Anisotropic tapered polarization-maintaining large mode area optical fibers

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Abstract: We demonstrate a novel type of tapered large mode area polarization-maintaining fiber. These birefringent fibers have an elliptical inner cladding and a core diameter that increases adiabatically from 8 µm to 70 µm. The polarization maintaining ability of the fiber samples was investigated by measuring the spatial distribution of polarization beat length by using optical frequency-domain reflectometry. The measurements show a clear correlation between the birefringence and the fiber core size, resulting in a modest 10-15% variation in polarization beat length along the fiber. There is no significant coupling of polarization modes or transverse modes in the tested fibers and, therefore, the linear polarization state of propagating light is preserved.

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References and links

1. J. D. Love, W. M. Henry, W. J. Stewart, R. J. Black, S. Lacroix, and F. Gonthier, “Tapered single-mode fibres and devices - part 1: adiabaticity criteria,” J. Optoelectronics 138(5), 343–354 (1991).
2. R. J. Black, S. Lacroix, F. Gonthier, and J. D. Love, “Tapered singlemode fibres and devices — Part 2: Experimental and theoretical quantification,” J. Optoelectronics 138(5), 355–364 (1991).
3. J. Ward, D. O’Shea, B. J. Shortt, M. J. Morrissey, K. Deasy, and S. Nic Chormaic, “Heat-and-pull rig for fiber taper fabrication,” Rev. Sci. Instrum. 77(8), 083105 (2006).
4. N. Vukovic, N. G. R. Broderick, M. Petrovich, and G. Brambilla, “Novel method for the fabrication of long optical fiber tapers,” IEEE Photonics Technol. Lett. 20(14), 1264–1266 (2008).
5. J. Bures, S. Lacroix, and J. Lapiere, “Analysis of a fused biconical single-mode fiber optic coupler,” Appl. Opt. 22, 1918–1922 (1983).
6. J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, “Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper,” Opt. Lett. 22(15), 1129–1131 (1997).
7. T. A. Birks, P. St. J. Russell, and D. O. Culverhouse, “The acousto-optic effect in single-mode fiber tapers and couplers,” J. Lightwave Technol. 14(11), 2519–2529 (1996).
8. T. A. Birks, W. J. Wadsworth, and P. St. J. Russell, “Supercontinuum generation in tapered fibers,” Opt. Lett. 25(19), 1415–1417 (2000).
9. F. Warken, E. Vetete, D. Meschede, M. Sokolowski, and A. Rauschenbeutel, “Ultra-sensitive surface absorption spectroscopy using sub-wavelength diameter optical fibers,” Opt. Express 15(19), 11952–11958 (2007).
10. V. E. Ustimchik, S. A. Nikitov, and Y. K. Chamorovskii, “Simulation of radiation generation in an active double-clad optical tapered fiber,” J. Commun. Technol. Electron. 56(10), 1249–1255 (2011).
11. J. Kerttula, V. Filipov, Y. Chamorovskii, V. Ustimchik, K. Golant, and O. G. Okhotnikov, “A comparative study of tapered fiber laser configurations,” Proc. SPIE 8237 82370W (2012).
12. J. Kerttula, V. Filipov, Y. Chamorovskii, V. Ustimchik, K. Golant, and O. G. Okhotnikov, “Tapered fiber amplifier with high gain and output power,” Laser Phys. 22(11), 1734–1738 (2012).
13. J. Kerttula, V. Filipov, Y. Chamorovskii, V. Ustimchik, K. Golant, and O. G. Okhotnikov, “Principles and Performance of Tapered Fiber Lasers: from Uniform to Flared Geometry,” Appl. Opt. 51(29), 7025–7038 (2012).
14. Y. Jung, G. Brambilla, and D. J. Richardson, “Polarization-maintaining optical microfiber,” Opt. Lett. 35(12), 2034–2036 (2010).
15. S. C. Rashleigh and M. J. Marrone, “Influence of the fiber diameter on the stress birefringence in high-
birefringence fibers,” Opt. Lett. 8(5), 292–294 (1983).
16. S. C. Rashleigh, “Origins and control of polarization effects in single-mode fibers,” J. Lightwave Technol. 1(2),
312–331 (1983).
17. P. Lu, J. Song, G. Niedermayer, J. Harris, L. Chen, and X. Bao, “Tapered polarization-maintaining fiber sensor
based on analysis of polarization evolution,” Proc. SPIE 9157, 915708 (2014).
18. X. Wang, G. Niedermayer, G. Lin, P. Lu, B. Wang, L. Chen, and X. Bao, “Polarization-maintaining property of
tapered polarization-maintaining fibers,” Appl. Opt. 52(8), 1550–1554 (2013).
19. J. Kerttula, V. Filippov, V. Ustimchik, Y. Chamorovskiy, and O. G. Okhotnikov, “Mode evolution in long
tapered fibers with high tapering ratio,” Opt. Express 20(23), 25461–25470 (2012).
20. M. E. Froggatt, D. K. Gifford, S. Kreger, M. Wolfe, and B. J. Soller, “Characterization of polarization-
maintaining fiber using high-sensitivity optical-frequency-domain reflectometry,” J. Lightwave Technol. 24(11),
4149–4154 (2006).
21. X. Wang, W. Li, L. Chen, and X. Bao, “Distributed mode coupling measurement along tapered single-mode
fibers with optical frequency-domain reflectometry,” J. Lightwave Technol. 30(10), 1499–1508 (2012).
22. B. Hutner, J. Reecht, N. Gisin, R. Passy, and J. P. Von der Weid, “Local birefringence measurements in single-
mode fibers with coherent optical frequency-domain reflectometry,” IEEE Photonics Technol. Lett. 10(10),
1458–1460 (1988).
23. B. Soller, D. Gifford, M. Wolfe, and M. Froggatt, “High resolution optical frequency domain reflectometry for
characterization of components and assemblies,” Opt. Express 13(2), 666–674 (2005).
24. W. Eickhoff and R. Ulrich, “Optical frequency domain reflectometry in single-mode fiber,” Appl. Phys. Lett.
39(9), 693–695 (1981).
25. V. V. Grigor’yants, A. N. Zalogin, G. A. Ivanov, V. A. Isaev, S. M. Kozel, V. N. Listvin, and Yu. K.
Chamorovskii, “Polarization effects in birefringent fiber,” “waveguides with an elliptic borosilicate cladding,”
Soviet J. Quantum Electron. 16(10), 1370–1372 (1986).
26. R. Paschotta, “RP Photonics encyclopedia”, https://www.rp-photonics.com/polarization_beat_length.html
27. J. G. Elhison and A. S. Siddiqui, “A fully polarimetric optical time domain reflectometer,” IEEE Photonics
Technol. Lett. 10(2), 246–248 (1998).
28. W. Eickhoff, “Stress-induced single-polarization single-mode fiber,” Opt. Lett. 7(12), 629–631 (1982).

1. Introduction

The combination of high efficiency, effective cooling and superior beam quality of optical fiber gain media have paved the way for the recent advent of high-power continuous-wave fiber lasers. Pulsed high-power fiber lasers, in contrast, are still being held back in terms of power by the harmful nonlinear processes arising from the small fundamental mode area in optical fibers compared to alternative technologies, such as disk lasers. Upscaling the pulse energy available from fiber lasers or amplifiers thus necessitates using a larger core, which normally leads to multimode operation. However, active fibers can also be made thicker without sacrificing the single-mode beam quality by employing tapered transitions, which function as mode area converters.

In the scientific literature, tapered fibers and conical transitions in different types of fibers are well-known due to their specific properties. Most research has focused on conical transitions manufactured by stretching already drawn fibers [1–4] heated to the glass softening point temperature. This manufacturing method forms tapered transitions with lengths ranging from a few millimeters to a few centimeters. Such transitions allow to achieve a considerable evanescent field with sensitivity to environmental parameters, changes in the set of propagating transverse modes and a significant increase in the local power density. These effects have already been applied to many areas, including special sensors, studies of nonlinear effects, mode coupling and the manufacturing of microcavities [5–9].

More recently, long tapered fibers have gained increasing attention. They are manufactured by drawing from the preform with a changing speed in such a way as to achieve an adiabatic increase in the mode area to over 40 000 µm². These fibers have been successfully demonstrated in high-power fiber lasers and amplifiers with high output beam quality. However, they have not been able to produce linearly polarized output beam [10–13].

Fiber lasers with a stable, linear polarization state can be built using polarization-maintaining fibers (PMF). They are generally anisotropic single-mode fibers where the coupling of the two polarization modes is prevented by the difference in their propagation constants. Conical transitions based on ordinary PM fibers have been already studied and are
promising for micro- and nanophotonic devices, highly efficient microcavities and polarization-sensitive sensors [14–18]. The polarization state of light has been shown to slightly change during propagation through taper transitions fabricated in standard PM fiber. The transitions studied earlier have lengths of several centimeters with a waist diameter of about 60-80 µm and an initial outer cladding diameter of 125 µm [17,18]. Long tapered polarization-maintaining fibers with increasing core diameter, on the contrary, still remain poorly studied.

A necessary condition for polarization maintaining is the preservation of the refractive index structure and stresses along the fiber length despite the changing fiber diameter. Relaxation of mechanical stresses inside the fiber may occur because of heating the fiber or preform and, as a consequence, the convergence of the parameters along the fast and slow axes may lead to a decrease in birefringence and, consequently, weak polarization extinction [15,16,18]. This harmful effect is also possible in the case of long tapered fibers.

An important parameter concerning tapered fibers is the condition of adiabatic expansion or contraction of the fiber core, which, if fulfilled, guarantees the absence of transverse mode coupling. Adiabaticity is essential for the optimal operation of long tapered fibers that are highly multimode at the thick end. Recent experimental studies have shown that adiabatic expansion of the fiber core allows strictly single mode propagation inside an isotropic tapered fiber (axisymmetric cross-section of the fiber and in the absence of prestressing and induced birefringence) whose the core diameter increases from 7 to 8 µm up to 120 µm along the its length of several meters [10–13,19]. At the input end, the fiber is strictly singlemode and thus only the fundamental mode is excited. The all light remains in the fundamental mode which expands during propagation without effective coupling to the higher order modes.

In this study, we present anisotropic polarization maintaining tapered fibers whose core diameters increase adiabatically from 8 µm to about 70 µm. We also characterize their polarization maintaining ability by measuring their spatial birefringence distributions. Most of the techniques allowing to obtain such information are destructive. These techniques are associated with iterative measurement of the polarization extinction or the polarization state of light before and after cleaving small fiber parts. Moreover, these methods provide only a rather coarse spatial resolution along the length of the tapered transition, since the length of a cleaved part has finite and quite tangible dimensions, often greater than the polarization beat length. This is particularly important in optical fibers with high birefringence and small polarization beat length. Furthermore, these techniques do not allow tracking the change in birefringence with random inhomogeneities of the fiber structure. For these reasons, we use the high-resolution optical frequency domain reflectometry (OFDR) method [18, 20–24] for the investigation of the birefringence distribution along the length of the anisotropic long tapered fibers. This method enables the measurement of polarization mode beating within the fiber with high resolution (unlike the time domain reflectometry OTDR) by direct measurement of the distribution of the phase and group birefringence according to OFDR principles.

The capability to fabricate long tapered polarization maintaining fibers with large mode area and to characterize them will advance the development of new high-power fiber lasers and amplifiers with a linear polarization, reduced nonlinearity and single-mode beam quality.

2. Experimental samples of long tapered fibers with large mode area

The preforms for the anisotropic fiber manufacturing have been made using the well-known method of grinding [25]. After the deposition of the required layers, the initial preform was polished symmetrically from both sides and then heated to a high temperature that was providing rounding of the outer boundary. The inner layers were deformed and, as a result, a structure was formed with a nominally circular core and an elliptical prestressing cladding, shown in Fig. 1 inset. Particular attention during manufacturing was paid to the homogeneity of the core refractive index. It was necessary because the quality of the propagating radiation
and the magnitude of optical mode coupling inside the fiber core is highly sensitive to any perturbations in cross-section and in refractive index profile when the core diameter is of the order of 10 - 100 wavelengths.

Fig. 1. Longitudinal geometric profile of the experimental samples of tapered fibers. Picture of the cross-section of the narrow part of the experimental sample of tapered fiber (inset).

Table 1. Parameters of experimental tapered fibers samples

| Parameter                                               | Nº 1  | Nº 2  | Nº 3  |
|---------------------------------------------------------|-------|-------|-------|
| The total length of the tapered fiber, m                | 14    | 12    | 12    |
| The diameter of the core in a narrow / wide parts, µm   | 9/71  | 8/71  | 8/73  |
| The diameter of the outer cladding in a narrow / wide part, µm | 140/1111 | 125/1115 | 125/1135 |
| Minor/major diameter of prestressing elliptical cladding, µm | 17/36 | 15/32 | 15/32 |
| Tapering ratio                                          | 7.9   | 8.9   | 9.1   |
| Ratio of outer cladding diameter to core diameter       | 15.6  | 15.6  | 15.6  |
| Core numerical aperture                                  | 0.11  | 0.11  | 0.11  |

The experimental samples of tapered fibers were drawn from the preform, wherein the outer diameter of the fibers was smoothly varied to form an anisotropic tapered longitudinal profile. Each tapered fiber had step-index refractive profile and circular shape of the core and the outer cladding in cross-section, shown in Fig. 1. Their core diameters increase gradually from about 8-9 µm, corresponding to strictly single mode propagation at the wavelength of 1550 nm, to over 70 µm along the fiber lengths of a few meters. Longitudinal geometric profiles of the tapered fiber samples are shown in Fig. 1. It is worth noting that the experimental fibers Nº 1, 2 had double-tapered structure with maximum core diameter in the center and the experimental fiber Nº 3 had a single tapered region. The anisotropy (birefringence) in the samples was due to the prestressing elliptical inner cladding (shown in Fig. 1) that formed asymmetrical transverse stress and index changes via the elasto-optic effect. Detailed parameters of the tapered fiber samples are given in Table 1.
3. Spectral measurements

Initially, the broadband transmission spectra of the fiber samples were measured and are shown in Fig. 2(a). In the case of the tapered fiber samples № 1,2 light was coupled into the narrow part of the tapered fiber and in case of the sample № 3 radiation was coupled into the wide part of the fiber. Intensity beating in the transmission spectra of the tapered fiber № 1 and 2 was caused by propagation of a few optical modes in the wide part of the tapered fiber caused noticeable (for spectral measurements) excitement of higher transverse optical modes within the fiber. However we did not observe significant decrease in light intensity after double tapered fiber samples № 1, 2 in comparison with the spectrum of light source. The total losses in tapered fibers were about 1 dB. This is evidence of insignificant transverse mode coupling in fiber samples. Moreover experimental conditions like fiber position and bending did not affect much on results. Also it is worth mentioning that adiabatic expansion of the core diameter and the fundamental mode area was not strongly violated, because the amplitude of the modulation was less than 2 dB. Such a small amplitude means that the optical power carried by higher order modes was 2-3 orders of magnitude less than the power in the fundamental mode.
Next, the polarization beat length was measured in samples of anisotropic tapered fiber by the spectral method with crossed polarizers. While measuring fiber samples were bent in coils with a radius of about 15 cm. Figure 2(b) shows the resulting spectrum for the sample № 1 exhibiting polarization beating typical for all the fiber samples. This method is widely used in the literature for the investigation of the polarization beat length of anisotropic fibers, excluding random or controlled fiber diameter inhomogeneity [26]. Thus it is possible to determine the average polarization beat length in the tested tapered fiber with a good accuracy. For sample № 1, the spectral distance between the minima is about 1.5 nm, shown in Fig. 2(b) inset, for the whole fiber length of 13.5 m. From these data, one can calculate the spatial polarization beat length. The measured polarization beat length has a value of about 13.1 mm for the tapered fiber № 1. Performing similar measurements for samples № 2 and 3, the spatial polarization beat length were obtained - 13.2 and 13.1 mm respectively. These values represent a mean value of the beat length averaged over the entire length of tapered fiber and did not significantly depend on the bending of the tapered fibers.

![Figure 3. The measured backscatter pattern of full amplitude of the reflected signal in samples of tapered fiber - black line (left scale). Red line - a geometric longitudinal profile, depending of the outer cladding diameter on the fiber length of the tapered fiber length (right scale).](image)

4. Optical frequency domain reflectometry method

Experimental samples of the tapered fibers were investigated using a commercially available OFDR device (LUNA-OBR-4400). The OFDR method has a high spatial resolution and allows to determine the distribution of the spatial polarization beat length along the whole test fiber length. Application of this method for determination of the magnitude of the birefringence and polarization beat length of the PMF has been discussed in detail in the published papers [20–24]. Herein OFDR allows to achieve the spatial resolution of the backscatter signal pattern up to 20 µm along fiber length and, therefore, in contrast to the OTDR and other methods, to determine with high accuracy the distribution of the
birefringence along the fiber length. Therefore it is possible to identify the impact of spatial inhomogeneities on the value of polarization beat length. This method involves the calculation of the autocorrelation of the backscattered radiation in the frequency and time domain which enables performing a complete characterization of the fibers with anisotropic structure [18,20–23].

Fig. 4. (a) Distribution of backscatter intensity pattern for two orthogonal states of polarization in initial section of tapered fiber sample \( \#3 \). (b) Autocorrelation function of the backscattered signal calculated in the frequency domain at a distance of 3.8 m from the beginning of the tapered fiber \( \#2 \).

Measurements were carried out for different positions and bending of the tapered fiber samples. Backscatter patterns show weak correlation with the experimental conditions. The typical dependences of the full amplitude of backscattered light along the length of the tapered fibers experimental samples are shown in Fig. 3. In this study the narrow part of the tapered fiber is spliced directly to the singlemode pigtail attached to the OFDR device. The device measured the backscattered signal resolved into two orthogonal polarization states. The total amplitude of the backscatter signal is calculated by adding the vector data of the two S and P polarizations. The sharp drop in the level of the reflected signal to the noise floor corresponds to the end of the tapered fiber. It can be seen that the total amplitude of the measured backscatter signal varies along the length of the tapered fiber and is strongly correlated with the longitudinal geometric profile of the tapered fiber. A pattern of backscatter
light in this case is determined mostly by Raleigh scattering, and also by the longitudinal profile of the sample. Reduction of the backscatter level of detectable signal with increasing diameter of the tapered fiber core is associated with increasing of the number of supported transverse modes of the core. Since the backscattered light generally excites the complete set of propagating modes, and modal filtration occurs at the tapered transition in the fiber, and, as a consequence, one can observe a decrease in the level of the detected signal. At the same time the forward propagating light still has singlemode structure due to adiabatically increasing of core radius.

Figure 4(a) shows the initial part of the backscatter pattern of sample № 3 resolved into the orthogonal S and P polarization states. This pattern can be observed only if the input states of polarization do not coincide with the eigen polarization states of fiber. In this case, one can expect the rotation of polarization state to be particularly pronounced when light propagates in the fiber. The induced birefringence can be clearly seen as a periodic exchange in the power between the two detected states of polarization [22, 23]. However, in practice such pattern is only observable in the first part of tested fiber and then gradually fades away at the distance of about 20 cm (see example of this fading in Fig. 4(a)). As a result, the direct observation of spatial distribution of polarization beat length is impossible along entire length of PMF [20]. It is also important to note that the oscillation period in the raw backscatter pattern is half of the real beat length because of the measuring technique based on double-pass scheme (forward and backward) and thus light experiencing the birefringence twice [22, 27]. The polarization beat lengths directly measured from the backscatter pattern of tapered fiber samples were 13,4 mm (period of observable beating 6,71 mm) for sample № 1; 13,6 mm (period of observable beating 6,78 mm) for sample № 2; 13,7 mm (period of observable beating 6,86 mm) for sample № 3. Despite the strong fading of the intensity beating of the polarization modes, the information required for the determination of the spatial polarization beat length is not lost. This fading can be understood as a decorrelation of the Rayleigh backscatter pattern.

The starting point of the analysis is the polarization-resolved complex-valued reflectivity data that describes the reflectivity of the tested fiber as a function of longitudinal position. In a birefringent fiber, the pattern is the same for both orthogonal polarization modes. However, because the modes propagate at different speeds, the two reflectivity patterns are time-shifted with respect to each other, which allows the determination of the birefringence. The time of arrival of the backscatter signal from specific tapered fiber section directly depends on propagation constant of the polarization mode, which in turn is determined by the longitudinal fiber profile. Calculation of the polarization beat length distribution along the length of anisotropic tapered fiber is possible when considering the data obtained in the frequency domain. For this purpose Fourier transform was calculated for both polarization-resolved backscatter patterns. Therefore total amplitude of tapered fiber reflectivity function in frequency domain can be calculated following way:

$$R_w (w) = |i_{s,w} (w)|^2 + |i_{p,w} (w)|^2,$$  \hspace{1cm} (1)

where $i_{s,w} (w)$ and $i_{p,w} (w)$ are the reflectivity spectra associated with the two S and P polarizations in frequency domain. The measurement is distributed in nature because it is possible to single out the portion of the data that belongs to a specific fiber section. This spatial slicing is realized by applying a moving window to the total reflectivity. For each windowed section, we calculated the autocorrelation function (example is shown in Fig. 4(b)), in which the existence of two polarization contributions is manifested as a side maximum [20, 21]. The total reflectance pattern generally contains two frequency-shifted versions of the same pattern. This is caused by the fiber dispersion because at some frequency $\omega_0$ the light in the slow polarization mode experiences the same effective refractive indexes as light with
The frequency $\omega_2$ propagating in the fast polarization mode and thus scatters similarly. The difference of these frequencies can be determined by taking the autocorrelation of the total reflectance spectra. We used Gaussian curve fitting to accurately determine the location of the side maximum, which tells the frequency shift between the polarization modes. In a uniformly birefringent PM fiber, this frequency shift is constant, otherwise it changes along the fiber length. The distributed beat length of the tapered fiber can then be calculated from the frequency shifts with Eq. (2).

$$L_{\text{beat}}(z_i) = \frac{c}{n_g \Delta f(z_i)}.$$  \hspace{1cm} (2)

where $n_g$ is the group index of the fiber and $\Delta f(z_i)$ is the frequency shift at location of moving window $z_i$. Applying the calculation of the autocorrelation function in frequency domain for each of the spatial windows along the tapered fiber length, we received the distribution of the polarization beat length of the fiber samples, shown in Fig. 5.

5. Results and discussions

Similar dependences of spatial polarization beat length on tapered fiber core diameter are observed for all samples of the investigated tapered fibers, results are shown in Fig. 5, – the polarization beat length decreases while the diameter of fiber core increases. In the case of a round fiber core in an elliptical inner cladding, shown in Fig. 1 inset, a stress distribution (that expands uniformly out the core and adjacent cladding) is formed via the mismatch of thermal expansion between inner and outer cladding \[16, 28\]. So in this case, the cladding region is
elliptical with major and minor diameters of 2A and 2B respectively and the core is perfectly circular, this birefringence is [16, 28]:

\[
|\beta_p - \beta_s| = \left| n_s - n_p \right| \frac{2\pi}{\lambda} = \frac{C_s A - B}{1 - \beta_p \Delta T \Delta \alpha \lambda A + B}
\]  

(3)

where

\[
C_s = 0.5k_p n_s^3 (n_{11} - n_{12}) \left(1 + \nu_p^2\right)
\]  

(4)

is a combination of fiber and material parameters referred to as strain-optical coefficient; \(n_s\) denotes the refractive index of the fiber; \(p_{11} - p_{12}\) - components of strain-optical tensor of fiber material; \(\nu_p\) - Poisson's coefficient of the cladding; \(\Delta \alpha\) - difference of thermal-expansion coefficients of inner and outer cladings and \(\Delta T\) is a positive thermal difference; \(\beta_p, \beta_s\) - propagation constants of P and S polarization modes respectively; \(\lambda\) - wavelength of radiation; \(n_s, n_p, n_{11}, n_{12}\) group index of S and P polarization modes respectively; \(k_p\) - wavenumber. According to Eq. (3), there is no direct dependence of the birefringence on the geometrical parameters of the fiber cross-section [16, 28]. Spatial polarization beat length by definition is:

\[
L_{\text{beat}} = \frac{2\pi}{|\beta_p - \beta_s|} = \frac{\lambda}{n_s - n_p}
\]  

(5)

Also it had been shown in those papers, that increasing of birefringence while core size increasing (as consequence decreasing of polarization beat length) might be the result of form and stress birefringence of fibers with elliptical core. It means that, according to the classical theory and assumption that cores of investigated tapered fibers were circular (shown in Fig. 1 inset), one can conclude that birefringence should remain constant when the fiber core diameter increases. However, our results show a different behavior of birefringence in long tapered fibers with increasing core diameter.

The similar effect has been demonstrated in paper [18], where it was experimentally shown that instead of increasing of the birefringence in the short SMF tapered regions due to the low refractive index of cladding modes, the birefringence of tapered standard PMF is decreased due to stress release during the tapering process [15, 18]. In both cases, the initial outer diameters of SMF and PMF were 125 µm and decreased in the tapered region. It was also showed that birefringence rapidly decreased at small waists size less 40 µm [18].

The same situation is observed in the case of long tapered PM fibers with large core diameter. Significant role in decreasing of polarization beat length in tested tapered fibers is played by the mechanism of the stress relaxation caused by different speeds of fiber drawing. In order to control the variation of diameter of the tapered fiber, the drawing speed changes depending on the desired geometric profile. It leads to a higher drawing speed at the narrow part of the tapered fiber and, as a consequence, stresses are released. However, this effect is not significant, since the polarization beat length is only reduced by 10-15%.

In this paper, birefringence has been investigated by several methods in long anisotropic tapered PM-fibers with gradually increasing core diameter up to 70 µm in the wide part. The OFDR method gives as a result that the polarization beat length decreased to about 11.8 -12.5 mm in the wide part of tapered fiber samples, whereas in the narrow part, this value ranges from 13.5 mm to 13.9 mm for the different samples. The average values, received as the arithmetic mean of all calculated points along fiber length, are 12.98 mm (sample 1), 13.41 mm (sample 2) и 12.99 mm (sample 3). These results are in good agreement with the values measured by the spectral method and differ by less than 2%. The measured values of the light
extinction ratio in the spectral region of 1550 nm passed through the tapered fiber samples are over 15 dB with the input light linearly polarized along the slow axis and more than 10 dB with input light linearly polarized along the fast axis of the tested fibers.

Figure 5 shows that the polarization beat length does not vary monotonously along the fiber length. This effect may be the evidence of random disturbances of longitudinal geometrical profile during drawing the fiber or local inhomogeneities of the birefringence of the relatively short lengths of investigated fibers. It might also be the result of transverse mode coupling. Any obvious evidence of mode coupling (either polarization mode coupling or transverse mode coupling) influence have not been found during experimental research. Indeed, in the case of a single mode (with polarization degeneracy) radiation propagation, calculation of the autocorrelation function gives a distinct picture with a central peak and two side maxima (shown in Fig. 4(b)) corresponding to each of the polarization modes. In the case when the number of propagating transverse modes of the fiber core is increasing - the number of side maxima would increase proportionally [21]. Since the amplitude of the side maxima carries information about the power propagating in an each of higher order modes, then significant increasing of the number of modes will lead to impossibility of required frequency shift determination in calculation of autocorrelation function. Consequently, the polarization beat length cannot be determined precisely at this point of the fiber. This effect was relatively strong for the tapered fiber sample № 1, in contradistinction to samples № 2 and 3. There is inhomogeneity in the wide part of tapered fiber № 1, as seen from the longitudinal geometric profile. Therefore, the adiabatic condition is slightly violated and higher order modes are excited. This leads to the disappearance of the strong side maximum in autocorrelation function and to the separation of power between additional weak side maxima at several points of conical narrowing of the sample. Consequently, the polarization beat length cannot be calculated. However, due to the reversibility of the light propagation, the further calculation of autocorrelation functions is possible along the remaining fiber length. This effect was not observed while researching tapered fiber samples № 2 and 3; for those fibers the adiabatic condition is strictly satisfied along the entire length. In addition previously in [11–13,19] we showed that $M^2$ and $S^2$ parameters of similar adiabatic isotropic tapered fibers with core diameter more than 100 µm correspond to nearly singlemode propagation of radiation. This confirms and validates the results obtained in this work about mode structure of propagating light and verifies propriety of conclusions that were received from autocorrelation function calculation.

6. Conclusions

Thus preservation of linear polarization state of light was demonstrated in long anisotropic tapered fibers with significant changes in the core diameter (from 8 µm to 70 µm) at entire length of tapered fiber about 10 m. The adiabatic condition of mode area expansion is satisfied to a good accuracy for both types of optical modes - the transverse modes and the polarization modes - in such kind of tapered fibers. Investigation of the spatial distribution of birefringence shows a strong correlation with the longitudinal geometric profile of the tapered fibers.

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