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The Structural Deformations Influence in Microstructured Optical Fibers on Signal Transmission Characteristics

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The paper considers the problem of assessing the influence of mechanical deformations on the characteristics of signal transmission in Microstructured Optical Fibers (MOFs) used in modern fiber-optic communication systems. The relevance of the research is due to increased requirements for the quality of data transmission in high-speed networks and the high sensitivity of MOF to external mechanical influences. The goal of the work is to research the influence of bends and twisting on the main parameters of signal transmission. A transverse model of an undeformed fiber and a modified model that takes into account structural changes caused by deformations have been constructed. The research methodology is based on an assessment of the influence of the ratio of the diameter of air channels to the pitch of their location (d/Λ) on the effective difference in refractive indices, chromatic dispersion and bending losses. The developed models allow taking into account geometric distortions of the fiber structure. The results obtained show that an increase in the parameter d/Λ leads to an increase in the effective refractive index and a significant change in waveguide dispersion. It is established that mechanical deformations cause additional changes in chromatic dispersion and increase bending losses due to the appearance of leaky modes. Quantitative analysis confirms a significant increase in losses and signal distortion with decreasing bending radius. The practical significance of the study lies in the possibility of using the obtained results in the design of dispersion compensation modules and fiber-optic communication lines. The conclusions confirm the high sensitivity of the MOF parameters to changes in the geometric structure and justify the need to take into account deformation effects to ensure reliable signal transmission.

Keywords: dispersion compensation; microstructured optical fiber; optical fiber dispersion; optical fiber losses

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Introduction

The main goal of managing SMART enterprises applying the concepts of Industry 4.0 and 5.0 is rapid adaptation to changing situations in real time using information feedback systems from sensors and executive devices. Many information sources and consumers impose strict requirements on data transmission networks. The challenges of industrial information communication networks are related to performance indicators such as low latency, high reliability, guaranteed security, and high throughput. In this regard, industrial networks in the intelligent enterprise must be based on the principles of guaranteed data delivery, meaning that every device can connect to any available network that provides a reliable connection.

In information and communication systems of intelligent enterprises, fiber-optic communication lines are widely used for data transmission. In long-haul transmission systems, particularly those employ-

ing Dense Wavelength Division Multiplexing (DWDM) technology, optical fiber dispersion has a significant impact on transmission quality. Dispersion arises from differences in the propagation velocities of optical modes or spectral components, resulting in pulse broadening, signal distortion, and degradation of signal reception and decoding. To mitigate the effects of dispersion, Dispersion Compensation Modules (DCMs) are employed to ensure reliable transmission of optical signals with minimal distortion (Fig. 1).

In dispersion compensators, along with standard optical fiber, Microstructured Optical Fibers (MOFs) are used, which, due to their specific cross-sectional structure, have unique properties compared to standard single-mode or multimode optical fibers. A microstructured optical fiber is one with a complex cross-sectional structure. The cladding of such fiber contains air holes, and the core can be quartz or hollow. Due to their complex structures and potential applications across various fields, MOFs are actively studied by many scientific groups.

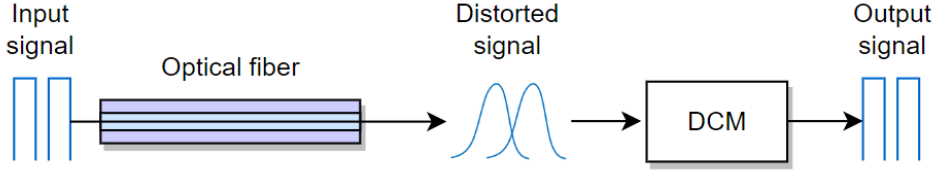


Fig. 1. Use of DCM in communication systems

In [1–4], a ring fiber with an air core and non-zero momentum is proposed, and its dispersion properties depending on the structural parameters are investigated. To achieve a large refractive-index difference, the authors chose a structure with an air core and determined several fiber parameters to achieve low dispersion.

The work [5] is devoted to the development and research of a photonic crystal fiber that provides a large normal dispersion coefficient and low losses over a wide wavelength range of $1.8 \dots 3.6 \mu\text{m}$. The effect of fiber bending on signal attenuation in a Bragg structure was studied in [6]. It was found that such a fiber has a smaller bending radius than that of standard optical fibers. Therefore, fibers of this type can potentially be used for communication and data transmission over long distances.

Works [7–9] are devoted to the study of optical fibers with a hollow core. In [10–12], the characteristics of four-core optical fibers with bonded cores with different arrangement steps were studied. Fiber modeling was carried out using the concatenation of segments of a four-core fiber with bending and twisting, the spatial dispersion of fiber modes with different core pitches was calculated and measured. In [13–16], optical signal losses in photonic crystal fibers arising in their connections due to transverse and angular displacements and the difference of mode fields were investigated.

Thus, the study of optical fibers with complex cross-sectional structures, as well as the influence of their optical-geometric parameters on various characteristics of signal transmission during the interaction between sensors and executive devices of modern intelligent objects, is relevant, and some tasks remain unresolved. This work focuses on the influence of bending deformation on the signal attenuation and dispersion characteristics of MOFs.

Unlike existing studies, this work focuses on a comprehensive analysis of the effects of mechanical deformation in MOFs on dispersion characteristics and bending losses. This approach enables the assessment of the impact of geometric changes in the fiber structure on the performance of DCMs and allows these effects to be taken into account during their design.

1 Determination of Signal Loss at the Optical Fiber Bend

The dispersion compensator is a passive device, which, technologically, is a segment of an optical fiber (sometimes several kilometers long). The optical fiber has a negative dispersion, which restores the distorted signal. During the insertion of an optical fiber into the box of the dispersion compensator, the fiber is deformed, bends and twists are formed, which leads to the occurrence of additional signal losses due to the formation of leaking modes (Fig. 2).

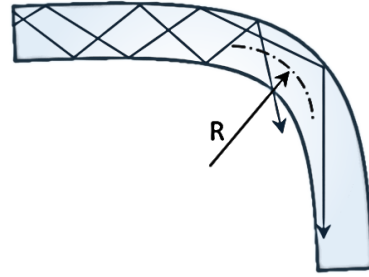


Fig. 2. Signal losses at the optical fiber bend

The amount of optical signal loss depends on the type of optical fiber used. For a multimode optical fiber with a gradient profile of the refractive index, the losses are described by the following expression:

$$\alpha_{\text{curve}} = -10 \lg \left(1 - \frac{u+2}{2u\Delta} \times \left(\frac{2r}{R} + \left(\frac{0.16\lambda}{R} \right)^{\frac{2}{3}} \right) \right), \quad (1)$$

where α_{curve} is bending loss (dB); u is a power exponent describing the change in the refractive index profile; R is the bending radius in the optical fiber (μm); r is the radius of the optical fiber core (μm); λ is the operating wavelength (nm); Δ is the relative difference in refractive indices.

The formula for calculating the attenuation of the signal at the bend, which considers the length of the section of curvature, will look like this:

$$\alpha_{\text{curve}} = \frac{a\chi^c}{R - R_{\text{cr}}}, \quad (2)$$

where a this is a parameter that depends on the numerical aperture and the diameter of the core; R is the bending radius (mm); R_{cr} is a constant parameter for a multimode optical fiber with a gradient profile of refractive index (mm), for which $\alpha_{\text{curve}} \rightarrow \infty$ (due

to breakage of the optical fiber or full exposure of the modes); χ is the number of complete or incomplete turns of optical fiber with a bend radius; c is a dimensionless parameter.

For a standard quartz gradient multimode optical fiber with a core-to-cladding radius ratio $a/b = 50/125 \text{ } \mu\text{m}$, $a = 3.538$, $c = 1/8$, $R_{\text{cr}} = 2.2 \text{ mm}$. The bend loss value of a standard optical fiber can be calculated using the formula:

$$\alpha_{\text{curve}} = -10 \lg \left(1 - \frac{2rn_1^2}{R(NA)^2} \right), \quad (3)$$

where r is the core radius (μm); n_1 this is the core refraction index; R is the bending radius in the optical fiber (μm); NA is the numerical aperture.

The bending loss for a single-mode optical fiber can also be calculated using the following formula:

$$\alpha_{\text{curve}} = \frac{33\Delta^{0.25}\lambda_0^{1.5}}{R^{0.5} - \lambda^2} \exp(-KR), \quad (4)$$

where Δ this is the relative difference in refractive indices; λ_0 is the cutoff wavelength (nm); R is the bending radius in the optical fiber (μm); λ is the operating wavelength (nm);

$$K = 1.244 \frac{\Delta^{1.5}}{\lambda} \left(2.748 - \frac{0.996\lambda}{\lambda_0} \right)^3. \quad (5)$$

Bending losses for MOF are determined by [17]:

$$\alpha_{\text{MOFcurve}} = 4.343 \left(\frac{\pi}{4A_{\text{eff}}R} \right)^{1/2} \left(\frac{1}{W_{\text{eff}}} \right)^{3/2} \times \exp \left(-\frac{4RW_{\text{eff}}^3\Delta_{\text{eff}}}{3A_{\text{eff}}V_{\text{eff}}^2} \right) \left(\frac{U_{\text{eff}}}{V_{\text{eff}}K_1W_{\text{eff}}} \right)^2, \quad (6)$$

where R is the bend curvature radius; Δ_{eff} is the relative difference between the core refractive index and the cladding effective refractive index; V_{eff} is the effective normalized frequency; A_{eff} is the effective area of the MOF mode field; U_{eff} and W_{eff} are the MOF structure parameters [17].

Equations (1)–(6) are mathematical models reported in the scientific literature for estimating the bending losses of multimode, single-mode, and MOFs. In this work, they are used as the fundamental mathematical relationships underlying the proposed research methodology.

To assess the effect of bending on signal attenuation, numerical calculations of losses were performed for standard single-mode fiber and microstructured optical fiber at different bending radii.

The calculations were performed at a wavelength $\lambda = 1.55 \text{ } \mu\text{m}$, which matches with operating range of DWDM systems. For a standard single-mode fiber, typical parameters were used: core radius $5 \text{ } \mu\text{m}$, SMF core refractive index 1.47 and numerical aperture 0.12. For a microstructured optical fiber, the

model parameters given in the next section were used. The results of the loss calculations are given in Table 1.

Table 1 Bending losses for different fiber types

Bending radius, mm	Losses SMF, dB	Losses MOF, dB
20	0.34	0.20
30	0.22	0.16
40	0.17	0.14
50	0.13	0.12
60	0.11	0.11
70	0.09	0.11
80	0.08	0.10
90	0.07	0.09
100	0.07	0.09

The results show that as the bending radius decreases, signal losses increase exponentially. At the same time, the microstructured optical fiber demonstrates lower losses compared to a standard single-mode fiber at the same bending radii, which is explained by the structural features of the studied microstructured fiber, in particular, a significantly larger core radius and an effective area of the mode field. This leads to lower mode-field sensitivity to fiber curvature and, accordingly, to reduced bending losses.

The critical bending radius, defined as the minimum radius at which the loss exceeds 0.1 dB, is 60 mm for SMF and 70 mm for MOF. Thus, the critical bending radius for MOF differs from that for SMF, and this must be considered when designing dispersion compensators and other fiber-optic devices [18].

In addition to the bending radius, the ratio of the diameter of the air holes d to the pitch of their location Λ has a significant impact on the amount of losses in a microstructured optical fiber. To assess this impact, the losses were calculated for different values of the parameter d/Λ (Table 2).

Table 2 The effect of the parameter d/Λ on losses

d/Λ	Losses, dB
0.25	0.316
0.30	0.193
0.35	0.183
0.40	0.114

The results show that as the parameter d/Λ increases, the effective difference in refractive indices increases, leading to changes in the mode propagation conditions and, accordingly, in signal losses.

In addition to attenuation, MOF deformation also affects signal dispersion. Dispersion characteristics of MOFs with an empty core have not been fully studied to date. Light in fibers of this type, unlike standard optical fibers, is propagated mainly by the air core, and not by quartz. Therefore, dispersion and losses depend primarily on the reflectivity of the periodic cladding structure in the transverse direction. And it, in turn, depends on the perfection of the periodic

structure, the extent in the radial direction and the clear observance of the condition of equality of the period of the structure of the total number of half-waves of radiation.

In contrast to the MOF with a hollow core, the zone structure of the MOF with a quartz core is manifested only indirectly, and the waveguide properties are mainly determined by the effect of total internal reflection. In this situation, a clear periodicity in the location of the air channels in the cladding is not required, as the average refractive index is a significant factor.

The number of directional modes in the quartz core of the MOF is determined only by the ratio of the diameter of the air channels to the distance between their axes.

The properties of the MOF of a simplified structure with the diameter of the air tubes almost the same as the distance between them are like the properties of a quartz fiber without a cladding at all. Due to the high contrast of refractive indices, the light wave field penetrates beyond the core at a distance smaller than the diameter of the air tube. Therefore, the influence of the fiber structure outside the first ring of air tubes turns out to be insignificant. Due to the strong concentration of light in the core, the properties of MOFs with a simplified structure differ little from those of MOFs with many holes.

In the MOF, which contains only one ring of air tubes surrounding the core, it is possible to obtain a combination of strong nonlinearity and low dispersion in a certain range of wavelengths. MOFs with a small core area and large holes allow the obtaining of nonlinear effects in fibers of short length. In addition, the large contrast in refractive indices provides significant waveguide dispersion, which can be used to compensate for quartz's material dispersion. This allows shifting the zero-dispersion wavelength to any point in the spectrum, in particular into the visible region, which is interesting for generating a spectral supercontinuum.

The absolute value of dispersion in microstructured fibers can be an order of magnitude higher than the value of dispersion in standard single-mode fibers and reach 2000 ps/(nm·km), and the dependence of dispersion on wavelength in a wide spectral range can be very weak. However, MOFs with a small-diameter core are very sensitive to minor structural changes.

The dispersion of a microstructured optical fiber can be defined as follows:

$$D_{\text{MOF}} = -10 \frac{\lambda}{c_0} \cdot \frac{d^2 n_{\text{eff}}}{d\lambda^2}, \quad (7)$$

where c_0 is the light speed in a vacuum; n_{eff} is the refractive effective index of the MOF; λ is the wavelength.

The effective refractive index of an MOF is defined as

$$n_{\text{eff}} \cong \bar{n} + (n_{\text{core}} - \bar{n}) \cosh^{-2} \frac{\lambda}{\Lambda}, \quad (8)$$

where

$$\bar{n} = \lim_{x \rightarrow D} n_{\text{clad}} = f n_{\text{air}} + (1 - f) n_{\text{core}},$$

$$f = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{\Lambda} \right)^2;$$

n_{clad} is the effective refractive index of the MOF cladding; n_{air} is the refractive index of air; n_{core} is the refractive index of the MOF core (quartz); Λ is the distance between the holes in the cladding [19].

Equations (7) and (8) are relationships used to determine the chromatic dispersion and effective refractive index of MOFs. In this study, they are employed to evaluate the effect of structural deformations on the fiber dispersion characteristics by modifying its geometric parameters.

2 Experimental Research

MOFs are a relatively new type of fiber and, unlike standard ones, there are still problems that require additional study. One such problem is the study of the dependence of MOF optical-geometric parameters on various mechanical influences.

First, deformations of a microstructured optical fiber, such as bending and twisting, affect the distribution of the mode field within the core. The conduct of a computer simulation demonstrates this (Fig. 3).

Fig. 3, a shows the cross-section of a model MOF and the distribution of the mode field within it. We see that the mode field is quite symmetrical about the center, containing only minor oscillations at the core-cladding boundary, which is due to the influence of the first (inner) circle of air holes.

Fig. 3, b shows how changing the shape of the air holes in the cladding and disturbing their spatial arrangement negatively affect the distribution of the mode field - the symmetry of the distribution is broken and leaking modes appear in the cladding.

Unlike existing mathematical models, the proposed approach accounts for mechanical deformations by modifying the geometric parameters of the microstructured optical fiber cross-section. This makes it possible to quantitatively evaluate their effects on the effective refractive index, chromatic dispersion, and signal attenuation without modifying the fundamental relationships given in (1)–(8).

Of course, such changes will inevitably lead to additional optical signal losses and deterioration in the chromatic dispersion parameter.

Fig. 4 shows the change in dispersion with the hole-diameter-to-hole-spacing ratio, which can be attributed to deformations of the MOF.

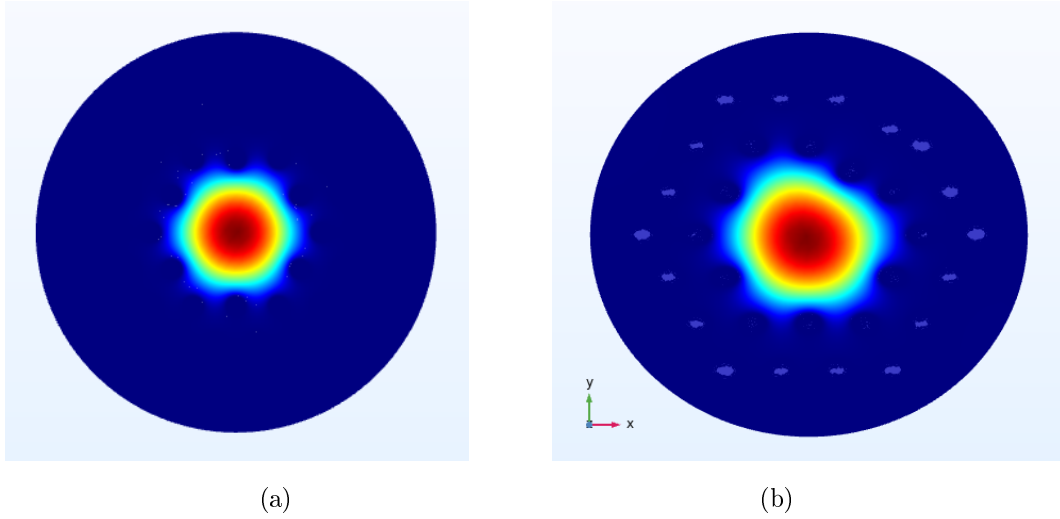


Fig. 3. Signal losses at the bend of the optical fiber: (a) distribution of the mode field in the MOF without deformations; (b) distribution of the mode field in the deformed MOF

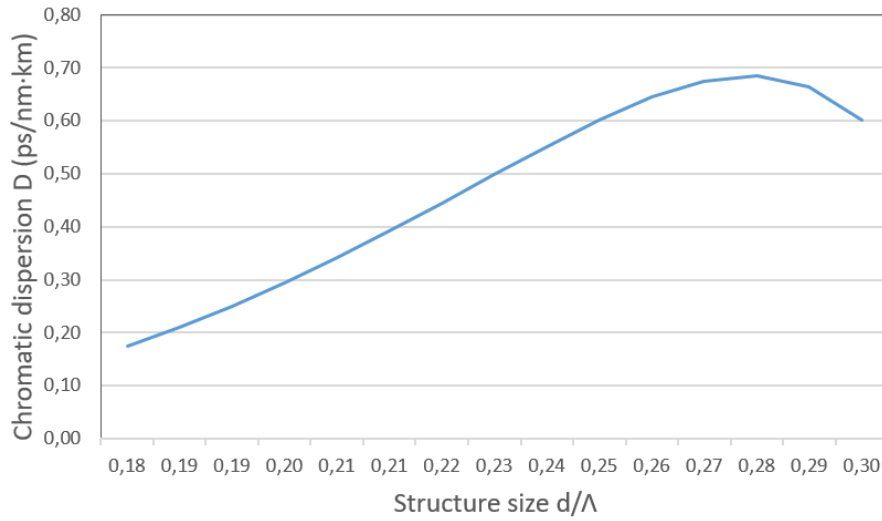


Fig. 4. Chromatic dispersion dependence on changes in the MOF structure

Studies of the chromatic dispersion of the sample and deformed MOF at different wavelengths were also conducted. Fig. 5 shows a smoothed graph of the dependence of the chromatic dispersion on the wavelength for a MOF without deformation with a core radius of $40 \mu\text{m}$, an air hole pitch of $12 \mu\text{m}$, an air hole diameter of $3.2 \mu\text{m}$ (solid line), and a deformed MOF (dashed line).

Table 3 shows the value of chromatic dispersion for both MOF models that participated in the experiment, as well as the calculated value of the absolute difference between them.

It can be seen that MOF structure deformation, as reflected in changes in hole shape and their spatial distribution, affects chromatic dispersion. In this case, the maximum difference in chromatic dispersion is $17 \text{ ps}/(\text{nm} \cdot \text{km})$ at a wavelength of $1.6 \mu\text{m}$, and the average is $5.6 \text{ ps}/(\text{nm} \cdot \text{km})$.

To assess the practical impact of MOF deformation on signal transmission parameters, a pulse broadening

calculation was performed for a section of a DWDM line 80 km long at a wavelength of $1.55 \mu\text{m}$:

$$\Delta t = D\Delta\lambda L, \quad (9)$$

where D is the dispersion, $\Delta\lambda$ is the spectral width of the signal, and L is the line length.

For a fiber without deformation, the pulse broadening value is 40 ps . After mechanical deformation, this parameter changes, resulting in a pulse broadening of 144 ps . The increase in pulse broadening during deformation is 260% , which can result in a decrease in the maximum section length without dispersion compensation or necessitate the use of additional compensating modules. The results indicate the influence of mechanical loads on the time characteristics of the transmitted signal and confirm the feasibility of accounting for deformation effects in the design of fiber-optic communication lines.

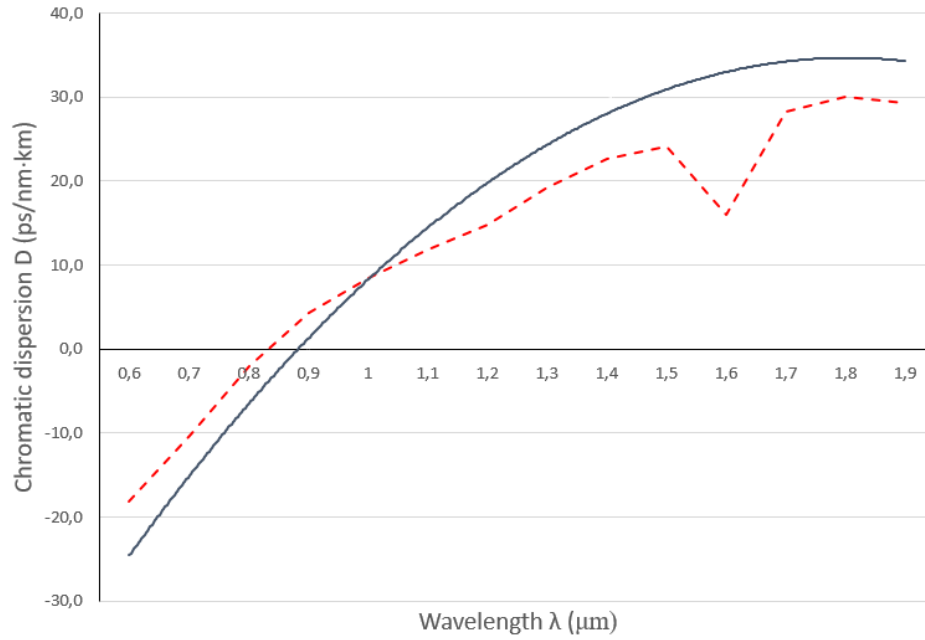


Fig. 5. Chromatic dispersion for MOF without deformation and deformed MOF

Table 3 Chromatic dispersion for the MOF models

Wavelength, μm	Dispersion of the MOF without deformation	Dispersion of deformed MOF	The absolute variance dispersion
0.8	-5.2	-2.1	3.1
1.0	6.1	8.4	2.3
1.2	20.0	14.8	5.2
1.4	30.1	22.7	7.1
1.6	33.0	16.0	17
1.8	34.0	30.1	3.7

The obtained results can be used in the design of DCMs to optimize the geometric parameters of MOFs, determine permissible bending radii, and define installation conditions. Taking into account the influence of mechanical deformations on chromatic dispersion and signal attenuation makes it possible to more accurately determine the parameters of the compensation fiber, reduce residual dispersion after compensation, and ensure stable signal transmission performance in DWDM systems.

Conclusion

The parameters of the elements of information and communication systems built on optical fibers, including microstructured ones, affect the quality of interaction between intelligent sensors and executive devices in modern production; therefore, they require control.

While standard optical fibers and their use in communication systems are well studied, microstructured fibers are a relatively new fiber type, and some problems remain under research and need to be resolved. One such problem is the dependence of

MOF optical and geometric parameters on mechanical influences.

The research presented in this paper showed the influence of microstructured optical fiber deformation on the parameters of the transmitted signal. A model of the MOF cross-section without deformations was built, as well as a model simulating changes in the fiber structure that occur during operation or the implementation of various devices, for example, dispersion compensators. First of all, these are deformations in the form of bending and twisting of the MOF.

A change in the shape of the air holes in the MOF cladding, as well as a violation of the distances between them, leads to a change in the chromatic dispersion values. The conducted studies showed that chromatic dispersion increases with increasing ratio of hole diameters to the distance between them in the MOF cladding. The chromatic dispersion of the sample and deformed MOF at different wavelengths was also investigated in the work. The maximum value of such changes in our case is 17 ps/(nm·km) at a wavelength of 1.6 μm , and the average is 5.6 ps/(nm·km) over the entire range of investigated wavelengths.

In addition, the formulas for calculating the attenuation of the optical signal due to bending in various types of optical fibers are provided. The amount of signal attenuation depends on the fiber's optical-geometric parameters and the radius of its bend. The calculations showed that as the parameter d/Λ increases, the relative difference in refractive indices increases, leading to an increase in the waveguide component of chromatic dispersion and changes in the MOF's mode characteristics. It was found that mechanical deformation induces an additional change in the effective refractive index, significantly affecting the fiber's dispersion parameters.

The scientific novelty of the obtained results lies in the development of a model of a deformed microstructured optical fiber that accounts for structural changes caused by mechanical loading and enables quantitative evaluation of their impact on the effective refractive index, chromatic dispersion, and bending losses. Unlike existing approaches, the proposed model simultaneously considers structural deformations and their influence on signal transmission characteristics, thereby improving the accuracy of designing dispersion-compensated fiber-optic communication systems.

A study of the effect of microstructured optical fiber deformation due to bending and twisting on chromatic dispersion showed that, for an 80 km DWDM line at $1.55 \mu\text{m}$, the pulse width increased from 40 ps to 144 ps, corresponding to a 260 % increase. Such a change can lead to significant deterioration in signal quality and to intersymbol interference during high-speed data transmission.

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Вплив структурних деформацій у мікроструктурованих оптичних волокнах на характеристики передавання сигналу

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Розглянуто задачу оцінювання впливу механічних деформацій на характеристики передавання сигналу в мікроструктурованих оптичних волокнах (МОВ), що застосовуються у сучасних волоконно-оптичних системах зв'язку. Актуальність дослідження зумовлена підвищеними вимогами до якості передавання даних у високошвидкісних мережах та високою чутливістю МОВ до зовнішніх механічних впливів. Метою роботи є дослідження впливу вигинів і скручування на основні параметри передавання сигналу. Побудовано поперечну модель недеформованого волокна та модифіковану модель, що враховує зміни структури, викликані деформаціями. Методика дослідження базується на оцінці впливу відношення діаметра повітряних отворів до

кроку їх розташування (d/Λ) на ефективну різницю показників заломлення, хроматичну дисперсію та втрати на вигині. Розроблені моделі дозволяють враховувати геометричні спотворення структури волокна. Отримані результати показують, що збільшення параметра d/Λ призводить до зростання ефективного показника заломлення та суттєвої зміни хвильовидної дисперсії. Встановлено, що механічні деформації викликають додаткові зміни хроматичної дисперсії та збільшують втрати на вигині внаслідок появи витікаючих мод. Кількісний аналіз підтверджує значне зростання втрат і спотворення сигналу при зменшенні радіуса вигину. Практичне значення роботи полягає у можливості використання отриманих результатів при проектуванні модулів компенсації дисперсії та волоконно-оптичних ліній зв'язку. Висновки підтверджують високу чутливість параметрів МОВ до змін геометричної структури та обґрунтовують необхідність урахування деформаційних впливів для забезпечення надійного передавання сигналу.

Ключові слова: компенсація дисперсії; мікроструктуроване оптичне волокно; дисперсія; оптичні втрати