RADIOPHYSICS

Original article
DOI: https://doi.org/10.18721/JPM.16416

SPUN FIBERS AND THEIR DESCRIPTION WITHIN THE JONES FORMALISM IN ANALYZING THE PRACTICAL FIBER-OPTIC CIRCUITS

V. S. Temkina✉, *L. B. Liokumovich, A. B. Archelkov, A. V. Medvedev, A. S. Kozlov, K. V. Greshnevikov*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ temkina_vs@spbstu.ru

Abstract. In this paper, an analytical form for the Jones matrix of a real spun fiber has been obtained, taking into account a slight deviation of its properties from an idealized representation of this fiber by the rotation matrix. The derivation was made within the framework of the optical element model with phase anisotropy. The features of using the Jones matrix of a real spun fiber in analysis of practical fiber-optic circuits and modeling their signals were considered. The experiments with the spun fiber revealing the parameter deviations of the polarization modes of the real spun fiber from the idealized model and allowing estimation of this deviation level were performed.

Keywords: Jones matrix formalism, spun fiber, phase anisotropy, polarization state of light

Funding: The reported study was funded by Russian Science Foundation Grant No. 22-19-00513 (https://rscf.ru/en/project/22-19-00513/)

Citation: Temkina V. S., Liokumovich L. B., Archelkov A. B., Medvedev A. V., Kozlov A. S., Greshnevikov K. V., Spun fibers and their description within the Jones formalism in analyzing the practical fiber-optic circuits, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (4) (2023) 198–214. DOI: https://doi.org/10.18721/JPM.16416

Научная статья
УДК 535.5, 535-4, 535.012.2
DOI: https://doi.org/10.18721/JPM.16416

ВОЛОКОННЫЕ СВЕТОВОДЫ SPUN-ТИПА И ИХ ОПИСАНИЕ В РАМКАХ ФОРМАЛИЗМА МАТРИЦ ДЖОНСА ПРИ АНАЛИЗЕ ПРАКТИЧЕСКИХ ОПТОВОЛОКОННЫХ СХЕМ

В. С. Темкина✉, *Л. Б. Лиокумович*, *А. Б. Арчелков*,
А. В. Медведев, *А. С. Козлов*, *К. В. Грешневиков*

Санкт-Петербургский политехнический университет Петра Великого,

Санкт-Петербург, Россия

✉ temkina_vs@spbstu.ru

Аннотация. В работе получено выражение для матрицы Джонса реального волоконного световода spun-типа, которое учитывает слабое отклонение его свойств от таковых для случая идеализированного представления этого волокна матрицей поворота. Вывод проведен в рамках модели оптического элемента с фазовой анизотропией. Рассмотрены особенности использования полученной матрицы Джонса реального spun-волокна при анализе практических оптоволоконных схем и моделировании их сигналов. Выполнены эксперименты со spun-волокном, демонстрирующие отклонение параметров поляризационных мод реального волокна от идеализированной модели и позволившие оценить уровень этого отклонения.

Ключевые слова: формализм матриц Джонса, spun-волокно, фазовая анизотропия, состояние поляризации света

Финансирование: Исследование выполнено за счет гранта Российского научного фонда № 00513-19-22 (https://rscf.ru/project/22-19-00513/).

Ссылка для цитирования: Темкина В. С., Лиокумович Л. Б., Арчелков А. Б., Медведев А. В., Козлов А. С., Грешневиков К. В. Волоконные световоды spun-типа и их описание в рамках формализма матриц Джонса при анализе практических оптоволоконных схем // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 4. С. 198–214. DOI: https://doi.org/10.18721/JPM.16416

Introduction

The improvement of fiber-optic technologies has contributed to the active development of various types of specialized optical fibers. One of the directions in this field is the development of a unique class of spun-type fibers, which have a particular internal anisotropy structure. Such fibers have the same internal structure as fibers with linear anisotropy, however, upon shifting along the longitudinal axis of the fiber, the direction of the polarization axes undergoes regular rotation. This is achieved by twisting a preform with a birefringent structure (polarization-maintaining fiber) during fiber drawing.

The type of intrinsic polarization modes of such a fiber depends on the ratio of two key parameters in the resulting fiber structure. The first parameter, V_L, rad/m, is the increment of the phase difference of the linear polarization modes of the local fiber segment, which characterizes the linear anisotropy caused by the transverse deformation of the core induced during manufacture. The second one, $V_{(}$, rad/m, is the linear velocity of the longitudinal rotation of the direction of the polarization axes.

Depending on the achieved ratio V_α/V_L, the eigenmodes of the spun fiber may have a different character, but it is important to note that with an increase in the value of V_α/V_L, the proper modes of the spun fiber tend to orthogonal circular polarizations [1].

Two types of spun fibers are known: with low (LoBi) and high (HiBi) birefringence.

The first type is characterized by the fact that a high value of the ratio V_α/V_L is due to a low value of V_L. These fibers are made from preforms without a PM structure twisted under drawing and have polarization eigenmodes with a fairly small phase difference [2–4]. With limited length and small bends, they function as isotropic optical fiber that preserves the polarization state of incident radiation. Spun-LoBi fibers are used, for example, to amplify light in high-power fiber lasers to overcome the drift of the polarization state of light in the fiber due to its heating during pumping [5, 6]. However, these fibers are significantly affected by induced anisotropy during bends and other external perturbations of the fiber.

On the contrary, the second type, spun-HiBi fiber, has a relatively high value of V_L and is made from preforms with a significant transverse PM structure by rapidly rotating the workpiece during fiber drawing [7]. Due to the relatively high V_α/V_L ratio, these fibers also have polarization eigenmodes close to circularly polarized modes [8], and the intrinsic anisotropy of such fibers is slightly distorted by bending, compression and other impacts. The second type of fiber is used for various purposes, for example, to create sensitive elements of high-precision fiber-optic current sensors [9–12]. Such an application is among the most promising, widely known and researched.

The interest in the use of spun fibers, especially with high birefringence, is caused by their potential to preserve circularly polarized modes. However, such polarization eigenmodes correspond only to the limiting case with an increase in the value of V_α/V_L. In practice, this ratio is limited, therefore for a number of reasons, even without taking into account the internal fluctuations of the structure that arise during manufacture and induced during fiber placement, the polarization eigenmodes of real spun fibers only approach circular modes and may differ markedly from the idealized case.

Many studies were dedicated to the analysis of the polarization properties of real spun fibers [1, 4, 8, 10, 12–15]. However, these studies are generally aimed at analyzing the complex mechanisms of regular and random transformation of light polarization during its propagation in inhomogeneous anisotropic fiber structure and are based on the application of the mode coupling formalism and the equations of coupled waves [4, 10, 12, 13]. Models of the formation of the Jones matrix of the spun fiber have also been considered in a number of works, both for the differential matrices of the segment and the resulting integral matrix [1, 8, 14, 15]. Such models have a complex structure in the form of a product of matrices, and they must take into account (even when reduced to an integral matrix) rigorous values of V_α, V_L and fiber lengths, which are usually unknown. In addition, such models do not allow to take into account the influence of possible fluctuations in parameters and anisotropy induced by external perturbations of the fiber for the Jones matrix of spun fiber. Therefore, although the results of such studies describe the properties of spun fibers, they are difficult to apply to the analysis and modeling of practical devices based on these fibers.

The goal of this study is to obtain the structure of the Jones matrix of a real spun fiber in the simplest possible integral form without using the parameters of the internal structure of the fiber, based only on the condition of a small difference in the polarization modes of such a fiber from an idealized representation, and to analyze the properties of the resulting matrix.

It is this case of the Jones matrix of spun fibers that is effective for analyzing and modeling devices based on these fibers; in addition, it is very useful to study the effect of imperfections (differences between real spun fibers and idealized ones) on the operation of these devices.

Jones matrix of idealized spun fiber

First of all, it should be borne in mind that there are different options in the literature for determining a polarized wave with a right or left direction of rotation as well as different options for taking into account the phases of components in Jones vectors and, as a result, in Jones matrices. It is important to understand these features in further analysis, so the Appendix (given at the end of the paper) contains the refinements we adopted.

As noted above, the polarization modes in the idealized representation of the spun fiber are considered to be circular. A device with circular eigenvectors in the linear Cartesian basis of Jones vectors is described by a rotation matrix. Therefore, we assume that the Jones matrix of idealized spun fiber has the form

$$\mathbf{M}_0 = \begin{bmatrix} \cos(\varphi/2) & \sin(\varphi/2) \\ -\sin(\varphi/2) & \cos(\varphi/2) \end{bmatrix}. \tag{1}$$

It is important to emphasize that the concept of idealized spun fiber described by a rotation matrix is not related to the idea of spun fiber with an ideal structure, in which regular rotation of the direction of the axes of linear anisotropy is introduced. In such a structure, even with regular parameters without fluctuations, the form of the matrix will differ from the presented form (1). The idealized spun fiber described by the rotation matrix implies precisely the idealized concept of converting the state of polarization of light in such fiber, when it is preferable to have an element with circularly polarized eigenmodes in the optical circuit.

Under the refining conditions described in the Appendix, matrix (1) rotates the azimuth of the polarization state by an angle $\varphi/2$ clockwise when observed towards the direction of wave propagation. At the same time, the phase difference of the eigenmodes φ is taken into account here, but the general phase shift Φ of the eigenwaves is not included, which is not difficult to take into account by introducing the factor $e^{-j\Phi}$, although this factor is not needed to consider only the transformation of the polarization state of light. From this point of view, matrix (1) belongs to the class of special unitary matrices with a determinant equal to unity.

The eigenvectors $\mathbf{J}_{01}$ and $\mathbf{J}_{02}$ of matrix (1), corresponding to the eigenvalues $\lambda_1 = e^{j\varphi/2}$ and $\lambda_2 = e^{-j\varphi/2}$ (φ here and below is assumed to be positive), correspond to waves with right and left circular polarization, which are generally written as follows [17 ,16]:

$$\mathbf{J}_{01} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}, \mathbf{J}_{02} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}. \tag{2}$$

According to the accepted rules, the vectors $\mathbf{J}_{01}$ and $\mathbf{J}_{02}$ for matrix (1) refer respectively to the fast and slow polarization modes of the idealized spun fiber.

It is important to note here that an alternative case of idealized spun fiber can be formulated, which rotates the polarization state of the light passing through the fiber counterclockwise. In practice, this is set by the direction of rotation of the preform during drawing. Such a case of idealized fiber will be described by the matrix $\mathbf{M}_0' = \mathbf{M}_0^T$, which also has eigenvectors (2), but the first will correspond to the slow mode, and the second to the fast one. In general, if this case needs to be considered, then all the expressions listed below can be used by replacing φ with $-\varphi$ (again, it is assumed that φ is positive).

Jones matrix of real spun fiber

Real spun fibers do not correspond to an idealized representation and are described by a Jones matrix different from the rotation matrix. At the same time, there is a fundamental difference from fibers with linear anisotropy (i.e., polarization-maintaining (PM) fibers), where the imperfection of the fiber is associated with fluctuations in the magnitude and direction of core deformations that arose during the manufacture of the fiber or induced by subsequent external perturbations.

Spun fiber with regular rotation of the orientation of the polarization axes differs from the idealized representation discussed above, even without fluctuations in the anisotropy parameters, since circular polarization eigenmodes are achieved only in the case of a limiting value of the ratio of fiber parameters, which cannot be done in practice. The intrinsic and induced fluctuations of the anisotropy parameters additionally distort the final polarization properties of the fiber, but are not the main reason for the deviation from the idealized representation.

In order to formulate a relatively simple representation of the Jones integral matrix for a segment of real spun fiber, we propose to use only the condition of a slight deviation in the polarization properties of such fiber from the idealized representation, i.e., a slight deviation in the polarization eigenstates from circular ones.

We assume that the spun fiber remains an element with phase anisotropy and is described by a unitary Jones matrix. This circumstance can be explained by the low loss of optical power in fibers of relatively short length (in practice, spun fibers up to several tens of meters in length are commonly used), which makes it possible to neglect the possible dichroism. We also do not take into account the total phase shift Φ of eigenmodes, which means we will consider a special unitary matrix.

In view of the above, the Jones matrix of real spun fiber should correspond to the matrix of an elliptical phase plate, whose eigenvectors are close to vectors (2) for circular polarizations.

Due to the importance of the properties of the eigenvectors of the optical element matrix, first consider the properties of the eigenvectors corresponding to the condition of proximity to the vectors (2). In the general case, in terms of the basic parameters of the polarization ellipse (ellipticity angle ε and azimuth Θ), two orthogonal Jones eigenvectors in the Cartesian basis are generally written as follows [16, 18]:

$$\mathbf{J}_1=\begin{bmatrix}\cos\Theta\cos\varepsilon-j\sin\Theta\sin\varepsilon\\ \sin\Theta\cos\varepsilon+j\cos\Theta\sin\varepsilon\end{bmatrix},\ \mathbf{J}_2=\begin{bmatrix}-\sin\Theta\cos\varepsilon+j\cos\Theta\sin\varepsilon\\ \cos\Theta\cos\varepsilon+j\sin\Theta\sin\varepsilon\end{bmatrix}, \quad (3)$$

where the parameters ε and Θ are set directly for vector $\mathbf{J}_1$, and vector $\mathbf{J}_2$ is obtained as orthogonal to $\mathbf{J}_1$.

Form (3) defines normalized vectors with unit length, and in general, orthogonal vectors are written to a constant complex factor, i.e., they can have different values of both length and initial phase.

It is useful to consider the transition to the idealized case with circular polarizations, for which it is necessary to take the value ε = π/4. Integrals (13) are then transformed to the form

$$\mathbf{J}_1=\frac{e^{-j\Theta}}{\sqrt{2}}\begin{bmatrix}1\\ j\end{bmatrix},\ \mathbf{J}_2=\frac{je^{j\Theta}}{\sqrt{2}}\begin{bmatrix}1\\ -j\end{bmatrix}. \quad (4)$$

The difference between the obtained expressions (4) and form (2) lies only in the factors depending on the azimuth; the latter give some additional arguments for Jones complex vectors. Such factors do not affect the shape of the polarization ellipses, which in this case are degenerated into a circle and formally do not have a definite azimuth. An additional factor does not change the unit length of the vector, but, strictly speaking, it still has meaning, since it determines the initial position of the end of the electric field strength vector of the wave on a circular hodograph. Thus, it is evident from the analysis of expressions (4), that the common representation of circular polarization vectors (2) formally corresponds to ε = π/4 and Θ = 0.

Let us assume that the polarization eigenstate differs little from circular polarization; this is characterized by an elliptical angle ε = π/4 – δ, where the deviation δ is assumed to be small (δ << 1). Then, approximations for trigonometric functions can be applied in the general form of Jones vectors (3) and approximate equalities can be used preserving the components of only first-order smallness:

$$\sin\left(\frac{\pi}{4}-\delta\right)\approx\frac{1}{\sqrt{2}}(1-\delta),\ \cos\left(\frac{\pi}{4}-\delta\right)\approx\frac{1}{\sqrt{2}}(1+\delta). \quad (5)$$

If we substitute expressions (5) into form (3) and apply the known trigonometric transformations, we obtain the eigenvectors of the matrix of imperfect spun fiber in the following form:

$$\mathbf{J}_1=\frac{e^{-j\Theta}}{\sqrt{2}}\begin{bmatrix}1+\delta\cdot e^{j2\Theta}\\ j\left(1-\delta\cdot e^{j2\Theta}\right)\end{bmatrix},\ \mathbf{J}_2=\frac{e^{j\Theta}}{\sqrt{2}}\begin{bmatrix}j\left(1-\delta\cdot e^{-j2\Theta}\right)\\ 1+\delta\cdot e^{-j2\Theta}\end{bmatrix}. \quad (6)$$

The polarization states described by vectors (6), taking into account the smallness of δ, are elliptical, although close to circular. Here, Θ has a clear meaning, the direction of the semi-major axis of the polarization ellipse and can have an arbitrary value in the full range of azimuth variation [0; π]. The considered polarization eigenstates of the spun fiber are shown in Fig. 1, illustrating the deviation of the polarization state of the vector $\mathbf{J}_1$ from the idealized representation (from point *A* to some point *B*) on the Poincaré sphere. The vector $\mathbf{J}_2$ corresponds to diametrically opposite points of the sphere.

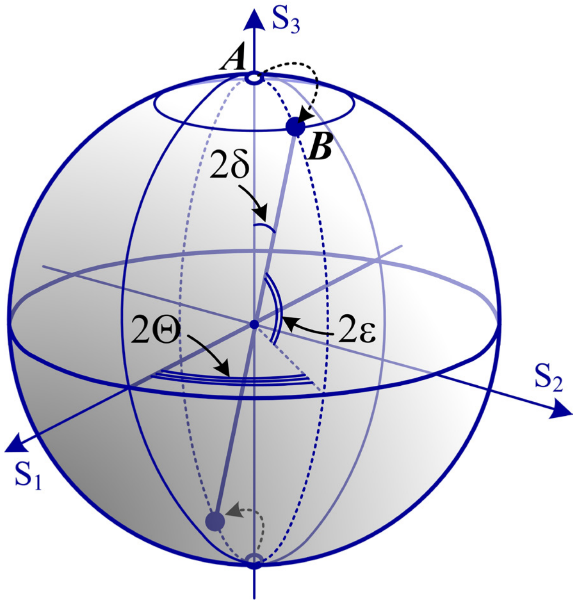

Fig. 1. Displacement of position of polarization eigenmode of spun fiber on the Poincaré sphere, taking into account its real characteristics: point *A* corresponds to polarization with the Jones vector $\mathbf{J}_1$ for the case of idealized spun fiber, point *B* for the case of real spun fiber; Θ, ε are the azimuth and ellipticity angle parameters; 2δ is the angular deviation of the polarization eigenmode from the point of circular polarization

Two approaches can be proposed to obtain the Jones matrix of real spun fiber $\mathbf{M}_{\text{SPUN}}$. The first is to use the general form of the phase anisotropy matrix expressed in terms of the eigenvalues λ_1, λ_2 and eigenvectors [18, 19]:

$$\mathbf{M} = \frac{1}{\mathbf{j}_{1x}\mathbf{j}_{2y} - \mathbf{j}_{1y}\mathbf{j}_{2x}} \begin{bmatrix} \mathbf{j}_{1x}\mathbf{j}_{2y}\lambda_1 - \mathbf{j}_{2x}\mathbf{j}_{1y}\lambda_2 & -(\lambda_1 - \lambda_2)\mathbf{j}_{1x}\mathbf{j}_{2x} \\ (\lambda_1 - \lambda_2)\mathbf{j}_{1y}\mathbf{j}_{2y} & \mathbf{j}_{1x}\mathbf{j}_{2y}\lambda_2 - \mathbf{j}_{2x}\mathbf{j}_{1y}\lambda_1 \end{bmatrix}, \tag{7}$$

where $\mathbf{j}_{1x}$, $\mathbf{j}_{1y}$ are components of the Jones vector $\mathbf{J}_1$; $\mathbf{j}_{2x}$, $\mathbf{j}_{2y}$ are components of the vector $\mathbf{J}_2$

If we consider a special unitary matrix that describes a system without losses and has eigenvalues $\lambda_1 = e^{j\varphi/2}$ and $\lambda_2 = e^{-j\varphi/2}$, then we obtain from the general form (7):

$$\mathbf{M} = \frac{1}{\mathbf{j}_{1x}\mathbf{j}_{2y} - \mathbf{j}_{1y}\mathbf{j}_{2x}} \begin{bmatrix} \mathbf{j}_{1x}\mathbf{j}_{2y}e^{j\varphi/2} - \mathbf{j}_{2x}\mathbf{j}_{1y}e^{-j\varphi/2} & -j2\mathbf{j}_{1x}\mathbf{j}_{2x}\sin(\varphi/2) \\ j2\mathbf{j}_{1y}\mathbf{j}_{2y}\sin(\varphi/2) & \mathbf{j}_{1x}\mathbf{j}_{2y}e^{-j\varphi/2} - \mathbf{j}_{2x}\mathbf{j}_{1y}e^{j\varphi/2} \end{bmatrix}. \tag{8}$$

The required matrix of real spun fiber $\mathbf{M}_{\text{SPUN}}$, which has eigenvectors (6), can be obtained by substituting expressions (6) into form (8).

Another way to obtain the required matrix $\mathbf{M}_{\text{SPUN}}$ is to use the expression for the Jones matrix of an arbitrary elliptical phase plate:

$$\mathbf{M}_{\text{EPP}} = \begin{bmatrix} \cos\frac{\varphi}{2} + j\cos 2\Theta \cdot \cos 2\varepsilon \cdot \sin\frac{\varphi}{2} & \left(\sin 2\varepsilon + j\sin 2\Theta \cdot \cos 2\varepsilon\right)\sin\frac{\varphi}{2} \\ -\left(\sin 2\varepsilon - j\sin 2\Theta \cdot \cos 2\varepsilon\right)\sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} - j\cos 2\Theta \cdot \cos 2\varepsilon \cdot \sin\frac{\varphi}{2} \end{bmatrix}. \tag{9}$$

Expression (9) was obtained in [20] by substituting expressions for orthogonal Jones vectors written in the general form (3) into form (8). To obtain the matrix $\mathbf{M}_{\text{SPUN}}$, it is necessary to take into account $\varepsilon = \pi/4 - \delta$ in matrix (9) and use simplifications (5).

In both cases, the result is a matrix of the form

$$\mathbf{M}_{\mathrm{SPUN}} = \begin{bmatrix} \cos\frac{\varphi}{2} + j2\delta\cos 2\Theta\cdot\sin\frac{\varphi}{2} & \left(1 + j2\delta\sin 2\Theta\right)\cdot\sin\frac{\varphi}{2} \\ -\left(1 - j2\delta\sin 2\Theta\right)\cdot\sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} - j2\delta\cos 2\Theta\cdot\sin\frac{\varphi}{2} \end{bmatrix}. \quad (10)$$

Notably, the determinant Δ of matrix (10) is expressed as

$$\Delta = 1 + 4\delta^2\cdot\sin^2(\varphi/2)$$

and it is real, but not equal to unity.

To obtain a strict correspondence to a normal unitary matrix, a multiplier of $1/\Delta$ can be introduced into expression (10), but in practical calculations it is advisable to neglect the second-order correction for a small parameter δ and use matrix (10) without additional factors.

As mentioned above, for the idealized representation of the fiber, we could choose not the rotation matrix $\mathbf{M}_0$, given by Eq. (1), but the matrix $\mathbf{M}_0' = \mathbf{M}_0^T$ (formally, this can be justified by replacing φ with $-\varphi$), rotating the azimuth of polarization counterclockwise. Both options are equivalent, since they are given by the direction of rotation of the fiber preform during drawing. In this case, the right circular polarization will be the slow mode of the matrix, and the left one will be the fast one.

Expressions for the eigenvectors $\mathbf{J}_1'$ and $\mathbf{J}_2'$ of the matrix $\mathbf{M}'_{\mathrm{SPUN}}$ can be obtained if we assume that $\varepsilon = -\pi/4 + \delta$ in form (3), since the vector $\mathbf{J}_1'$ is close to the left circular polarization. As a result, we obtain the following expressions:

$$\mathbf{J}_1' = \frac{e^{j\Theta}}{\sqrt{2}}\begin{bmatrix} 1 + \delta\cdot e^{-j2\Theta} \\ j\left(\delta\cdot e^{j2\Theta} - 1\right) \end{bmatrix}, \ \mathbf{J}_2' = \frac{e^{-j\Theta}}{\sqrt{2}}\begin{bmatrix} j\left(\delta\cdot e^{j2\Theta} - 1\right) \\ 1 + \delta\cdot e^{j2\Theta} \end{bmatrix}, \quad (11)$$

$$\mathbf{M}'_{\mathrm{SPUN}} = \begin{bmatrix} \cos\frac{\varphi}{2} + j2\delta\cos 2\Theta\cdot\sin\frac{\varphi}{2} & -\left(1 - j2\delta\sin 2\Theta\right)\cdot\sin\frac{\varphi}{2} \\ \left(1 + j2\delta\sin 2\Theta\right)\cdot\sin\frac{\varphi}{2} & \cos\frac{\varphi}{2} - j2\delta\cos 2\Theta\cdot\sin\frac{\varphi}{2} \end{bmatrix}. \quad (12)$$

It can be seen from expression (12) that the matrix $\mathbf{M}'_{\mathrm{SPUN}}$, as expected, corresponds to the matrix transposed to $\mathbf{M}_{\mathrm{SPUN}}$, similarly to the matrices $\mathbf{M}_0'$ and $\mathbf{M}_0$ for idealized spun fiber.

Specifics of applying the Jones matrix for real spun fiber in analysis and modeling of fiber optic circuits

The Jones matrix representation of real spun fiber can be used to analyze and model systems containing such fibers. As a rule, such analysis is aimed at clarifying the effect of imperfection of fibers and other polarization elements on the operation of the system as a whole. The models obtained within the framework of the Jones formalism usually contain many parameters characterizing polarization mismatches, which must be varied in analytical or numerical calculations. Therefore, the obtained expression (10), which is a simple explicit form of the Jones matrix of real spun fiber and takes into account the small difference between the polarization eigenmodes of the fiber and their idealized representation using a small parameter δ, is attractive for these calculations.

Matrix (10) contains three parameters: δ, Θ and φ; all of them can affect the transformation of the polarization state when light passes through the spun fiber and, as a result, the formation of signals in the optical circuit. Therefore, when performing analysis or numerical calculations, it is necessary to determine which parameter values to use.

The small parameter δ sets a quantitative measure of the deviation of the real spun fiber from the idealized representation. This deviation can be related both to the limited value of the ratio V_α/V_L, which is provided during the creation of the fiber, and to fluctuations in parameters that occur during the manufacture or placement of the fiber. As a result, the specific value of δ for real fibers can be difficult to predict. The most appropriate approach for analysis is to determine a certain threshold value of δ_{max} for the fiber in question. Such a value can be obtained by separate theoretical consideration of the specific structure of the spun fiber or determined empirically. Further, the calculations should consider the effect of mismatches by varying the parameter δ in the range from 0 to δ_{max}.

The azimuth of the eigenstates in a certain orientation basis, depending how the spun fiber is connected and using which elements, must be generally considered unknown, uncontrolled and any possible value of the parameter Θ in the range from 0 to π.

The phase difference of the polarization modes φ, formed when light passes through the fiber, also turns out to be a virtually unknown and uncontrolled parameter. Even if the key parameters of spun fiber are known, in the case of sufficiently long (several meters or more) spun fiber with high birefringence, the phase difference of eigenmodes is difficult to calculate or determine precisely; taking into account fluctuations of the parameters and possible significant changes of temperature, the value of φ may actually be random in the range from 0 to 2π. Therefore, in the analysis and calculations, it should also be varied in the specified range.

As for the phase difference φ, we should make one more important remark. We noted above that spun-HiBi fibers are most commonly used in fiber-optic sensors as sensitive elements. The most common example of using such fibers are fiber-optic current sensors, where it is assumed that due to the Faraday effect, the phase difference in spun fiber wound around a current-carrying conductor changes between two circularly polarized orthogonal modes. Thus, when analyzing such schemes, it should be borne in mind that the phase difference φ must also contain a component induced by the measured effect. In this case, the non-reciprocal anisotropy induced by the measured magnetic field as a consequence of the Faraday effect is circular. If the spun fiber corresponded to the idealized representation and was described by the matrix $\mathbf{M}_0$ (or $\mathbf{M}'_0$), then, obviously, during modeling, the phase difference φ should be given as

$$\varphi = \varphi_0 + \varphi(t),$$

where φ_0 is the quasi-stationary component of the phase difference between circularly polarized modes in the fiber.

The value of φ_0, as indicated above, can actually be any in the range of $0-2\pi$. But since the real spun fiber differs a priori from the idealized representation and the eigenmodes of such fiber are not strictly circular, setting the phase difference φ in the form of the above sum will be approximate. Such an approximation may be quite acceptable in practice in the analytical study and numerical modeling of signals in measuring circuits with spun fiber.

Experimental

To analyze schemes with spun fiber based on the obtained form of the Jones matrix, it is necessary to estimate the possible range of values of the main parameter characterizing the deviation of the fiber from the idealized representation, the parameter δ. Such an estimate can be made both based on additional studies of fiber anisotropy factors and experimentally. The following are the results of experiments that allow us to estimate the parameter δ for specific spun fiber and illustrate the analysis presented above.

For measurements, we used the fact that if two polarization modes are excited during propagation through an element with phase anisotropy (for example, through anisotropic optical fiber), then when the phase difference φ of the modes changes by 2π, the evolution of the polarization state at the output from the element on the Poincaré sphere forms a circle [17, 19]. The change in φ leads to the rotation of the sphere around the axis, which is set by the points of the polarization eigenstates, and the angular radius R of the circle is determined by the ratio of the amplitudes of the polarization modes. Therefore, the experimental formation and detection of such an evolution as well as its subsequent analysis with the determination of the parameters Θ_0 and ε_0 of the center of the small circle of the sphere allow to measure the polarization eigenstates of the element. Fig. 2, *a*, *b* illustrates this approach and provides a diagram of the experimental setup for its implementation.

The key issue determining the possibility of the correct implementation of this approach to measuring the fiber polarization eigenstates is the method of organizing changes in the phase difference φ. We used fiber heating for this purpose. Unlike other measures such as longitudinal tension that change the optical length of the fiber, heating has a smaller effect on the inner structure of the fiber determining its anisotropy. In addition, this method can be used with relatively long fibers.

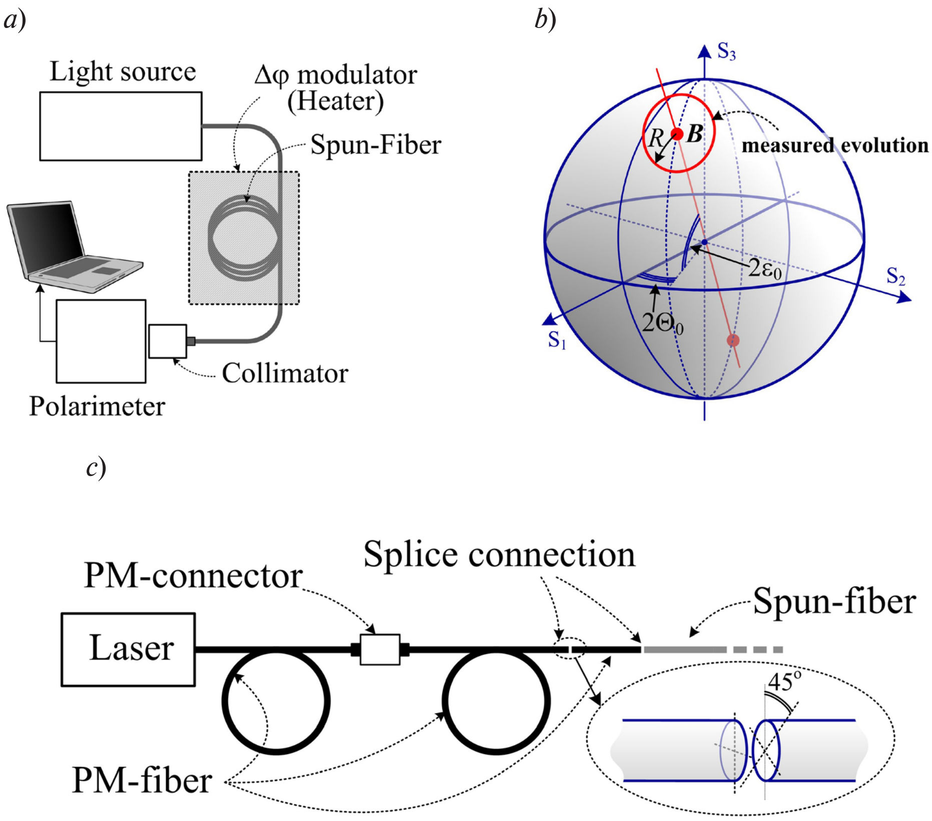

Fig. 2. Schematic of the experiment (*a*) with inset (*c*) illustrating the passage of light to the input into the tested spun fiber as well as the evolution of the polarization state on the Poincaré sphere, recorded during measurements (*b*)

However, the measurement approach used has its own specifics.

Firstly, heating the fiber can still lead not only to a change in the phase difference φ. A change in temperature, due to various mechanisms, can change the ratio of linear and circular anisotropy and transform the nature of its eigenmodes. This should lead to a more complex evolution of the polarization state at the fiber output, since the point on the Poincaré sphere will move along a circle when both the center of the circle and its radius are changed. The latter is due to the fact that if the polarization eigenmodes of the fiber change, then taking into account the fixed radiation parameters of the source, the ratio of the excited polarization modes will also change. However, the change in the parameter φ with an increase in fiber temperature should occur faster than the change in the angular parameters of the eigenmodes. We believe that if a fragment of the evolution of the polarization state observed during measurements corresponds well to the small circle of the Poincaré sphere, then this allows to estimate the values of ε_0 and Θ_0 of the polarization eigenstates of the fiber corresponding to this fragment. As a result of the experiment, our measurements can show not only the parameters of the eigenmodes of real fiber, but also detect their fluctuations when external conditions change.

Secondly, the azimuth of the points recorded by the polarimeter is determined by the position of the polarimeter axis, which is set virtually arbitrarily relative to the end of the fiber. Therefore, the absolute value of the measured azimuth Θ_0 of the polarization mode will not be informative (for the second mode, the azimuth will be shifted by $\pi/2$). However, when analyzing spun fiber, as discussed above, the deviation of the fiber from the idealized representation is characterized not by azimuth, but by the imperfection parameter δ, which is related only to how much the ellipticity angle of the polarization mode ε_0 differs from $\pi/4$. However, if the value of Θ_0 changes during the measurement process, then these changes will indeed characterize changes in their polarization eigenmodes.

The experiments used spun fiber manufactured by Fibercore (model SHB1500(8.9/125)), the length of the test segment was 80 m, the fiber was wound around a standard coil with a diameter of 16 cm. The scheme of the radiation source to which the fiber was connected is shown in Fig. 2,*c*. A DFB laser from Optilab was used (model DFB 1550 PM-20, wavelength 1550 nm, output power 9.5 MW), which had a fiber output (PM fiber with an APC-type connector). Next, a segment of PM fiber of the Bow-Tie type manufactured by Fibercore (model HB1250, the beat length of polarization modes is 3.28 mm) was spliced to the laser output via a connector. A short fiber segment (approximately 0.82 mm long) was formed at the end of the fiber input, rotated 45° relative to the axes of the main segment, after which the spun fiber was spliced. This segment served as a quarter-wave phase plate.

When linearly polarized radiation passes from the laser output through the PM fiber input and the quarter-wave plate rotated by 45°, circularly polarized radiation should be formed, and one polarization mode should be excited in it in the idealized representation of the spun fiber. However, since the real spun fiber has polarization modes other than circular ones, and the formed fiber phase plate is not an ideal quarter-wave, in fact two polarization modes in an unequal amplitude ratio were excited in the tested fiber. This exactly corresponded to the conditions required for measurements: it was possible to directly monitor the correspondence of fragments of the evolution of the polarization state to circular trajectories on the Poincaré sphere and measure the parameters of the polarization modes of the fiber.

The polarization state was recorded with the Thorlabs polarimeter PAX1000IR2 (USA), which allowed measuring the azimuth and elliptical angle of the polarization state with an accuracy of 0.25°. A collimator was used to connect the fiber to the polarimeter.

During the experiment, the tested fiber was slowly heated to 40 °C (in 50 minutes). The evolution of the recorded polarization state of light at the fiber outlet caused by heating is shown in Fig. 3,*a*. Evidently, the trajectory of the point of the output state of polarization on the Poincaré sphere forms many turns covering the pole of the sphere under heating. The radius of the turns varies noticeably, and their shape does not always correspond to circles, which is quite understandable for the reasons mentioned above.

Nevertheless, many turns in the trajectory of the polarization state correspond well to circles. Such fragments illustrate a situation where, with stable polarization eigenstates of the fiber, the phase difference φ changes. For example, Fig. 3,*b* shows three fragments of the observed evolution of the polarization state at the output of the spun fiber, which are consistent with the circles on the sphere. This can be seen by the correspondence between the points measured by the polarimeter and the circles on the sphere approximating these points. Such fragments make it possible to determine the parameters of the polarization eigenmodes in a given segment of the trajectory. The table shows the values of the circle parameters for the three fragments shown in Fig. 3,*b*.

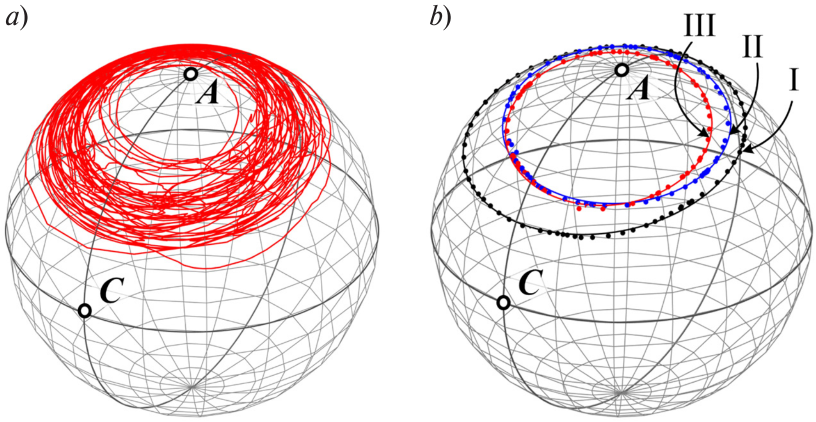

Fig. 3. Complete evolution of polarization state (*a*) and fragments of evolution I, II and III (*b*) at the output from the spun fiber, shown on the Poincaré spheres

Solid lines correspond to the approximation of the fragment points by circles on the sphere. Points *A* and *C* correspond to right circular polarization ($\varepsilon = 45°$) and linear polarization along the axis *X* ($\Theta = \varepsilon = 0$), respectively

Additionally, the measured evolution of the polarization state allows to estimate the average normalized temperature sensitivity of the phase difference φ of the polarization modes. This sensitivity was approximately 0.02 rad/(m·°C).

A change in the value of R (see Table) means that when the parameters of the polarization eigenstates change, the ratio of their excitation by radiation at the fiber input also changes. As evident from the examples with three fragments of a fixed trajectory on the Poincaré sphere, the azimuth Θ_0 of the polarization ellipse of its eigenmodes changes most significantly (by almost 20°). The ellipticity angle ε_0, which characterizes the difference between the fiber and the idealized case, varies significantly less. If we convert the value of ε_0 into the parameter δ, then, according to Table, the average value of δ is approximately 8.3°, and the difference between the maximum and minimum values is 2.4°.

Thus, the measurement results indicate for the fiber tested that it is possible to make quite definite estimates for the main parameter (δ) characterizing its imperfection and necessary for the analysis of optical circuits using the obtained Jones matrix of the spun fiber.

Table

Parameters of circles approximating the measured fragment points of evolution in polarization states on the Poincaré sphere (see Fig. 3,*b*)

Angular parameter	Parameter value, degrees, for fragment		
	I	II	III
Radius R	48.4	36.9	32.8
Azimuth Θ_0	2.9	15.7	12.5
Ellipticity angle ε_0	37.6	37.3	35.2

Conclusion

An expression for the Jones matrix of real spun fiber is obtained within the framework of the phase anisotropy model. The expression takes into account a slight deviation of the fiber properties from the idealized case with polarization eigenstates in the form of right and left circular polarizations. For this purpose, a small parameter δ is used, which takes into account the deviation of the ellipticity angle of the polarization eigenstate from $\pi/4$. The resulting expression can be used to describe and analyze optical circuits containing spun-type fibers based on the Jones formalism.

The results of the proposed and conducted experiments on measuring the parameters of the polarization eigenstates of the fiber illustrate the deviation of the real spun fiber from the idealized representation and show the difference between the polarization eigenstates and circular polarization. At the same time, measurements for the fiber model used allowed to estimate the value of the imperfection parameter δ in the range of about 7°–10°.

Appendix

Variability of representation of polarization state in the Jones formalism

Although the representation of polarized waves is well-established in the literature and the Jones formalism is widely used to describe transformations of the polarization state, unfortunately, there are confliciting viewpoints on some details of such a description. In general, the choice of certain formulations does not affect the correct result. However, given the importance of these features for the material of this paper, it is preferable to clarify some points of the approaches we use in order to avoid confusion and possible questions.

The first aspect for which there are conflicting viewpoints in the literature is the accounting for phases when constructing Jones vectors and the correspondence of slow and fast polarization eigenmodes to the eigenvalues of the Jones matrix.

Consider the polarization eigenmodes of some optical element with phase anisotropy. Let us assume for the first mode that the X component of the field at the input to the optical element has the form

$$E_x^{\text{in}} = A_1\cos(\omega t + \varphi_0),$$

where ω, φ_0 are the angular frequency and the initial phase of the oscillation.

The Y component with the initial phase shifted by $\delta\varphi$ has the form

$$E_y^{\text{in}} = A_2\cos(\omega t + \varphi_0 + \delta\varphi).$$

Then the Jones eigenvectors $\mathbf{J}_1^{\text{in}}$ and $\mathbf{J}_2^{\text{in}}$ (in the Cartesian basis) are written as follows:

$$\mathbf{J}_1^{\text{in}} = \begin{bmatrix} A_1 \\ A_2 e^{j\delta\varphi} \end{bmatrix}, \mathbf{J}_1^{\text{in}} = \begin{bmatrix} -A_2 e^{-j\delta\varphi} \\ A_1 \end{bmatrix}. \tag{A1}$$

The second vector is represented so that it is orthogonal to the first one.

Jones vectors can also include an overall factor $\exp(j\varphi_0)$, but it is typically omitted because it does not affect the shape and orientation of the polarization ellipse. In such notation, the components of the vector contain complex amplitudes, whose arguments are given as initial phases. In this case, for the vector $\mathbf{J}_1^{\text{in}}$, assuming $\delta\varphi > 0$, it turns out that the X component of the vector is delayed relative to the Y component.

Passing through an optical element with phase anisotropy, in the case when polarization-independent losses are negligibly small, the eigenmodes acquire only a phase delay, each a different one. The first and second modes acquire phase delays Φ_1 and Φ_2, respectively:

$$\Phi_1 = n_1 L/\lambda, \ \Phi_2 = n_2 L/\lambda,$$

where L is the geometric wavelength of the waves in the optical element; λ is the wavelength of light; n_1, n_2 are the effective refractive indices for polarization eigenmodes.

If we include the average refractive index n and the difference Δn of the form

$$n = (n_1 + n_2)/2, \ \Delta n = n_2 - n_1$$

(Δn characterizes the anisotropy of the element), then the phase delays can be written as

$$\Phi_1 = \Phi - \varphi/2, \ \Phi_2 = \Phi + \varphi/2,$$

where $\Phi = nL/\lambda$, $\varphi = \Delta n L/\lambda$.

The value of φ is positive if $\Delta n > 0$. In this case, the first mode propagates faster and has a lower phase delay, while the second one propagates slower and acquires a greater phase delay. Therefore, when $\varphi > 0$, it is logical to call the first and second modes "fast" and "slow", respectively.

Taking into account the Cartesian components of the first mode introduced above at the input to the optical element, they can be written as

$$E_x^{\text{out}} = A_1\cos[\omega t + \varphi_0 - (\Phi - \varphi/2)],$$

$$E_y^{\text{out}} = A_2\cos[\omega t + \varphi_0 + \delta\varphi - (\Phi - \varphi/2)].$$

Similarly, the components of the second mode at the output of the optical element are obtained by adding the terms $-(\Phi + \varphi/2)$ to the phase of the components at the input.

It is easy to prove that if the Jones vectors take into account the initial phases of the field oscillations, then the relationship between the input ($\mathbf{J}_1^{\text{in}}$, $\mathbf{J}_2^{\text{in}}$) and output ($\mathbf{J}_1^{\text{out}}$, $\mathbf{J}_2^{\text{out}}$) vectors of eigenmodes should have the following form:

$$\begin{aligned} \mathbf{J}_1^{\text{out}} &= e^{-j\Phi} \cdot \mathbf{M} \cdot \mathbf{J}_1^{\text{in}} = e^{-j\Phi} \cdot e^{j\varphi/2} \cdot \mathbf{J}_1^{\text{in}}; \\ \mathbf{J}_2^{\text{out}} &= e^{-j\Phi} \cdot \mathbf{M} \cdot \mathbf{J}_2^{\text{in}} = e^{-j\Phi} \cdot e^{-j\varphi/2} \cdot \mathbf{J}_2^{\text{in}}. \end{aligned} \tag{A2}$$

The Jones matrix $\mathbf{M}$ of the optical element is introduced in (A2), which does not take into account the average phase shift and is a special unitary matrix with eigenvalues

$$\lambda_1 = e^{j\varphi/2}, \ \lambda_2 = e^{-j\varphi/2}.$$

It is clear from the above arguments that if $\varphi > 0$, then the vectors with eigenvalues λ_1 and λ_2 belong to the fast and slow modes of the anisotropic element, respectively.

The described representation of phases in terms of vectors and Jones matrices is widely used in textbooks, monographs and articles [16, 17, 21]. However, an alternative approach to constructing phases in terms of vectors and Jones matrices can also be found in the literature [19]. It is based on the representation of a harmonic wave propagating along the z axis with the wavenumber k in terms of the function $\cos(\omega t - kz)$. Then the phase shift of the wave relative to the zero initial phase can be interpreted as a phase delay due to the passage of a certain path. It is not the initial phases that are taken into account in the notation for the vectors and Jones matrices, but phase delays, i.e., negative changes in the initial phases are taken into account as positive delays and vice versa.

In this representation, the same E_x^{in} and E_y^{in} can be written as

$$E_x^{\text{in}} = A_1\cos[\omega t - (-\varphi_0)],\ E_y^{\text{in}} = A_2\cos[\omega t - (-\varphi_0 - \delta\varphi)],$$

where the phase delays are now given in parentheses.

In this case, the vectors $\mathbf{J}_1^{\text{in}}$ and $\mathbf{J}_2^{\text{in}}$ are already written as

$$\mathbf{J}_1^{\text{in}} = \begin{bmatrix} A_1 \\ A_2 e^{-j\delta\varphi} \end{bmatrix},\ \mathbf{J}_2^{\text{in}} = \begin{bmatrix} -A_2 e^{j\delta\varphi} \\ A_1 \end{bmatrix}. \tag{A3}$$

If it is necessary to take into account the phase φ_0, then the overall phase factor exp $(-j\varphi_0)$ must be included into Eq. (A3). The components E_x^{out} and E_y^{out} also do not change, but the output vectors are now represented as

$$\begin{aligned} \mathbf{J}_1^{\text{out}} &= e^{j\Phi} \cdot \mathbf{M} \cdot \mathbf{J}_1^{\text{in}} = e^{j\Phi} \cdot e^{-j\varphi/2} \cdot \mathbf{J}_1^{\text{in}}; \\ \mathbf{J}_2^{\text{out}} &= e^{j\Phi} \cdot \mathbf{M} \cdot \mathbf{J}_2^{\text{in}} = e^{j\Phi} \cdot e^{j\varphi/2} \cdot \mathbf{J}_2^{\text{in}}. \end{aligned} \tag{A4}$$

Here, the optical element with phase anisotropy is also represented by a special unitary matrix $\mathbf{M}$ with the same eigenvalues $e^{j\varphi/2}$ and $e^{-j\varphi/2}$. However, in this representation, a vector with an eigenvalue $\lambda_1 = e^{j\varphi/2}$ corresponds to a slow mode, and a vector with an eigenvalue $\lambda_2 = e^{-j\varphi/2}$ corresponds to a fast mode (at $\varphi > 0$).

In this paper, we adhere to the first case of the representation of Jones vectors, when they take into account the initial phases of Cartesian components, rather than phase delays.

The second aspect on which there are conflicting viewpoints in the literature is the definition of polarized waves with right and left directions of rotation of the electric field intensity vector.

Most textbooks and monographs [16, 22, 23] define a right-polarized wave as the one where the electric field strength vector rotates clockwise if looking towards the direction of wave propagation. Accordingly, the left-polarized wave has a counterclockwise rotation of the electric field intensity vector. In this article, we adhere to this definition. However, an equally valid opposing opinion can be found in the literature for the definition of right- and left-polarized waves [21].

The third aspect important for this paper is the way Jones vectors are written for right and left circular polarizations.

In accordance with the definition of right- and left-polarized waves, which we adhere to, it is not difficult to verify the following. For the right circular polarization, the component E_x is delayed relative to the component E_y by $\pi/2$. For example, when $E_x = A\cos(\omega t + \varphi_0)$, the right circular polarization is followed by $E_y = -A\sin(\omega t + \varphi_0)$. Consequently, the initial phase of the Y component is additionally increased by $\pi/2$. For the left circular polarization, on the contrary, the component E_y is delayed relative to the component E_x. Therefore, taking into account all the conditions we adopted, the Jones vectors for the right and left circular polarizations will be described by vectors (2).

Nevertheless, it is important to note that the comparison of Jones vectors (2) with right and left circular polarizations by some researchers in the available literature may be the opposite, due to differences in the adopted notations for the phases in terms of Jones vectors and matrices, as well as definitions of right- and left-polarized light. For example, in [21], the use of an alternative variant of vectors is associated with an alternative definition of the names of the direction of rotation, and in [19] it is associated with an alternative representation of Jones vectors using phase delays.

REFERENCES

1. **Liu Y., Song H.,** Theoretical analysis on polarization characteristics of spun birefringent optical fiber based on an analytical Jones matrix model, Optik. 228 (Febr) (2021) 166179.
2. **Barlow A. J., Ramskov-Hansen J. J., Payne D. N.,** Birefringence and polarization mode-dispersion in spun single-mode fibers, Appl. Opt. 20 (17) (1981) 2962–2968.
3. **Payne D. N., Barlow A. J., Ramskov-Hansen J. J.,** Development of low- and high-birefringence optical fibers, IEEE Trans. Microw. Theory Tech. 30 (4) (1982) 323–334.
4. **Polynkin P., Blake J.,** Polarization evolution in bent spun fiber, J. Light. Technol. 23 (11) (2005) 3815–3820.
5. **Fedotov A., Ustimchik V., Rissanen J., et al.,** Active tapered double-clad fiber with low birefringence, Opt. Express. 29 (11) (2021) 16506–16519.
6. **Fedotov A., Ustimchik V., Rissanen J., et al.,** Large mode area double-clad ytterbium-doped spun tapered fiber, J. Opt. Soc. Am. B. 38 (12) (2021) F161–F169.
7. **Laming R. I., Payne D. N.,** Electric current sensors employing spun highly birefringent optical fibers, J. of Lightwave Technology. 7 (12) (1989) 2084–2094.
8. **Gubin V. P., Isaev V. A., Morshnev S. K., et al.,** Use of Spun optical fibres in current sensors, Quantum Electron. 36 (3) (2006) 287–291.
9. **Müller G. M., Frank A., Yang L., et al.,** Temperature compensation of interferometric and polarimetric fiber-optic current sensors with spun highly birefringent fiber, J. Light. Technol. 37 (18) (2019) 4507–4513.
10. **Przhiyalkovsky Ya. V., Gubin V. P., Starostin N. I., et al.,** Detection of electric current pulses by a fibre-optic sensor using spun fibre, Quantum Electron. 48 (1) (2018) 62–69.
11. **Temkina V., Medvedev A., Mayzel A.,** Research on the methods and algorithms improving the measurements precision and market competitive advantages of fiber optic current sensors, Sensors. 20 (21) (2020) 5995.
12. **Peng N., Huang Y., Wang S., et al.,** Fiber optic current sensor based on special spun highly birefringent fiber, IEEE Photon. Technol. Lett. 25 (17) (2013) 1668–1671.
13. **Wang Y., Xu C.-Q., Izraelian V.,** Characterization of spun fibers with millimeter spin periods, Opt. Express. 13 (10) (2005) 3841–3851.
14. **Hu H., Huang J., Huang Y, et al.,** Modeling of the birefringence in spun fiber, Opt. Commun. 473 (15 Oct) (2020) 125919.
15. **Yao P., Chen X., Hao P., et al.,** Introduction and measurement of the effective Verdet constant of spun optical fibers, Opt. Express. 29 (15) (2021) 23315–23330.
16. **Azzam R. M. A., Bashara N. M.,** Ellipsometry and polarized light, Third ed., North Holland Publishing Company, Amsterdam, Netherlands, 1999.
17. **Collett E.,** Polarized light in fiber optics, SPIE Press, Bellingham, Washington, USA, 2003.
18. **Ishchenko E. F., Sokolov A. L.,** Polyarizatsionnaya optika [Polarization optics], Third Ed., Fizmatlit Publishing, Moscow, 2019 (in Russian).
19. **Huard S.,** Polarization of light, John Wiley & Sons, Inc., Chichester, UK, 1997.
20. **Temkina V. S., Liokumovich L. B., Archelkov A. B., et al.,** Description of polarization-maintaining fibers in analyzing the practical fiber-optic circuits using the Jones formalism, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3) (2023) 95–114 (in Russian).
21. **Yariv A., Yeh P.,** Optical waves in crystals: propagation and control of laser radiation, John Wiley & Sons, Inc., New York, Chichester, Brislane, Toronto, Singapore, 1984.
22. **Gerrard A., Burch J. M.,** Introduction to matrix methods in optics, Dover Publications, Inc., New York, USA, 2012.
23. **Born M., Wolf E.,** Principles of optics, Cambridge University Press, Cambridge, United Kingdom, 2019.

СПИСОК ЛИТЕРАТУРЫ

1. **Liu Y., Song H.** Theoretical analysis on polarization characteristics of spun birefringent optical fiber based on an analytical Jones matrix model // Optik. 2021. Vol. 228. February. P. 166179.

2. **Barlow A. J., Ramskov-Hansen J. J., Payne D. N.** Birefringence and polarization mode-dispersion in spun single-mode fibers // Applied Optics. 1981. Vol. 20. No. 17. Pp. 2962–2968.

3. **Payne D. N., Barlow A. J., Ramskov-Hansen J. J.** Development of low- and high-birefringence optical fibers // IEEE Transactions on Microwave Theory and Techniques. 1982. Vol. 30. No. 4. Pp. 323–334.

4. **Polynkin P., Blake J.** Polarization evolution in bent spun fiber // Journal of Lightwave Technology. 2005. Vol. 23. No. 11. Pp. 3815–3820.

5. **Fedotov A., Ustimchik V., Rissanen J., Kolosovskii A., Voloshin V., Vorob′ev I., Gumenyuk R., Chamorovskiy Y., Filippov V.** Active tapered double-clad fiber with low birefringence // Optics Express. 2021. Vol. 29. No. 11. Pp. 16506–16519.

6. **Fedotov A., Ustimchik V., Rissanen J., Noronen T., Gumenyuk R., Kolosovskii A., Voloshin V., Vorob′ev I., Chamorovskii Y., Filippov V.** Large mode area double-clad ytterbium-doped spun tapered fiber // Journal of the Optical Society of America. B. 2021. Vol. 38. No. 12. Pp. F161–F169.

7. **Laming R. I., Payne D. N.** Electric current sensors employing spun highly birefringent optical fibers // Journal of Lightwave Technology. 1989. Vol. 7. No. 12. Pp. 2084–2094.

8. **Губин В. П., Исаев В. А., Моршнев С. К., Сазонов А. И., Старостин Н. И., Чаморовский Ю. К., Усов А. И.** Использование волоконных световодов типа Spun в датчиках тока // Квантовая электроника. 2006. Т. 36. № 3. С. 287–291.

9. **Müller G. M., Frank A., Yang L., Gu X., Bohnert K.** Temperature compensation of interferometric and polarimetric fiber-optic current sensors with spun highly birefringent fiber // Journal of Lightwave Technology. 2019. Vol. 37. No. 18. Pp. 4507–4513.

10. **Пржиялковский Я. В., Губин В. П., Старостин Н. И., Моршнев С. К., Сазонов А. И.** Регистрация импульсов электрического тока волоконно-оптическим датчиком с использованием spun-световодов // Квантовая электроника. 2018. Т. 48. № 1. С. 62–69.

11. **Temkina V., Medvedev A., Mayzel A.** Research on the methods and algorithms improving the measurements precision and market competitive advantages of fiber optic current sensors // Sensors. 2020. Vol. 20. No. 21. P. 5995.

12. **Peng N., Huang Y., Wang S., Wen T., Liu W., Zuo Q., Wang L.** Fiber optic current sensor based on special spun highly birefringent fiber // IEEE Photonics Technology Letters. 2013. Vol. 25. No. 17. Pp. 1668–1671.

13. **Wang Y., Xu C.-Q., Izraelian V.** Characterization of spun fibers with millimeter spin periods // Optics Express. 2005. Vol. 13. No. 10. Pp. 3841–3851.

14. **Hu H., Huang J., Huang Y, Xia L., Yu J.** Modeling of the birefringence in spun fiber // Optics Communications. 2020. Vol. 473. 15 October. P. 125919.

15. **Yao P., Chen X., Hao P., Xiao H., Ding Z., Liu T., Yao X. S.** Introduction and measurement of the effective Verdet constant of spun optical fibers // Optics Express. 2021. Vol. 29. No. 15. Pp. 23315–23330.

16. **Аззам Р., Башара Н.** Эллипсометрия и поляризованный свет. Пер. с англ. М.: Мир, 1981. 584 с.

17. **Collett E.** Polarized light in fiber optics. Bellingham, Washington, USA: SPIE Press, 2003. 540 p.

18. **Ищенко Е. Ф., Соколов А. Л.** Поляризационная оптика. 3-е изд., испр. и доп. М.: Физматлит, 2019. 576 с.

19. **Huard S.** Polarization of light. Chichester, UK: John Wiley & Sons, Inc., 1997. 352 p.

20. **Темкина В. С., Лиокумович Л. Б., Арчелков А. Б., Бучилко И. Р., Медведев А. В., Петров А. В.** Описание волоконных световодов с линейным двулучепреломлением при анализе практических оптоволоконных схем методом векторов и матриц Джонса // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3. С. 95–114.

21. **Ярив А., Юх П.** Оптические волны в кристаллах. Пер. с англ. М.: Мир, 1987. 616 с.

22. **Джеррард А., Бёрч Дж. М.** Введение в матричную оптику. Пер. с англ. М.: Мир, 1978. 344 с.

23. **Борн М., Вольф Э.** Основы оптики. Пер. с англ. М.: Наука, 1973. 720 с.

THE AUTHORS

TEMKINA Valentina S.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
temkina_vs@spbstu.ru
ORCID: 0000-0003-2083-8989

LIOKUMOVICH Leonid B.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
leonid@spbstu.ru
ORCID: 0000-0001-5988-1429

ARCHELKOV Arseniy B.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
arsarch11@gmail.com
ORCID: 0009-0007-4713-1293

MEDVEDEV Andrei V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
medvedev@rphf.spbstu.ru
ORCID: 0000-0001-7083-9184

KOZLOV Artemy S.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
kozlov_as@spbstu.ru
ORCID: 0000-0002-1722-1964

GRESHNEVIKOV Konstantin V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
kgreshnevikov@yandex.ru
ORCID: 0000-0002-6154-2538

СВЕДЕНИЯ ОБ АВТОРАХ

ТЕМКИНА Валентина Сергеевна – *ассистентка Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
temkina_vs@spbstu.ru
ORCID: 0000-0003-2083-8989

ЛИОКУМОВИЧ Леонид Борисович – *доктор физико-математических наук, профессор Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
leonid@spbstu.ru
ORCID: 0000-0001-5988-1429

АРЧЕЛКОВ Арсений Борисович – *студент Института электроники и телекоммуникаций Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
arsarch11@gmail.com
ORCID: 0009-0007-4713-1293

МЕДВЕДЕВ Андрей Викторович – *кандидат физико-математических наук, доцент Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
medvedev@rphf.spbstu.ru
ORCID: 0000-0001-7083-9184

КОЗЛОВ Артемий Сергеевич – *инженер Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
kozlov_as@spbstu.ru
ORCID: 0000-0002-1722-1964

ГРЕШНЕВИКОВ Константин Владимирович – *кандидат физико-математических наук, доцент Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
kgreshnevikov@yandex.ru
ORCID: 0000-0002-6154-2538

Received 29.09.2023. Approved after reviewing 09.11.2023. Accepted 09.11.2023.
Статья поступила в редакцию 29.09.2023. Одобрена после рецензирования 09.11.2023. Принята 09.11.2023.