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POLARIZATION MODE DISPERSION COMPENSATOR BASED ON ANISOTROPIC OPTICAL FIBER

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Abstract. In this paper, a new method of polarization mode dispersion (PMD), which can significantly limit the speed and range of transmission of fiber optic transmission systems (FOTS), compensation was developed and analyzed. In contrast to the existing types of PMD compensators, in which the optical fiber is subjected to mechanical stresses to create a photoelastic anisotropy, in this work the use of alternative method of creating photoelasticity in optical fiber (OF) by creating a helical ordered rotation of the glass microstructure (ORMG) is proposed. The helical orientation of the microstructure of the OF glass is achieved by acting on the fiber in the process of manufacture (drawing), when it is in a hot state, electromagnetic field, the power lines of which are directed in a circle. I am not sure what this sentence is trying to say. The result is an asymmetry of the dielectric constant of the fiber glass material and therefore the anisotropy of the optical properties. When the optical signal propagates in such OF, there is a double refraction, which is the cause of artificial PMD in the compensator fiber. Compensation is achieved by performing the equality of the modulus and the sign-opposite between the linear path PMD and the PMD of the anisotropic OF with the ORMG. The expression of the calculation of the PMD of the compensator, which depends on the rotation step of the microstructure of the glass, the chemical composition of the OF, the length of the line, the width of the radiation spectrum and the wavelength of the optical signal, and the optical characteristics of the OF, is analyzed, as well as the spectral dependence of polarization mode dispersion for different chemical compositions of the OF. The expression of determining the length of the OF with the ORMG is presented to compensate for the set value of the PMD in the line. The results of the studies made it possible to determine the lengths of the segments of OF with ORMG, which will provide partial or complete compensation of PMD over a wide range of wavelengths and create passive compensators for dispersion.

Key words: optical fiber, anisotropic medium, photoelasticity, polarization mode dispersion, dispersion compensator.

Анотація. У даній статті розроблено та проаналізовано новий спосіб компенсації поляризаційної модової дисперсії (ПМД), яка може суттєво обмежувати швидкість та дальність передавання волоконно-оптичних систем передачі (ВОСП). На відміну від існуючих видів компенсаторів ПМД, в яких оптичне волокно піддане впливу механічних навантажень для створення фотопружної анізотропії, в даній роботі запропоновано використати альтеративний спосіб створення фотопружності в ОВ за рахунок створення спіральної впорядкованої орієнтації мікроструктури скла (ВОМС) волокна. Спіральна орієнтація мікроструктури скла ОВ досягається шляхом дії на волокно в процесі виготовлення (витяжки), коли воно знаходиться в гарячому стані електромагнітного поля, силові лінії якого направлені по колу. В результаті має місце асиметрія діелектричної проникності матеріалу скла волокна і, як наслідок, анізотропія оптичних властивостей. При розповсюдженні оптичного сигналу в такому ОВ спостерігається подвійне променезаломлення, яке є причиною виникнення штучної ПМД у волокні компенсатора. Компенсація досягається шляхом виконання рівності за модулем та протилежності за знаком між ПМД лінійного тракту та ПМД анізотропного ОВ з ВОМС. У статті отримано вираз розрахунку ПМД компенсатора, яка залежить від кроку обертання мікроструктури скла, хімічного складу ОВ, довжини лінії, ширини спектра випромінювання та довжини робочої хвилі оптичного сигналу, оптичних характеристик ОВ, а також проаналізовано спектральну залежність поляризаційної модової дисперсії для різних хімічних складів ОВ. Надано вираз для визначення довжини ОВ з ВОМС для компенсації заданої величини ПМД в лінії. Результати проведених досліджень дозволили встановити довжини відрізків ОВ з ВОМС, які забезпечать часткову або повну компенсацію ПМД в широких межах довжин хвиль та створити пасивні компенсатори дисперсії.

Ключові слова: оптичне волокно, анізотропне середовище, фотопружність, поляризаційна модова дисперсія, компенсатор дисперсії.

Аннотация. В данной статье разработан и проанализирован новый способ компенсации поляризационной модовой дисперсии (ПМД), которая может существенно ограничивать скорость и дальность передачи волоконно-оптических систем передачи (ВОСП). В отличие от существующих видов компенсаторов ПТД, в которых оптическое волокно подвергнуто воздействию механических нагрузок для создания фотоупругих анизотропии, в данной статье предложено использовать альтернативный способ создания фотоупругости в ОВ за счет создания спиральной упорядоченной ориентации микроструктуры стекла (ВОТС) волокна. Спиральная ориентация микроструктуры стекла ОВ достигается путем воздействия на волокно в процессе изготовления (вытяжки), когда оно находится в горячем состоянии электромагнитного поля, силовые линии которого направлены по кругу. В результате имеет место асимметрия диэлектрической проницаемости материала стекла волокна и, как следствие, анизотропия оптических свойств. При распространении оптического сигнала в таком ОВ наблюдается двойное лучепреломление, которое является причиной возникновения искусственной ПМД в волокне компенсатора. Компенсация достигается путем выполнения равенства по модулю и противоположности по знаку между ПМД линейного тракта и ПМД анизотропного ОВ с ВОТС. В статье получено выражение расчета ПМД компенсатора, которая зависит от шага вращения микроструктуры стекла, химического состава ОВ, длины линии, ширины спектра излучения и длины рабочей волны оптического сигнала, оптических характеристик ОВ, а также проанализировано спектральную зависимость поляризационной модовой дисперсии для различных химических составов ОВ. Представлено выражение для определения длины ОВ с ВОТС для компенсации заданной величины ПМП в линии. Результаты проведенных исследований позволили установить длины отрезков ОВ с ВОТС, которые обеспечат частичную или полную компенсацию ПТД в широких пределах длин волн и создать пассивные компенсаторы дисперсии.

Ключевые слова: оптическое волокно, фотоупругость, анизотропная среда, поляризационная модовая дисперсия, компенсатор дисперсии.

Introduction. At the present stage of the development of the telecommunications services market, fiber optic transmission systems (FOTS) are widely used both in the construction of transport telecommunication lines and in the construction of distribution, corporate and in-house networks. With the gradual increase in the transmission rate, there is a need to optimize the parameters of FOTS. When the transfer rate of 10 Gbit/s and above one of the main limiting factors when transmitting over fiber-optic communication line (FOCL) is the polarization mode dispersion (PMD).

Compensation of PMD is of scientific and practical interests, since increasing transmission speed is one of the main tasks of the FOTS components developers.

Currently, designs of PMD compensators based on spiral-laying photoelastic optical fibers (OF) and active PMD compensators are known. In the first type of PMD compensators, the optical fiber is subjected to mechanical stress to create a photoelastic anisotropy, which can cause microcracks in the OF glass and shorten the life of the entire device. An alternative way of creating a photoelastic anisotropy of OF is to create a helical orientation of the microstructure of a glass fiber [1 - 5].

Anisotropic optical fiber (AOF) provides the required PMD value by the birefringence and difference in group velocities of propagation of two ordinary and extraordinary waves.

The purpose of this article is to develop and analyze a new method of PMD compensation by usage the helical orientation of the fiber microstructure.

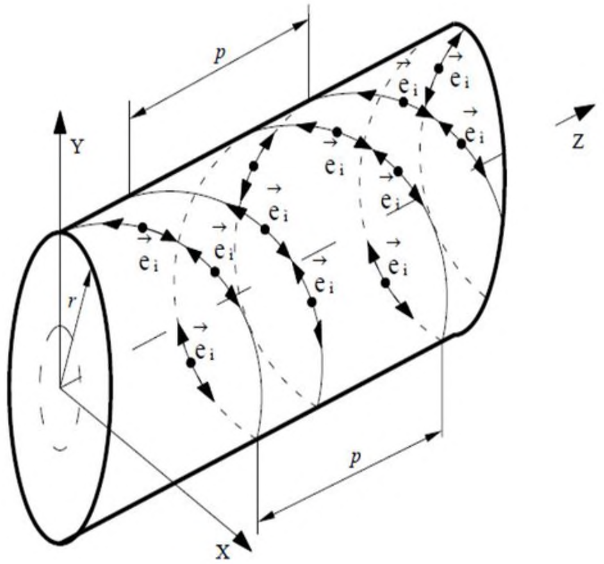

Figure 1 – The orientation of the quartz molecule axes in the OF with ORMG

Optical fiber with ordered rotational microstructure of glass (OF with ORMG). The glass from which an OF is made is optically isotropic and consists of anisotropic molecules and other structural elements, in particular of microcrystals, and the orientation of axes of these microelements is chaotic. In this article, the helical orientation of the OF glass microstructure is achieved by acting on the fiber in the manufacturing process, when it is in a hot state (during vertical drawing), using an electromagnetic field whose force lines are directed in a circle. Under the influence of the electromagnetic field, the axes of the glass microelements are displaced along the force lines of the field, and in the case of vertical drawing, the axes are directed along a spiral line.

The pitch of the OF with ORMG helix is regulated by selecting the frequency of change of the electromagnetic field. Upon further cooling of the glass, this orientation of the microstructure is preserved and the OF receives gradient properties.

In Fig. 1 is a simplified representation of the general view of the proposed circular OF with homogeneous chemical composition (may be pure quartz glass), where – the axis of the quartz molecule, locally oriented along the spiral line of step *p*.

The result is an asymmetry of the dielectric constant (the elements of the dielectric tensor located on the main diagonal differ from the value of the dielectric constant of the isotropic OF, all others are non-zero) and, as a consequence, the anisotropy of the optical properties is obtained [1, 2]. When an optical signal enters the given OF, the fundamental mode splits into two waves with inter-orthogonal polarizations – ordinary and extraordinary, i.e., there is the birefringence, which is the cause of artificial PMD in the OF with ORMG. The numerical value of the created PMD can be adjusted by selecting the step *p* (the rotation step of the rotational microstructure of glass).

PMD compensator based on the OF with ORMG. The proposed PMD compensator is a section of anisotropic OF with ORMG, in which the polarization mode dispersion is artificially introduced due to the difference in the group velocities of propagation of the ordinary (HE_{11}^{o}) and extraordinary (HE_{11}^{e}) waves. If the artificially caused PMD in the OF with ORMG is equal to the module and is opposite to the sign of PMD in the linear path, then full compensation of PMD is performed at the point of connection of OF with ORMG.

The equation of PMD compensation in the proposed method is as follows [3, 4]:

– in case the ordinary wave is ahead of the extraordinary one

$$PMD \cdot \sqrt{L_{FOCL}} + \sigma \cdot L_{AOF} = 0 , \qquad (1)$$

– in case the extraordinary wave is ahead of the ordinary one

$$PMD \cdot \sqrt{L_{FOCL}} - \sigma \cdot L_{AOF} = 0 , \qquad (2)$$

where *PMD* – the coefficient of polarization mode dispersion of the used OF in the linear path, $ps/\sqrt{km}$; L_{FOCL} – length of the fiber optic cable, km; σ – polarization mode dispersion in the OF with ORMG, ps/km; L_{AOF} – the length of the anisotropic OF with ORMG, km.

In turn, PMD in OF with ORMG is determined by expression [5, 6]:

$$\sigma = \frac{w \cdot \lambda \cdot \Delta\omega}{p \cdot c^2 \cdot \sqrt{\varepsilon(r)}^3}(\sin\varphi + \cos\varphi) \cdot \left\{ -\sum_{i=1}^{3} \frac{A_i \cdot \lambda^2 \cdot l_i^2}{\left(\lambda^2 - l_i^2\right)^2} \cdot \left[1 + \frac{3}{2\varepsilon(r)} \sum_{i=1}^{3} \frac{A_i \cdot \lambda^2 \cdot l_i^2}{\left(\lambda^2 - l_i^2\right)^2} \right] - \right.$$
$$\left. -\frac{\lambda^2}{2} \cdot \sum_{i=1}^{3} \frac{3A_i}{\lambda^2 - l_i^2} - \frac{7A_i \cdot \lambda^2}{\left(\lambda^2 - l_i^2\right)^2} + \frac{4A_i \cdot \lambda^4}{\left(\lambda^2 - l_i^2\right)^3} \right\} \cdot 10^{21}, \qquad (3)$$

where w – mode field radius of HE_{11} wave in the OF, mkm; λ – wavelength of the signal, mkm; p – step of the rotating microstructure of glass, mkm; Δω – the width of the transmission spectrum, rad/s; c – the speed of light in a vacuum (in this expression should be used $c = 3 \cdot 10^{14}$ mkm/s); $\varepsilon(r)$ – symmetric profile of the dielectric constant of the OF without ordered rotational microstructure of the material (isotropic); φ – polar coordinate (is calculated from the moving rotating Cartesian coordinate $\vec{x}(z)$), rad; v – OF rotation, 1/mkm; A_i, l_i – the coefficients of the Selmeyer series for the material of the OF core; l_i is measured in microns.

Thus, the problem is that, by selecting the step of rotation of the microstructure of the glass, to achieve equation (1), (2) for a given chemical composition of the OF, the length of the line, the width of the radiation spectrum and the wavelength of the optical signal, the optical characteristics of the OF. Standard single-mode OFs with a radius of 4,5 μm were selected for the studies. The chemical compositions of these optical fibers are given in Table 1.

In this study, PMD dependences in on the wavelength of the signal for the OF with ORMG were obtained. The forms of dependencies obtained are shown in Fig. 2. A 5 microns rotation pitch was chosen for the studies.

Table 1 – Chemical compositions of Ofs with ORMG selected for the study

OF number	The chemical composition of the OF core	The chemical composition of the OF cladding
OF-1	100 % SiO2	1 % F, 99 % SiO2
OF-2	2,2% GeO2, 3,3% B2O3, 94,5% SiO2	3% B2O3, 97% SiO2
OF-3	9,1% P2O5, 90,9% SiO2	7% GeO2, 93% SiO2
OF-4	2,2% GeO2, 3,3% B2O3, 94,5% SiO2	13,5% BeO2, 86,5% SiO2
OF-5	0,1% GeO2, 5,4% B2O3, 94,5% SiO2	3,5% B2O3, 96,5% SiO2
OF-6	4,03% GeO2, 9,7% B2O3, 86,27% SiO2	100% SiO2
OF-7	3,3% GeO2, 9,2% B2O3, 87,5% SiO2	13,5% B2O3, 86,5% SiO2
OF-8	3,5% GeO2, 96,5% SiO2	100% SiO2
OF-9	7,9% GeO2, 92,1% SiO2	5,8% GeO2, 94,2% SiO2

The results demonstrate the following:

1) as the wavelength of the signal increases the PMD in the OF with the ORMG increases, depending on the composition of the OF glass it can vary in the range of 0.5… 10 ps / km;

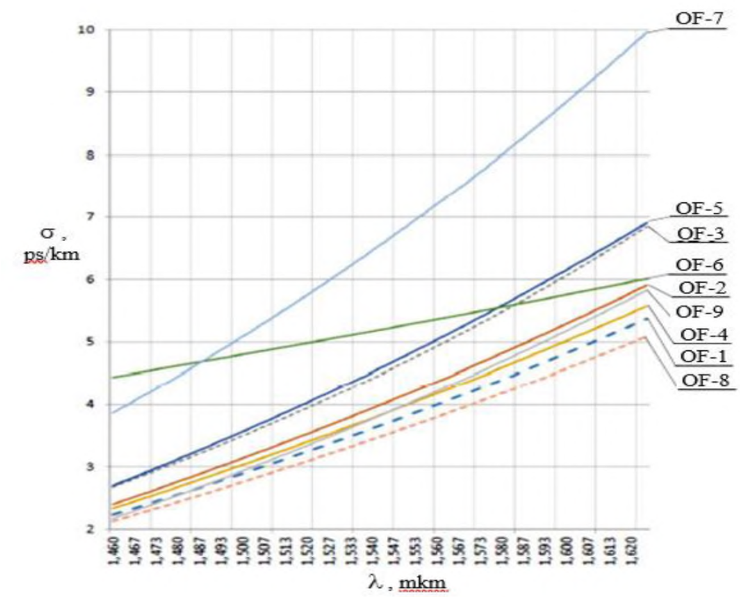

Figure 2 – Spectral dependencies of PMD in OF with ORMG

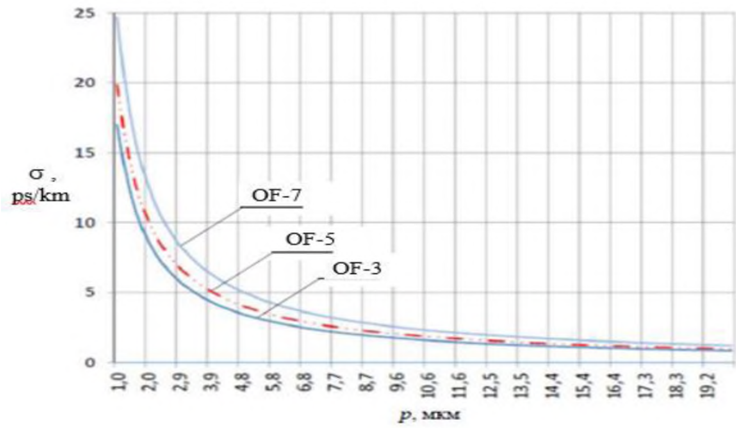

Figure 3 – The dependence of PMD in the FO with ORMG on the step of rotation *p*

2) maximum PMD values in OFs with ORMG were obtained for OF-3, OF-5, OF-7;

3) in the range of λ = 1,46 … 1,625 mkm with p = 5 mkm the PMD in OF with ORMG has a positive value, confirming that it is a ordinary wave HE_{11}^{o} is ahead of the extraordinary wave HE_{11}^{e}.

The next step was to determine the dependence of the PMD in the OF with ORMG on the rotation step of the microstructure of glass p. This dependence for OF-3, OF-5, OF-7 is shown in Fig. 3. For the studies a signal wavelength was selected as λ = 1,55 mkm, the width of the radiation spectrum (Δλ) was 0,1 nm, rotation step of the ORMG in the range of 0 … 20 mkm.

The obtained forms of PMD dependences in the OF with ORMG on the step of rotation of the microstructure of glass showed that by selecting the parameter p it is possible to adjust the PMD values within 17… 0,85 ps / km for OF-3, 19,85 .. 0,99 ps / km for OF-5, 24,68… 1,23 ps / km for OF-7. Thus, it is possible to achieve the necessary to compensate for the value of PMD in the OF with ORMG if the dispersion in a line is due to the wave speed advance of HE_{11}^{e} the speed of wave HE_{11}^{o}.

The expression for determining the length of the OF with the ORMG providing compensation for the PMD has the form [3, 4]:

$$L_{AOF} = \frac{PMD \cdot \sqrt{L_{FOCL}}}{\sigma}. \qquad (4)$$

The lengths of sections of OFs with ORMG, the chemical composition of which corresponds to OF-3, OF-5, OF-7 with providing the PMD compensation are defined. The results are shown in Table 2. The connection point of PMD compensator is the receiving end of the line. The PMD compensation conditions were investigated for the following parameters of the linear tract FOCL and the parameters of the OFs with ORMG:

1) transmission system - STM-16;

2) the wavelength of the optical signal λ = 1,55 μm;

3) OF type - standard single-mode (ITU G.652.B, G.652.D) and single-mode non-zero dispersion shifted (ITU G.655.C, G.655.D, G.655.E);

4) length of optical line - 10 km, 100 km and 1000 km;

5) the core radius of the OF with ORMG - 4,5 μm;

6) the step of ORMG rotation is 2 μm.

Table 2 – Lengths of sections of OFs with ORMG to compensate the line PMD based on OF with type SF and type NZDSF over line lengths of 10 km, 100 km, 1000 km

Type of OF with ORMG for PMD compensation	The length of the optical line		
	PMD coefficient, $ps/\sqrt{km}$	The PMD value of the line, ps	LAOF length for PMD compensation, m
	LFOCL = 10 km		
OF-3	0,2	0,632	54,16
OF-5	0,2	0,632	53,02
OF-7	0,2	0,632	37,07
	LFOCL = 100 km		
OF-3	0,2	2	171
OF-5	0,2	2	168
OF-7	0,2	2	117
	LFOCL = 1000 km		
OF-3	0,2	6,32	541,5
OF-5	0,2	6,32	530,2
OF-7	0,2	6,32	370,7

Conclusions.

1. As a result of the performed work, a new method is proposed and a structure of a new type of PMD compensator that provides the appearance of the necessary value of the PMD at the point of its connection is shown. This effect is achieved by performing the equality of the module and the opposite of the sign between the linear PMD (total PMD of OF, FOTS devices, connectors, etc.) and PMD of anisotropic OF with ORMG. Adjustment of the necessary value of PMD of OF with ORMG is performed at the stage of its production by selecting the necessary step of rotation of the microstructure of glass (molecules, microcrystals).

2. The results of the work made it possible to establish that:

1) on the basis of the equations that relate the chemical compositions of the OF, the parameters of the ordered rotating microstructure of the glass, the length of the line, the PMD of the linear path, the parameters of the optical radiation source, the lengths of the OF sections with the ORMG are provided, which provide compensation of the PMD.

2) the performed spectral analysis proves the possibility of implementation of the proposed device, since there is equality in the module and the opposite in sign between the PMD of line and PMD of OF with ORMG.

3) in the course of work, it is established that the features of double refraction in OF with ORMG allow to control the PMD in a wide range and to achieve the optimum value of PMD with minimal loss of signal power.

4) the main advantages of the proposed design of the PMD compensator in comparison with the current existing compensators based on spiral photoelastic OFs and active PMD compensators are:

- compensation using the proposed method is achieved for wider values of PMD compared to the technical capabilities of existing compensators;
- in the proposed PMD compensator the optical fiber is not subjected to mechanical stress, such as in the photoelastic compensator PMD, which improves the reliability of the device (to prevent the occurrence of microcracks in the glass OF), and
- the proposed PMD compensator is completely passive, does not require power supply, it can be connected at any point of the FOTS linear path (at coupling points, at connection points to the station equipment).

3. This developed method of PMD compensation can be recommended for usage in FOTS for partial or complete elimination of polarization-mode dispersion arising in FOCL.

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