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OPTICAL VORTICES IN WEAKLY ELLIPTICAL ANISOTROPIC FIBRES WITH TORSIONAL MECHANICAL STRESS

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In the present paper we have obtained the modes and the corresponding propagation constants of weakly elliptical anisotropic optical fibres with torsional mechanical stress. Far from the resonance values of the pitch twist, the modes are found to coincide with the modes of ideal fibres with stress with high accuracy. Moreover, the circularly polarized optical vortices with topological charges ±1 are demonstrated to be robust in such a fibre. The analysis of the mode propagation constants shows that the mutual influence of stress-induced circular birefringence and the spin-orbit interaction provides the effective reduction of linear anisotropy-induced mode dispersion.

Keywords: optical vortex, optical fibre, mode dispersion.

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INTRODUCTION

Optical fibres with torsional mechanical stress (TMS) induced by twisting a fibre around its axis hold a special place among other types of optical fibres. It is due to their unique ability to significantly reduce the polarization mode dispersion (PMD) [1-3], which is one of the main causes of pulse lengthening in the fibre systems and decreasing of sensitivity of the various transducers [4, 5]. To date such fibres have been comprehensively studied. In particular, it was theoretically and experimentally demonstrated [6] that the fundamental modes of ideal (without any additional optical imperfections) fibres with TMS are the circularly polarized fields propagating with different phase velocities. In particular, it means that the twist induces circular birefringence in an optical fibre This leads to the well known effect of the rotation of the linearly polarized light launched into the twisted fibre. Recently, efforts have been paid to investigate the structure of the higher-order modes of fibres with TMS as well. It was shown [7] that the modes with the azimuthal number $l=1$ of ideal fibres with TMS are represented by two circularly polarized optical vortices (OVs) with the topological charges ± 1 and the conventional $TE_{0,n}$ and $TM_{0,n}$ modes (n being the radial mode number). At the same time, the modes with $l>1$ are found [7] to consist of four circularly polarized OVs with topological charges $\pm l$. The corresponding propagation constants of the modes were also obtained. Besides, the coupling of the modes with different azimuthal numbers induced by TMS has been studied [8]. As a result, the coupled modes are found to obey a kind of selection rule – they must have the same total (the sum of spin and orbital) angular momentum in the direction of propagation.

Study of the effect of TMS on the light propagation has not been limited only to the case of ideal fibres. Indeed, it was shown [6] that in the presence of some kind of optical perturbations (such as linear anisotropy of the material or of the shape of the fibre's cross-section) the fundamental modes of anisotropic fibres with TMS are elliptically polarized. The question of the OVs propagation through such fibres was also considered [9]. In particular, the possibility of the stable transmission of circularly polarized OVs with unity topological charge through elliptical fibres with TMS was theoretically demonstrated under the condition that the influence of ellipticity and TMS suppresses the spin-orbit interaction (SOI) in the fibre.

Quite recently, the combined effect of relatively small linear anisotropies of material and shape on the modes propagation in fibres with TMS near the resonance points was studied [10]. As a result, the conclusion was made that such fibres can be used for highly effective and stable generation of practically valuable radially and azimuthally polarized vector beams.

Meanwhile, as far as we know, the effect of small linear anisotropy on the structure of the higher-order modes and the spectrum of the propagation constants of fibres with TMS far from resonance points has not been studied yet. At the same time, along with academic interest, a purely practical interest to this question is connected with the problem of OVs propagation in optical fibres. Indeed, the OVs have a number of unique properties that make them the very prospective tools for encoding and transmitting information [11, 12], for trapping and manipulating microparticles [13], for astronomy purposes [14, 15] etc. To transmit the OVs over distance the various types of optical fibres have been proposed [16-20]. Probably, one of the most cheap and thus practically attractive types of optical fibres for the robust OVs transmission is an ideal fibre with TMS [7-9]. At that, however, one should take into account that any real fibre inevitably possesses some amount of linear anisotropy [6] that, in particular, causes the PMD thus impairing the transmission abilities of a fibre. While the effect of the anisotropy-induced PMD reduction by twisting a fibre at a sufficiently high rate was demonstrated for the fundamental modes, the question on the analogous influence of TMS on the OVs in the presence of small linear anisotropy has not been addressed yet. In light of this, we pursue two main goals in this paper. The first one is to derive the higher-order $l=1$ modes of weakly anisotropic fibres with TMS. The second one is to establish the mode propagation constants and answer the question of whether TMS suppresses the influence of small linear anisotropy on the propagation constants of the modes thus leading to the reduction of the anisotropy-induced mode dispersion.

1. MODEL AND PERTURBATION THEORY APPROACH

It is usually assumed that the fibre consists of the core with the radius r_0 and an infinite cladding and the refractive index of the model in the problem can be presents as [10]:

$$\hat{n}^2 = n^2(r)\hat{1} - 2n_{co}^2 \Delta f_r' \cos 2\varphi\,\hat{1} + \delta n^2 \hat{\varepsilon} + q p_{44} n_{co}^4 r \begin{pmatrix} 0 & 0 & \sin\varphi \\ 0 & 0 & -\cos\varphi \\ \sin\varphi & -\cos\varphi & 0 \end{pmatrix}. \quad (1)$$

Here the first term describes the axially symmetric distribution of the refractive index in the ideal fibres: $n^2(r) = n_{co}^2(1 - 2\Delta \cdot f(r))$, $\Delta = \left(n_{co}^2 - n_{cl}^2\right)/2n_{co}^2$ is the height of the refractive index profile, $n_{co}^2 = \frac{1}{2}\left(n_x^2 + n_y^2\right)$ and n_{cl}^2 are the values of the squared refractive index in the core and cladding, respectively, and for the fibre with step-like distribution of the refractive index the profile function reads as $f(r) = \theta(r/r_0 - 1)$, θ being the unity step. The second term in Eq. (1) corresponds to the ellipticity of the fibre's cross-section. Indeed, the most simple way of introducing the ellipticity is to make the scale transformation: $x \to x(1+\delta)$, $y \to y(1-\delta)$, where the ellipticity parameter $\delta << 1$, and then expand the refractive index in δ. The prime stands for derivative with respect to r. Linear anisotropy of material is taken into account by introducing the third term in Eq. (1), where $\hat{\varepsilon} = \mathrm{diag}(1,-1,-1)$, $\delta n^2 = 0.5\left(n_x^2 - n_y^2\right) << 1$. The last term in Eq. (1) accounts for the influence of TMS on the optical properties of the fibre through the photoelastic effect and $p_{44} = 0.5\left(p_{11} - p_{12}\right)$, p_{11} and p_{12} are the photoelastic constants, $q = 2\pi/H$, H being the twist pitch. Cylindrical polar coordinates (r, φ, z) are implied and the axis z is the fibre's axis. Note that the tensor in Eq. (1) operates on the Cartesian components of the electric field: $\vec{E} = \mathrm{col}\left(E_x, E_y, E_z\right)$.

To find the modes of elliptical anisotropic fibres with TMS let us consider the vector wave equation for nonmagnetic anisotropic media with the refractive index in Eq. (1) [10]:

$$\left(\vec{\nabla}^2 + k^2 \hat{n}^2\right)\vec{E} = -\vec{\nabla}\left(\left(\vec{E} \cdot \vec{\nabla} \ln \varepsilon\right) + q p_{44} n_{co}^4 r \left(\sin\varphi \frac{\partial E_x}{\partial z} - \cos\varphi \frac{\partial E_y}{\partial z}\right)\right), \quad (2)$$

where $\vec{\nabla} = \left(\partial/\partial x, \partial/\partial y, \partial/\partial z\right)$, $k = 2\pi/\lambda$, λ is the wavelength in vacuum. The second term in the right hand side of Eq. (2) is emerged owing to the tensorial nature of (1) and it was taken into account that the refractive index can be presented in the form: $\hat{n}^2(r,\varphi) = \varepsilon \hat{1} + \delta\hat{\varepsilon}$. In addition, we have disregarded the influence of ellipticity and material anisotropy in the gradient term. This is valid under the following two conditions:

$$\Delta >> \delta n^2 \text{ and } H << \frac{\left(2\pi \bar{n}^2 r_0\right)^2 |p_{44}|}{\lambda \delta n^2}. \quad (3)$$

It is also worth noting that the gradient term $\vec{\nabla}\left(\vec{E} \cdot \vec{\nabla} \ln n^2(r)\right)$ describes the spin-orbit interaction (SOI) of light in an ideal fibre [21].

Given the translation invariance of Eq. (1) in the z - direction, it is possible to seek for a solution of Eq. (2) in the factorized form: $\vec{E} = \vec{e}(r,\varphi)e^{i\beta z}$, where β is the propagation constant. Substituting the ansatz in Eq. (2), one can present the wave equation in the form of the following eigenvalue problem:

$$\left(\hat{H}_0 + \hat{V}_{ell} + \hat{V}_{an} + \hat{V}_{TMS}\right)|\psi\rangle = \beta^2 |\psi\rangle, \tag{4}$$

where the ket-vector $|\psi\rangle = \mathrm{col}\left(e_x, e_y, e_z\right)$, the operator $\hat{H}_0$ governs the light propagation in the ideal optical fibres allowing for the gradient term [22], the operators $\hat{V}_{ell} = -2k^2 n_{co}^2 \Delta \delta r f_r' \cos 2\varphi \hat{1}$ and $\hat{V}_{an} = k^2 \delta n^2 \hat{s}$ account for the effect of ellipticity and material anisotropy on the light propagation, correspondingly, and

$$\hat{V}_{TMS} = k^2 q p_{44} n_{co}^4 r \begin{pmatrix} 0 & 0 & \sin\varphi \\ 0 & 0 & -\cos\varphi \\ \sin\varphi & -\cos\varphi & 0 \end{pmatrix} +$$

$$+ iqp_{44} n_{co}^2 \beta \begin{pmatrix} 0.5\sin 2\varphi r\nabla_r - \sin^2\varphi \nabla_\varphi & -1 - \cos^2\varphi r\nabla_r + 0.5\sin 2\varphi \nabla_\varphi & 0 \\ 1 + \sin^2\varphi r\nabla_r + 0.5\sin 2\varphi \nabla_\varphi & -0.5\sin 2\varphi r\nabla_r - \cos^2\varphi \nabla_\varphi & 0 \\ ir\beta \sin\varphi & -ir\beta\cos\varphi & 0 \end{pmatrix}$$

is owing to TMS.

It is easy to see that the operators in Eq. (4) have the following orders: $\hat{H}_0 \propto k^2 n_{co}^2$, $\hat{V}_{ell} \propto k^2 n_{co}^2 \Delta\delta$, $\hat{V}_{an} \propto k^2 \delta n^2$, and $\hat{V}_{TMS} \propto k^2 q p_{44} n_{co}^4 r_0$, where the typical values of the parameters are as follows: $n_{co} = 1.5$, $\Delta = 10^{-1} - 10^{-3}$ (for weakly guiding fibres), $\delta = 10^{-1} - 10^{-2}$, $\delta n^2 = 10^{-3} - 10^{-8}$, $p_{44} = -0.075$ (for silica) and $H > 10^{-2} m$. As a result, $\hat{H}_0 >> \hat{V}_{ell}, \hat{V}_{an}, \hat{V}_{TMS}$ and one can use the perturbation theory approach for solving Eq. (4), treating $\hat{H}_0$ as a zero-order operator and the operator $\hat{V} = \hat{V}_{ell} + \hat{V}_{an} + \hat{V}_{TMS}$ as a perturbation. As is well known [23], the key point of this method is that the system could be described with the so-called perturbation matrix, which has to be built by averaging the total operator $\hat{H}_0 + \hat{V}$ over the eigenstates $\left|\psi_{l,n}^{(0)}\right\rangle_i$ of the zero-order operator: $\hat{H}_0 \left|\psi_{l,n}^{(0)}\right\rangle_i = \beta_i^{(0)2} \left|\psi_{l,n}^{(0)}\right\rangle_i$. Since we are interested in modes with the azimuthal number $l = 1$, as the basis for the perturbation theory we take the following zero-order modes:

$$\left|\psi_{1,n}^{(0)}\right\rangle_1 = \mathrm{col}\left(F_{1,n}(r), \quad iF_{1,n}(r), \quad \frac{i}{\tilde{\beta}_{1,n} r}\left[rF'_{1,n} - F_{1,n} \right] e^{i\varphi} \right) e^{i\varphi},$$

$$\left|\psi_{1,n}^{(0)}\right\rangle_2 = \mathrm{col}\left(F_{1,n}(r), \quad -iF_{1,n}(r), \quad \frac{i}{\tilde{\beta}_{1,n} r}\left[rF'_{1,n} - F_{1,n} \right] e^{-i\varphi} \right) e^{-i\varphi},$$

$$\left|\psi_{1,n}^{(0)}\right\rangle_3 = \begin{pmatrix} -F_{1,n}(r)\sin\varphi \\ F_{1,n}(r)\cos\varphi \\ 0 \end{pmatrix}, \quad \left|\psi_{1,n}^{(0)}\right\rangle_4 = \begin{pmatrix} F_{1,n}(r)\cos\varphi \\ F_{1,n}(r)\sin\varphi \\ \frac{i}{\tilde{\beta}_{1,n} r}\left[rF'_{1,n} + F_{1,n} \right] \end{pmatrix}, \qquad (5)$$

where the radial function for the step-index fibres is $F_{l,n}(r) = \begin{cases} \dfrac{J_l(\tilde{U}_n R)}{J_l(\tilde{U}_n)}, R \le 1, \\ \dfrac{K_l(\tilde{W}_n R)}{K_l(\tilde{W}_n)}, R \ge 1, \end{cases}$ and $R = \dfrac{r}{r_0}$ [22]. The modes $\left|\psi_{1,n}^{(0)}\right\rangle_1 \equiv |1,1,n\rangle$ and $\left|\psi_{1,n}^{(0)}\right\rangle_2 \equiv |-1,-1,n\rangle$ are right and left circularly polarized OVs, where the first index inside the ket-vector describes the sign of polarization, while the second one specifies topological charge; the modes $\left|\psi_{1,n}^{(0)}\right\rangle_3 \equiv |TE_{0,n}\rangle$ and $\left|\psi_{1,n}^{(0)}\right\rangle_4 \equiv |TM_{0,n}\rangle$ represent the standard transverse electric and magnetic mode, correspondingly. The perturbation matrix is given by:

$$H_{ij} = {}_i\left\langle \psi_{l,n}^{(0)} \right| \hat{H}_0 + \hat{V} - \beta^2 \hat{1} \left| \psi_{l,n}^{(0)} \right\rangle_j, \qquad (6)$$

where the standard definition of the scalar product is implied: $\langle \Phi | \Psi \rangle = \int_0^{\infty} \int_0^{2\pi} \begin{pmatrix} \Phi_x^* & \Phi_y^* & \Phi_z^* \end{pmatrix} \begin{pmatrix} \Psi_x \\ \Psi_y \\ \Psi_z \end{pmatrix} r dr d\varphi$.

Using Eqs. (4) – (6), we obtain the perturbation operator for $l = 1$ modes:

$$\hat{H}=\begin{pmatrix} \tilde{\beta}_n^2-\beta^2+A_n+C_n & 0 & i\left(D_n+E\right) & E-D_n \\ 0 & \tilde{\beta}_n^2-\beta^2+A_n-C_n & -i\left(D_n+E\right) & E-D_n \\ -i\left(D_n+E\right) & i\left(D_n+E\right) & \tilde{\beta}_n^2-\beta^2 & 0 \\ E-D_n & E-D_n & 0 & \tilde{\beta}_n^2-\beta^2+2B_n \end{pmatrix}, \quad (7)$$

where the SOI constants for the step-index fibres are $A_n=\frac{\Delta}{Q_n r_0^2}\left(F_n F_n'-F_n^2\right)_{R=1}$, $B_n=\frac{\Delta}{Q_n r_0^2}\left(F_n^2+F_n F_n'\right)_{R=1}$, $Q_n=\int\limits_0^\infty RF_n^2\left(R\right)dR$, $\tilde{\beta}_{l,n}$ is the well known scalar propagation constant [22], $C_n=-2\left(\Sigma_n+\Theta\beta-\frac{\Theta\beta^2}{\tilde{\beta}_n}\right)$ is proportional to the twist, $\Sigma_n=\frac{k^2 q\left|p_{44}\right| n_{co}^4}{\tilde{\beta}_n}$ and $\Theta=0.5q\left|p_{44}\right| n_{co}^2$, $D_n=-k^2 n_{co}^2\Delta\delta/Q_n$ and $E=k^2\delta n^2$ are the constants of ellipticity and material anisotropy, correspondingly. Here and in what follows the azimuthal number is omitted and assumed to be unity.

The analytical expressions of modes and the corresponding propagation constants are to be obtained by solving the following equation:

$$\hat{H}\vec{x}=0. \quad (8)$$

Here the vector $\vec{x}_k$ has the components a_k^i representing the desired modes in the basis (5): $\left|\psi\right\rangle_k=\sum_i a_k^i\left|\psi_n^{(0)}\right\rangle_i$.

3. HIGHER-ORDER $l=1$ MODES THE MODE PROPAGATION CONSTANTS

Strictly speaking, solving Eq. (8) with the matrix in Eq. (7) would give the modes of elliptical anisotropic fibres at arbitrary reasonable values of the fibre parameters. The excat expressions for the modes, however, would be too cumbersome for physical analasyse. Besides, finding the exact propagation constants seems to be a holpless task, that is owing to the nontrivial dependence of the matrix in Eq. (7) on β through the constant C_n. Meanwhile, since we are interested only in the particular case of weak linear anisotropy when $E, \left|D_n\right| << \left|C_n\right|, \left|A_n\right|, \left|B_n\right|$, it looks reasonable to find an approximate solution of Eq. (8) by means of perturbation approach. Following this idea, one should treat the operator $\hat{\hat{H}}_0=\hat{H}\left(E=D_n=0\right)$ as a zero-order one and the operator

$\hat{V}_{lan} = \begin{pmatrix} 0 & 0 & i(D_n + E) & E - D_n \\ 0 & 0 & -i(D_n + E) & E - D_n \\ -i(D_n + E) & i(D_n + E) & 0 & 0 \\ E - D_n & E - D_n & 0 & 0 \end{pmatrix}$ as a perturbation, which corresponds to linear anisotropies of both types.

As was demonstrated in [7], the zero-order eigenfunctions coincide with the fields in Eq. (5), while the corresponding propagation constants are:

$$\beta_{1,2}^{(0)} = \tilde{\beta}_n + \frac{1}{2\tilde{\beta}_n}\left(A_n \mp 2\Sigma_n\right), \quad \beta_3^{(0)} = \tilde{\beta}_n, \quad \beta_4^{(0)} = \tilde{\beta}_n + \frac{B_n}{\tilde{\beta}}. \tag{9}$$

This spectrum has the unique feature of demonstrating the so-called accidental degeneracy, which is in our case the intersection of some of the spectral branches at the given values of the pitch H. The corresponding case has been considered in [10]. Here we are interested in finding a solution of Eq. (8) far from such resonance values of the parameter H. The desired regime is implemented in the fibre under the two conditions:

$$\left|2\Sigma_n - |A_n|\right| >> |E + D_n|, \quad \left|2\Sigma_n - \left(2|B_n| - |A_n|\right)\right| >> |E - D_n|. \tag{10}$$

When these inequalities are obeyed, there is no degeneracy in the spectrum in Eq. (9) and, consequently, the influence of the perturbation $\hat{V}_{lan}$ should be taken into account by making use the perturbation theory without degeneracy [23]. In accordance with it, the first-order corrections to the eigenfunctions of the zero-order operator are known to have the order: $\frac{V_{ik}}{\beta_i^{(0)^2} - \beta_k^{(0)^2}} << 1$. If one also recalls that, in contrast to the phase corrections, the corrections to the field amplitude do not accumulate under the light propagation through a fibre, it becomes clear that it is possible to disregard the effect of small linear anisotropy on the structure of the modes. In other words, the $l = 1$ modes of weakly elliptical anisotropic fibres with TMS are those of ideal fibres with TMS in the first-order approximation.

The first-order corrections to the eigenvalues $\beta_i^{(0)^2}$ of the zero-order operator $\hat{\tilde{H}}_0$ are known to be given by: $\delta\beta_i^{(1)} = \beta_i^2 - \beta_i^{(0)^2} = V_{ii}$, where V_{ii} are the diagonal elements of the matrix of the operator $\hat{V}_{lan}$ in the $\hat{\tilde{H}}_0$-representation. It follows from the above that the propagation constants in the first-order approximation read as:

$$\beta_i \approx \beta_i^{(0)} + \frac{\delta\beta_i^{(1)}}{2\tilde{\beta}} . \tag{11}$$

At the same time, the direct calculations show that

$$\delta\beta_i^{(1)} = 0 , \tag{12}$$

in the case of the perturbation of the form $\hat{V}_{lan}$. Thus, it turns out that to study the effect of linear anisotropy on the propagation constants one has to consider the higher-order terms of the perturbation theory. In so doing and allowing for Eq. (12), one gets the following form for the propagation constants in the second-order approximation:

$$\beta_i \approx \beta_i^{(0)} + \frac{\delta\beta_i^{(2)}}{2\tilde{\beta}} . \tag{13}$$

where the second-order correction is defined as [23]: $\delta\beta_i^{(2)} = \sum_{k \neq i} \frac{\left|V_{k,i}\right|^2}{\beta_k^{(0)^2} - \beta_i^{(0)^2}}$. It yields the spectrum of the propagation constants of the $l = 1$ modes of weakly elliptical anisotropic fibres with TMS up to the second-order terms:

$$\beta_1 = \tilde{\beta}_n + \frac{1}{2\tilde{\beta}_n}\left\{ A_n - 2\Sigma_n - \frac{(D-E)^2}{A_n - 2B_n - 2\Sigma_n} \right\},$$

$$\beta_2 = \tilde{\beta}_n + \frac{1}{2\tilde{\beta}_n}\left\{ A_n + 2\Sigma_n + \frac{(D+E)^2}{|A_n| - 2\Sigma_n} \right\},$$

$$\beta_3 = \tilde{\beta}_n - \frac{(D+E)^2}{2\tilde{\beta}_n\left(|A_n| - 2\Sigma_n\right)}, \quad \beta_4 = \tilde{\beta}_n + \frac{1}{2\tilde{\beta}_n}\left\{ 2B_n + \frac{(D-E)^2}{A_n - 2B_n - 2\Sigma_n} \right\}. \tag{14}$$

As is seen from Eq. (14), the anisotropy-induced corrections are imparted to the structure of the mode propagation constants, thus ensuring additional mode dispersion as compared with the case of ideal fibres with TMS. At that, however, it is important that these corrections are strongly suppressed by the mutual influence of the SOI and TMS-induced circular birefringence, thus being negligibly small. It directly leads to the significant reduction of linear anisotropy-induced mode dispersion. Finally, one should also note that the important feature of the spectrum in Eq. (14) is the absence of degeneracy. It allows us to make a conclusion on stability of modes in Eq. (5), and, specifically, on robustness of OVs $|1,1,n\rangle$ and $|-1,-1,n\rangle$.

CONCLUSION

It is considered the higher-order mode propagation through weakly elliptical anisotropic optical fibres with torsional mechanical stress. It is found that, at certain fibre's parameters, the fibres modes are the modes of ideal fibes with stress. The analysis of the mode propagation constants shows that the mutual effect of stress-induced circular birefringence and the spin-orbit interaction leads to the strong reduction of the linear anisotropy-induced mode dispersion. Besides, the circularly polarized optical vortices with topological charges ± 1 are found to be the robust fields in the fibre considered. It is owing to the absence of degeneracy in the spectrum of the mode propagation constants.

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References

1. A. J. Barlow, J. J. Ramskov-Hansen and D. N. Payne, *Appl. Opt.* **20**, 2962 (1981).
2. M. J. Li, X. Chen and D. A. Nolan, *Opt. Lett.* **29**, 448 (2004).
3. M. Wang, T. Li and S. Jian, *Opt. Express* **11**, 2403 (2003).
4. A. Smith, *Appl. Opt.* **17**, 52 (1978).
5. T. Yoshino, *J. Opt. Soc. Am. B* **22**, 1856 (2005).
6. R. Ulrich, A. Simon, *Appl. Opt.* **18**, 2241 (1979).
7. C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky, *J. Opt. A: Pure Appl. Opt.* **10**, 095007 (2008).
8. C. N. Alexeyev, E. V. Borshak, A. V. Volyar and M. A. Yavorsky, *J. Opt. A: Pure Appl. Opt.* **11**, 094011 (2009).
9. C. Alexeyev, E. Barshak, Y. Fridman and M. Yavorsky, *Appl. Opt.* **51**, C163 (2012).
10. C. N. Alexeyev, E. V. Barshak, T. A. Fadeyeva, A. V. Volyar and M. A. Yavorsky, *J. Opt.* **13**, 075706 (2011).
11. G. Gibson, J. Courtial, M. Padgett, M. Vasnetsov, V. Pas'ko, S. Barnett and S. Franke-Arnold, *Opt. Express* **12**, 5448 (2004).
12. N. J. Cerf, C. Adami and P. G. Kwiat, *Phys. Rev. A* **57**, R1477 (1998).
13. K. T. Gahagan, G. A. Swartzlander, Jr., *Opt. Lett.* **21**, 827 (1996).
14. G. A. Swartzlander, Jr., *J. Opt. A: Pure Appl. Opt.* **11**, 090422 (2009).
15. G. A. Swartzlander, Jr., E. L. Ford, R. S. Abdul-Malik, L. M. Close, M. A. Peters, D. M. Palacios and D. W. Wilson, *Opt. Express* **16**, 10200 (2008).
16. C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky, *J. Opt. A: Pure Appl. Opt.* **6**, S162 (2004).
17. C. N. Alexeyev, M. A. Yavorsky, *J. Opt. A: Pure Appl. Opt.* **6**, 824 (2004).
18. C. N. Alexeyev, B. P. Lapin and M. A. Yavorsky, *Phys. Rev. A* **78**, 013813 (2008).
19. C. N. Alexeyev, T. A. Fadeyeva, B. P. Lapin and M. A. Yavorsky, *Phys. Rev. A* **83**, 063820 (2011).
20. C. N. Alexeyev, M. A. Yavorsky, *Phys. Rev. A* **78**, 043828 (2008).
21. C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky, "*Fiber Optical Vortices,*" in *Lasers, Optics and Electro-Optics Research Trends*, Ed. by L. I. Chen (Nova Publishers, 2007).
22. A. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman and Hall, London, 1985).
23. A. S. Davydov, *Quantum Mechanics*, 2d ed. (Pergamon, Oxford, 1976).

Яворський М. О. Оптичні вихори у слабо еліптичних анізотропних волокнах з крутильними механічними напругами / М. О. Яворський // Вчені записки Таврійського національного університету імені В. І. Вернадського. Серія : Фізико-математичні науки. – 2013. – Т. 26 (65), № 2. – С. 20-30.
Визначені моди і стали поширення слабо еліптичних анізотропних оптичних волокон з крутильним механічним напруженням. Встановлено, що далеко від резонансних значень кроку скрутки моди волокна співпадають з модами ідеальних волокон з напруженням. Більш того, продемонстровано, що циркулярно поляризовані оптичні вихори із топологічними зарядами ±1 мають властивість структурної стійкості у цих волокнах. У результаті аналізу сталих поширення встановлено, що сукупний вплив породженого напруженнями циркулярного подвійного променезаломлення та спин-орбітальної взаємодії забезпечує ефективне заглушення дисперсії мод, яка наведена лінійною анізотропією.
Ключові слова: оптичний вихор, оптичне волокно, дисперсія моди.

Яворский М. А. Оптические вихри в слабо эллиптических анизотропных волокнах с крутильными механическими напряжениями / М. А. Яворский // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2013. – Т. 26 (65), № 2. – С. 20-30.
В данной работе мы получили моды и соответствующие постоянные распространения слабо эллиптических анизотропных оптических волокон с крутильными механическими напряжениями. Установлено, что вдали от резонансных значений шага скрутки моды системы совпадают с модами идеальных волокон с напряжениями. Более того, показано, что циркулярно поляризованные оптические вихри с топологическими зарядами ±1 являются устойчивыми в данных волокнах. В результате анализа постоянных распространения установлено, что совместное влияние индуцированного напряжениями циркулярного двулучепреломления и спин-орбитального взаимодействия обеспечивает эффективное подавление модовой дисперсии, вызванной линейной анизотропии.
Ключевые слова: оптический вихрь, оптическое волокно, модовая дисперсия.

Список литературы

1. Barlow A. J. Birefringence and polarization mode-dispersion in spun single-mode fibers / A. J. Barlow, J. J. Ramskov-Hansen and D. N. Payne // Appl. Opt. – 1981. – Vol. 20. – P. 2962.
2. Li M. J. Effects of residual stress on polarization mode dispersion of fibers made with different types of spinning / M. J. Li, X. Chen and D. A. Nolan // Opt. Lett. – 2004. – Vol. 29. – P. 448.
3. Wang M. Analytical theory for polarization mode dispersion of spun and twisted fiber / M. Wang, T. Li and S. Jian // Opt. Express. – 2003. – Vol. 11. – P. 2403.
4. Smith A. Polarization and magnetooptic properties of single-mode optical fiber / A. Smith // Appl. Opt. – 1978. – Vol. 17. – P. 52.
5. Yoshino T. Theory for the Faraday effect in optical fiber / T. Yoshino // J. Opt. Soc. Am. B – 2005. – Vol. 22. – P. 1856.
6. Ulrich R. Polarization optics of twisted single-mode fibers / R. Ulrich, A. Simon // Appl. Opt. – 1979. – Vol. 18. – P. 2241.
7. Alexeyev C. N. Optical vortices in twisted optical fibres with torsional stress / C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky // J. Opt. A: Pure Appl. Opt. – 2008. – Vol. 10. – P. 095007.
8. Angular momentum conservation and coupled vortex modes in twisted optical fibres with torsional stress / C. N. Alexeyev, E. V. Borshak, A. V. Volyar and M. A. Yavorsky // J. Opt. A: Pure Appl. Opt. – 2009. – Vol. 11. – P. 094011.
9. Optical vortices in twisted elliptical fibres with torsional stress / C. Alexeyev, E. Barshak, Y. Fridman and M. Yavorsky // Appl. Opt. – 2012. – Vol. 51. – P. C163.
10. Generation of radially and azimuthally polarized beams with elliptical anisotropic twisted optical fibres / Alexeyev C. N., Barshak E. V., Fadeyeva T. A., [et al.] // J. Opt. – 2011. – Vol. 13. – P. 075706.
11. Free-space information transfer using light beams carrying orbital angular momentum / G. Gibson, J. Courtial, M. Padgett, [et al.] // Opt. Express. – 2004. – Vol. 12. – P. 5448-5456.

12. Cerf N. J. Optical simulation of quantum logic / N. J. Cerf, C. Adami and P. G. Kwiat // Phys. Rev. A. – 1998. – Vol. 57. – P. R1477.
13. Gahagan K. T. Optical vortex trapping of particles / K. T. Gahagan, G. A. Swartzlander, Jr. // Opt. Lett. – 1996. – Vol. 21. – P. 827.
14. Swartzlander G. A., Jr. The optical vortex coronagraph / G. A. Swartzlander, Jr. // J. Opt. A : Pure Appl. Opt. – 2009. – Vol. 11. – P. 090422.
15. Astronomical demonstration of an optical vortex coronagraph / G. A. Swartzlander, Jr., E. L. Ford, R. S. Abdul-Malik, [et al.] // Opt. Express. – 2008. – Vol. 16. – P. 10200.
16. Alexeyev C. N. Vortex-preserving weakly guiding anisotropic twisted fibres / C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky // J. Opt. A : Pure Appl Opt. – 2004. – Vol. 6. – P. S162.
17. Alexeyev C. N. Optical vortices and the higher order modes of twisted strongly elliptical optical fibres / C. N. Alexeyev, M. A. Yavorsky // J. Opt. A : Pure Appl. Opt. – 2004. – Vol. 6. – P. 824.
18. Alexeyev C. N. Helical core optical fibers maintaining propagation of a solitary optical vortex / C. N. Alexeyev, B. P. Lapin and M. A. Yavorsky // Phys. Rev. A. – 2008. – Vol. 78. – P. 013813.
19. Generation of optical vortices in layered helical waveguides / C. N. Alexeyev, T. A. Fadeyeva, B. P. Lapin and M. A. Yavorsky // Phys. Rev. A. – 2011. – Vol. 83. – P. 063820.
20. Alexeyev C. N. Generation and conversion of optical vortices in long-period helical core optical fibers / C. N. Alexeyev, M. A. Yavorsky // Phys. Rev. A. – 2008. – Vol. 78. – P. 043828.
21. Alexeyev C. N. Fiber Optical Vortices / C. N. Alexeyev, A. V. Volyar and M. A. Yavorsky // Lasers, Optics and Electro-Optics Research Trends ; L. I. Chen, ed. – Nova Publishers, 2007.
22. Snyder A. W. Optical Waveguide Theory / A. W. Snyder and J. D. Love. – London : Chapman and Hall, 1985. – 734 p.
23. Davydov A. S. Quantum Mechanics / A. S. Davydov. – Pergamon, Oxford, 1976. – 637 p.

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