are shown and compared with the physically measured dispersion profiles in figure 12. The experiments confirmed that the dispersion remains normal in the whole considered spectral range and also has a very similar profile to the fabricated ‘bow-tie’ structure (dispersion characteristics shown in figure 11).

4. Birefringence characterization

In a highly birefringent fiber, the two orthogonal polarization modes experience the different propagation constants $\beta_x(\lambda)$ and $\beta_y(\lambda)$ due to slightly varying refractive indices $n_x$ and $n_y$, respectively. When light is launched into the fiber and one of the fiber’s polarization modes is excited, the coupling between the two modes is greatly reduced and a state of polarization is maintained along the fiber. The magnitude of birefringence is characterized by the beat length $L_B(\lambda)$ of two polarization modes, which is defined as:

$$L_B(\lambda) = \frac{2\pi}{\beta_x(\lambda) - \beta_y(\lambda)}.$$  \hfill (6)

The phase birefringence $B(\lambda)$ can then be expressed by:

$$B(\lambda) = n_x - n_y = \frac{\lambda}{L_B(\lambda)}$$ \hfill (7)

and the group birefringence $G(\lambda)$ as:

$$G = B(\lambda) - \lambda \frac{dB(\lambda)}{d\lambda}. \hfill (8)$$

The phase and group birefringence characteristics obtained numerically for the modeled structure, shown in figure 3, are presented in figure 13.

The obtained values of phase birefringence are relatively low, in the order of $10^{-5}$, i.e. the same order of magnitude as an induced birefringence in a material; see figure 4(b). However, similar birefringence values were observed in [21] as being sufficient to improve the quality of an all-normal dispersion supercontinuum pulse in a fiber with nominally smaller, unintentional form birefringence. Birefringence in the structure as shown in figure 4 originates from built-in stress. The group birefringence takes lower absolute values than the phase birefringence (figure 13), and at wavelengths close to the material transmission cutoff of the fiberglass, it takes values of an opposite sign.

Group birefringence can be measured using a simple experimental set-up, which uses the standard crossed polarizer method as shown in figure 14.

Similar to the dispersion measurement, a supercontinuum was used as a light source, and the light was coupled into the fiber with a $60 \times$ microscope objective. The output light from the fiber was coupled into the OSA over free space, after collimating with an aspheric lens. The coupling efficiency into the fiber and the mode structure was monitored using an
IR camera and a flip mirror. The broadband linear polarizer at the input was adjusted in such a way as to excite both polarization modes in the fiber, and the analyzer at the output was oriented to obtain the interference birefringence pattern. Group birefringence \((G)\) is obtained from the recorded interferogram using the expression:

\[
|G| = \frac{\lambda_0^2}{\Delta \lambda \cdot L}
\]  

where \(\lambda_0\) and \(\Delta \lambda\) are the average wavelength and the distance between the two successive fringes, respectively, and \(L\) is the length of the fiber.

Figure 15(a) presents interference fringes obtained for group birefringence of the ‘bow-tie’ fiber. Coupling to the fiber was adjusted to obtain the best possible fringes at different wavelengths. Intensity in the \(y\) axis is normalized and fringes from different spectral regions were stitched. The wide fringe around 1400 nm corresponds to the zero group birefringence wavelength. Figure 15(b) shows that the group birefringence obtained experimentally is in very close agreement with the results of numerical simulations. The sign of the group birefringence cannot be determined experimentally, so it was established by comparison with the profile obtained from numerical simulations.

Group birefringence of the ‘bow-tie’ test fiber takes much larger values than estimated numerically for an ideal (not squeezed) structure shown in figure 3. For the longest wavelengths recorded experimentally, it reaches the order of \(10^{-3}\). We note that this large difference of group birefringence between the designed structure and the physical fiber is assigned to the ellipticity of the latter.

The birefringence characteristic measured for the elliptical fiber, shown in figure 16(b), is at much higher values than that of the regular structure with stress-inducing elements (numerical results shown in figure 6) and also slightly higher than those of the ‘bow-tie’ structure with both ellipticity and stress rods. In our elliptical fiber, measurements and simulations revealed that group birefringence changes sign at around roughly 1500 nm, and increases with wavelength up to the order of \(10^{-3}\) at about 2000 nm, as shown in figure 16(b).

Additionally, by performing numerical simulations, the possibility was examined of introducing a comparable birefringence in a structure with stress rods and without ellipticity. For this purpose, a simulation of the structure presented in figure 3 was created, with the value of the thermal expansion coefficient of the glass forming the stress rods increased by a factor of 1.5. The other parameters were the same as in the initial simulation. The resulting birefringence is shown in figure 17.

Enhancing the thermal expansion coefficient of the glass of stress-applying zones allows an increase of the mechanical stresses introduced into the fiber, which in turn results in a significant rise in birefringence (figure 17). The obtained values are approximately one order of magnitude greater than those in the initial structure (figure 13). This proves the possibility of obtaining a highly birefringent PCF with a regular structure, but requiring a substantial improvement of one of the stress-applying zones’ material properties.
ANDi PM fibers on the soft glass platform are vital to extending the dispersion engineering freedom for highly nonlinear fibers for polarized, coherent supercontinuum generation. The fiber designs proposed here have experimentally confirmed birefringence properties corresponding to existing designs realized and reported for silica glass fiber technology. Although the fiber structures presented here are weakly PM, they are characterized by significantly enhanced nonlinear properties. This includes higher nonlinearity related to the high value of the nonlinear refractive index of the SF6 glass used for the core and lattice of the discussed fibers. However, it is fostered with a weak dependence of the effective mode area on the wavelength, which stems from the waveguide design. This in turn results in a strong nonlinear response over the Tm$^{3+}$ and Ho$^{3+}$ amplification wavelengths (1900–2200 nm) and holds the promise of the nonlinear soft glass platform PCFs reproducing or even extending excellent nonlinear performance at these wavelengths, previously demonstrated with silica ANDi PCFs at the Yb$^{3+}$ band (1000–1100 nm). A comparison of relevant parameters of selected fibers is set out in table 4.

The estimated nonlinear coefficient values in table 4, apart from fiber 1 (value explicitly given in [23]), were calculated using the formula:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

and the parameters taken from sources referred to in table 4. With the effective mode area at the level of 3.7 $\mu$m$^2$, corresponding to a nonlinear refractive index ($n_2$) of 21 $\cdot$ 10$^{−20}$ m$^2$ W$^{−1}$ (at a wavelength of 1500 nm) [13], the soft glass fibers reported here constitute an alternative to silica-based fibers, because of the potential to decrease requirements on the peak pump power for efficient operation in the nonlinear regime. At a wavelength of 2 $\mu$m, they allow for a nonlinear coefficient even of the order of 10$^5$ W$^{−1}$ km$^{−1}$ (table 4).

6. Conclusions

Numerical simulations and characterizations were performed of physically developed test structures of all-solid glass, all-normal dispersion, weakly PM photonic crystal fibers. The obtained results indicate the feasibility of delivering PM fibers with the engineered, normal dispersion characteristics and nonlinearity earlier reported for non-PM, nonlinear PCFs for octave-spanning, pulse-preserving supercontinuum generation. Two types of birefringence introduction were investigated. A hexagonal, all-solid glass photonic lattice of a non-PM fiber, reported earlier in [13], was taken as a starting point. Microstructure layouts with ‘bow-tie’ type stress rods around the photonic lattice and with core ellipticity were then investigated for birefringence properties. By introducing ‘bow-tie’ stress rods using glass with a thermal expansion coefficient of 10.55 $\cdot$ 10$^{−6}$ 1/K, weak birefringence of the order of 10$^{−5}$ was estimated with
Table 3. Birefringence results obtained in all-normal dispersion photonic crystal fibers for wavelength ranges of three rare earth-doped fiber-based femtosecond lasers.

| No. | Fiber (type, material, way of introducing birefringence) | about 1000 nm (Yb$^{3+}$ fs laser) | about 1560 nm (Er$^{3+}$ fs laser) | about 2000 nm (Tm$^{3+}$ + Ho$^{3+}$ fs laser) | Reference |
|-----|---------------------------------------------------------|-----------------------------------|-----------------------------------|----------------------------------------------|-----------|
| 1   | ANDi PCF optimized for 1000 nm, silica glass, bow-tie   | 4.2 · 10$^{-4}$                  | —                                 | —                                             | [10]      |
| 2   | ANDi PCF optimized for 1500–2000 nm, Ge:silica, stress rods | —                                 | 1.4 · 10$^{-4}$                  | 1.7 · 10$^{-4}$                               | [12]      |
| 3   | Ultra-high numerical aperture PM fiber optimized for 1900—2100 nm (Coherent-Nufern PM2000D) | —                                 | 1.7 · 10$^{-5}$ (group)          | 9 · 10$^{-5}$ (group)                         | This work, [22] |
| 4   | ANDi PCF optimized for 1500–2000 nm, silicate soft glass, elliptical | —                                 | 0 (group)                         | 6.6 · 10$^{-4}$ (group)                       | This work (elliptical) |
| 5   | ANDi PCF optimized for 1500–2000 nm, silicate soft glass, bow-tie | —                                 | 1 · 10$^{-4}$ (group)            | 6.1 · 10$^{-4}$ (group)                       | This work ('bow-tie') |
Table 4. Nonlinear properties of all-normal dispersion photonic crystal fibers at near-infrared wavelengths.

| No. | Fiber (type, material, way of introducing birefringence) | \( n_2 \times 10^{-20} \text{ m}^2 \text{ W}^{-1} \) | \( A_{\text{eff}} \) (\( \mu \text{m}^2 \)) | Estimated nonlinear coefficient (\( \gamma \)) (1 W\(^{-1}\) km\(^{-1}\)) | Reference |
|-----|--------------------------------------------------------|---------------------------------|---------------------------------|-------------------------------------------------|---------|
| 1   | ANDi PCF optimized for 1000 nm, silica glass, bow-tie  | 2.68                            | 3.8 (1064 nm)                   | \(~37\) (1064 nm)                                | [23, 24]|
| 2   | ANDi PCF optimized for 1500–2000 nm, Ge:silica, stress rods | 2.6                             | 20.2 (2000 nm)                  | 4 (2000 nm)                                     | [12]    |
| 3   | Ultra-high numerical aperture PM fiber optimized for 1900–2100 nm (Coherent-Nufern PM2000D) | 2.68                            | 12.6 (2000 nm)                  | 6.7 (2000 nm)                                   | [23, 25]|
| 4   | ANDi PCF optimized for 1500–2000 nm, silicate soft glass, elliptical | 21                              | 5.4 (2000 nm)                   | 122.2 (2000 nm)                                | This work (elliptical), [13] |
| 5   | ANDi PCF optimized for 1500–2000 nm, silicate soft glass, bow-tie | 21                              | 5.8 (2000 nm)                   | 113.7 (2000 nm)                                | This work (‘bow-tie’), [13] |
numerical simulations. Fabricated bow-tie test fiber was squeezed during drawing and the measured birefringence attained around $10^{-3}$ at a wavelength of 2000 nm. This was confirmed with numerical simulations performed for geometrical parameters of this test fiber. These simulations further revealed that in this particular fiber, the micro-structure ellipticity counteracted the effect of the stress rods, nullifying it entirely and introducing birefringence of its own. The dominant effect of core ellipticity in the birefringence of the proposed fibers was further confirmed by numerical simulations and measurements on a physical fiber featuring only core ellipticity, without any stress rods. Numerical simulations enabled an estimate to be made that a stress-induced birefringence of around $10^{-4}$ would be possible in a structure without any ellipticity, if the stress rod glass had a thermal expansion coefficient 1.5 times larger than that of the glass used in the actual technological process.

The developed fibers confirm the feasibility of obtaining weakly-PM functionality, while preserving a normal dispersion characteristic over wavelengths matching the mature and weakly-PM functionality, while preserving a normal dispersion characteristic over wavelengths matching the mature and weakly-PM functionality, while preserving a normal dispersion characteristic over wavelengths matching the mature and weakly-PM functionality, while preserving a normal dispersion characteristic over wavelengths matching the mature and weakly-PM functionality. Further work with the developed fibers is planned and will focus on detailed, spectro-temporal characterization of femtosecond-pumped supercontinuum generation in the PM regime.

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