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IDENTIFYING THE INFLUENCE OF INHOMOGENEITIES IN MULTIMODE OPTICAL FIBERS ON THE QUALITY OF SIGNAL TRANSMISSION

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The object of this study is fiber-optic communication lines operating under increased mechanical loads arising during cable installation, operation in aggressive environments, or on moving objects. The problem lies in the insufficient understanding of the impact of mechanical loads on the parameters of optical fibers, which complicates their use in challenging operating conditions. The aim of the work is to improve the reliability and durability of such lines by studying the effect of tensile and compressive loads on the characteristics of multimode optical fibers (MOFs).

During the experiments, the initial attenuation values (1.09 dB/km) and their changes under tensile loads were measured. Test samples, approximately 20 meters long, were subjected to gradually increasing tensile force. Prolonged exposure to the load significantly increased the attenuation coefficient, particularly in the shortwave part of the spectrum. Fiber failure occurred after 113 minutes, indicating a critical reduction in strength. This effect can be attributed to the intensification of material inhomogeneities in the fiber, leading to increased light scattering.

The impact of compressive loads on dispersion was studied at a wavelength of 1.06 μm. It was found that the shortwave spectrum is more sensitive to deformations due to the specific structure of the fiber. A comprehensive analysis of the loads identified critical factors affecting the reliability of MOFs. The results obtained enable the prediction of the durability of fiber-optic communication lines, accounting for mechanical impacts in their design and developing recommendations for improved operation. The practical significance lies in applying the findings to enhance fiber condition assessment methods and create more reliable communication systems

Keywords: optical fibers, signal attenuation, tensile loads, compressive loads, pulse dispersion

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1. Introduction

Fiber-optic communication systems play a key role in telecommunications due to their high bandwidth, electromagnetic resistance, and ability to transmit data over long distances. However, the mechanical reliability of optical fiber remains an important aspect, especially under tensile and compressive loads arising during cable installation, operation in aggressive environments, or on moving objects. Mechanical impacts can cause changes in fiber parameters, such as signal attenuation and dispersion, which degrade data transmission quality or lead to communication line failures. This is particularly critical for modern railway networks, where stability and reliability are essential to ensure train safety and maintain high-speed, accurate data transmission. Despite advancements in optical fiber manufacturing, mechanical durability remains a limiting factor for railway applications in extreme conditions, necessitating further research and development of new standards and technologies.

Given modern requirements for the reliability and durability of optical communication lines, research focused on the impact of mechanical loads on MOF characteristics is especially relevant. With the expanding applications of MOFs, including infrastructure exposed to high levels of vibration, variable loads, and extreme operating conditions, it is important to understand how mechanical impacts, such as tensile and compressive forces, influence attenuation, dispersion, and strength properties of fibers. This not only enables the prediction of fiber durability but also helps optimize their design for specific operating conditions, including telecommunications, sensors, and data transmission systems in challenging environments. Such an approach allows for the development of more robust and reliable communication systems that meet the needs of high-load and critical infrastructure facilities.

These loads lead to an increase in inhomogeneities within OFs, significantly affecting transmission quality by causing birefringence and nanopore scattering. Nanopore scattering generates higher-order spatial modes.

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2. Literature review and problem statement

The study [1] demonstrated the impact of compressive force on the attenuation coefficient in optical fibers, showing that mechanical stresses create local distortions that degrade signal transmission quality. However, the effect of prolonged loads on the accumulation of such distortions remains insufficiently studied due to the challenges of replicating real-world operating conditions in laboratory experiments.

The study [1] examined the combined effect of mechanical and thermal impacts but focused on single-event influences, limiting the understanding of progressive fiber degradation processes. This limitation is attributed to constraints in experimental setups, which do not allow for the modeling of complex multifactorial conditions.

The study [2] identified the effect of residual stresses on polarization mode dispersion, but there is no quantitative analysis of random distortions in real communication systems. One reason is the high cost and complexity of experimental research involving a wide range of fibers and operating conditions.

The study [3] explores ionization processes in carbon aerosols under long laser pulses. While this research details the physical processes related to laser exposure, it does not sufficiently address how medium inhomogeneities affect signal transmission stability in multimode optical fibers (MOFs). These inhomogeneities, arising from material structural variations or external mechanical impacts, can significantly influence signal attenuation parameters, particularly in shortwave spectral regions.

The study [4] focuses on numerical modeling of heat accumulation effects under repeated laser pulse exposure. However, the influence of inhomogeneities, such as microstructural defects or residual stresses, on signal transmission quality in MOFs under prolonged loads was not considered. These aspects require further investigation to assess the long-term reliability of optical systems.

The study [5] aims to reduce data processing errors in laser sensing systems. However, it does not analyze how inhomogeneities in MOFs affect mode distribution and contribute to increased attenuation coefficients. This limits the applicability of the proposed methods for improving signal transmission quality under real operating loads.

The study [6] examined the mechanical reliability of optical fibers, although the effect on MOF characteristics was not sufficiently addressed. This highlights the need for research on the mechanical-optical correlation in MOFs under stress. However, unresolved issues remain regarding the specific role of these factors in multimode signal degradation, likely due to the complexity of modeling MOF behavior under various mechanical conditions.

The study [7] focuses on optical solitons in multimode fibers (MOFs). The author analyzes advancements in soliton stability to minimize dispersion and nonlinear effects. However, the study does not adequately consider how MOF structural inhomogeneities affect soliton stability, especially under mechanical loads that may cause local signal distortions. The study [8] examines nonlinear effects in MOFs, but their contribution to signal degradation under mechanical loads remains unclear.

The analysis of the identified problems allows for the systematization of key unresolved issues:

– how mechanical and thermal impacts interact with inhomogeneities and contribute to the progressive degradation of fiber structural characteristics and, consequently, multimode signal transmission parameters;

– how these impacts can be effectively modeled and monitored in real time.

The unresolved nature of these issues is primarily due to technological limitations in studying combined loads and constraints of current experimental techniques.

Thus, a detailed study of the mechanical-optical correlation in MOFs under prolonged combined loads is essential for improving the reliability and durability of OFs in order to identify degradation patterns in high-safety-demand applications.

3. The aim and objectives of the study

The aim of the study is to identify patterns of changes in attenuation and strength characteristics of multimode optical fibers (MOFs) under tensile and compressive loads. This will facilitate the prediction of MOF behavior under operating conditions and improve the reliability and durability of communication lines across various fields, including telecommunications and industry.

To achieve this aim, the following objectives must be accomplished:

– to experimentally investigate the impact of tensile and combined loads on the attenuation coefficient of MOFs;

– to assess the reliability of MOFs under tensile loads.

4. Materials and methods

The object of the study is MOFs subjected to various mechanical loads, including tensile and compressive forces. The main hypothesis of the study is that, given existing inhomogeneities in OFs, tensile and compressive loads alter the attenuation and strength characteristics of MOFs, which affects their operational performance and durability.

Accepted assumptions:

– all measurements are carried out under stable temperature and humidity conditions;

– the applied load does not cause significant damage to the fibers until the end of the experiment;

– the parameters (attenuation and strength) are representative of most types of MOFs used in modern telecommunication systems.

Accepted simplifications:

– for experimental purposes, it is assumed that thermal and mechanical impacts can be considered separately, although in real conditions they can be combined;

– measurements are carried out for one type of MOFs with an initial attenuation of 1.09 dB/km, which limits the generalizability of the conclusions to other fiber types but allows for a more in-depth study of the behavior of this particular material.

Measurements were carried out using an experimental setup consisting of two identical vertically positioned cylinders with a diameter of 6 cm. The upper cylinder was fixed to a stationary stand, while the lower one was suspended on optical fiber coils [7]. The output sections of the MOF were wound around the cylinder with a diameter of 6 cm for 3–4 turns and secured with adhesive tape. The MOF was tensioned evenly between the two cylinders without overlapping coils. Weights of a given mass were suspended on the lower cylinder.

For basic measurements, OFs ranging from 100 to 1,000 m in length were used. The application time for each longitudinal tensile load, incrementally, did not exceed 20 seconds. Each time, the no-load transmission coefficient was preliminarily checked. After applying the load, the test OF section was broken off when attenuation after removing the load was exceeded by 5 %.

The experiment used G.651 standard MOFs with a 20-meter section length and an initial attenuation of 1.09 dB/km. These fibers have a bend radius of 15 mm.

Experiments were carried out on a specially designed setup consisting of two vertically positioned cylinders with a diameter of 6 cm, where the upper cylinder was fixed to a stationary stand, and the lower one was suspended on optical fiber (OF) coils, as shown in Fig. 1. The output sections of the MOF were wound around the lower cylinder for 3–4 turns and secured with adhesive tape.

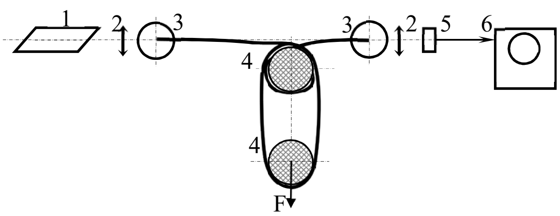

Fig. 1. Measurement scheme for pulse dispersion in optical fiber as a function of compressive force

In the center of the setup there is a neodymium laser with a wavelength of 1.06 μm, a lens for precise beam direction into the fiber, a rotary stage with an angle control system for adjusting the fiber inclination relative to the laser, two cylinders that create uniform fiber tension for load simulation, a photonic electronic amplifier (PEA) for detecting the optical signal and an oscilloscope (LeCroy) for recording time characteristics and measuring pulse dispersion [8].

Fig. 2 shows the laboratory setup for measuring pulse dispersion in the MOF as a function of compressive force. The laser with a wavelength of 1.06 μm is connected to the optical fiber passing through the measuring section. The lens system focuses the laser beam [9], and the rotary stage adjusts its angle of incidence on the fiber for optimized measurements. The fiber is tensioned between two cylinders, and the lower cylinder can be loaded with weights to modify the compressive force [10]. The oscilloscope (LeCroy) records pulse dispersion, analyzing the dependence of signal attenuation on applied loads.

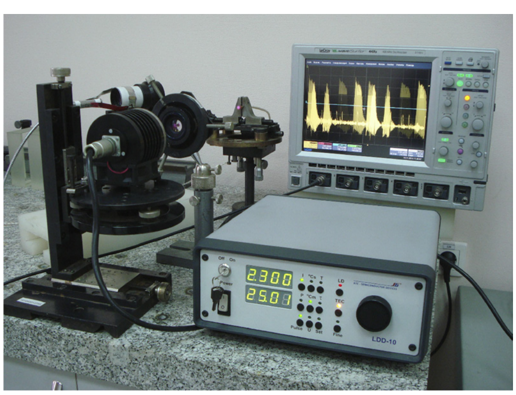

Fig. 2. Laboratory setup for measuring dispersion in optical fiber

This image clearly demonstrates how each component of the setup contributes to studying the fiber's optical characteristics and their dependence on mechanical loads, which is a key aspect of this research.

The stress acting on the optical fiber can be measured using the optical properties of the glass itself or fiber-based sensors. The two most common optical methods are phase shift and transit time [11, 12]. Both methods rely on measuring the transit time of a light pulse in the fiber. The fiber strain, ε, is determined by the measured difference in transit time between the tensioned and untensioned cable, Δτ:

$$\varepsilon=\left(\frac{1}{L}\right)\left(\frac{c}{N}\cdot\frac{1}{k}\right)\Delta\tau, \quad (1)$$

where L is the fiber length, c is the speed of light in a vacuum, N is the fiber's group index, and k is the optical stress coefficient, accounting for the refractive index dependence on strain [13]. The transit time and phase shift methods are based on measuring Δτ and give an average strain value over the fiber length. These methods are best suited for structures where the fiber passes straight after cable tensioning. When using optical fiber in multicore cables, additional bending stresses must be considered. Stimulated Brillouin scattering, despite offering better length resolution, also averages strain over meters of fiber [14–17]. This method provides higher length resolution than the previous two methods but still averages strain over meters of fiber:

$$\varepsilon=\frac{\Delta\lambda_{bragg}}{\lambda_{bragg}}\cdot\frac{1}{k}. \quad (2)$$

The change in the back radiation wavelength ($\Delta\lambda_{bragg}$) is linearly related to the stress applied to a fiber having a Bragg grating [18]. The spectra of light reflected by Bragg grating sensors are recorded using an optical spectrum analyzer. The length of a standard Bragg grating is about 1 cm. Fiber drawing is performed at relatively low stress. For standard single-mode and multimode fibers, the tensile stress affects optical properties more significantly than mechanical ones. The residual surface tension of standard single-mode fiber is several MPa. After drawing, the fiber is wound onto fairly large-diameter spools with low winding tension. Usually, during processing, the fiber is guided using pulleys and rollers [19–21].

Attenuation in optical fiber characterizes the degree of signal power loss during propagation and is determined by the formula:

$$A=10\log_{10}\left(\frac{P_{in}}{P_{out}}\right), \quad (3)$$

where A is the attenuation coefficient in decibels (dB), P_{in} is the input signal power, and P_{out} is the output signal power. This parameter is crucial in designing fiber-optic communication lines, as it affects the signal transmission range and system efficiency. Attenuation arises from several factors, including Rayleigh scattering, fiber material absorption, and connection losses [9, 22].

Additionally, the effect of mechanical stress on the optical properties of the fiber can be accounted for through the attenuation coefficient associated with fiber length, strain, and applied force. The stress σ acting on the fiber is calculated by the formula:

$$\sigma=\frac{F}{A}, \quad (4)$$

where F is the applied force in Newtons, and A is the cross-sectional area of the fiber in square meters. The fiber strain ε is determined by the ratio:

$$\varepsilon=\frac{\Delta L}{L}, \quad (5)$$

where ΔL is the fiber elongation, and L is its initial length. Strain affects the refractive index and can alter signal dispersion.

The relationship between strain and attenuation can also be expressed through the change in pulse dispersion Δt, calculated by the formula:

$$\Delta t=\frac{nl}{c}(1+k\varepsilon), \quad (6)$$

where n is the refractive index of the fiber material, Δt is the time interval (s).

Thus, attenuation in optical fiber results from the combined effects of the material's intrinsic properties and external factors such as mechanical stress and bending.

Experimental methods, including the use of cylindrical samples and weights, were chosen to ensure precise and reproducible control of load conditions. Laser and photometric setups enable high-accuracy measurements of fiber characteristics. Theoretical methods, in turn, are essential to predict fiber behavior and compare it with experimental data, as well as to identify broader patterns that can be useful in various fiber-optic communication applications.

5. Results of the study on the effect of inhomogeneities in multimode optical fibers

5. 1. Effect of tensile and combined loads on the attenuation coefficient of multimode optical fibers

The experiments presented in Tables 1, 2 revealed that longitudinal tensile loads significantly affect the attenuation coefficient of MOFs. For example, according to Table 1, at a wavelength of 0.53 μm, the attenuation coefficient increased from 13.19 dB/km with no load to 13.77 dB/km with a 15 N load. Similar changes were observed for other wavelengths, indicating an increased sensitivity of the optical fiber to mechanical impacts.

Fig. 3, 4 present diagrams illustrating the differences in MOF attenuation at different wavelengths. The diagram shows how the fiber attenuation coefficient varies depending on the radiation wavelength, allowing for a visual assessment of the effect of spectral characteristics on optical fiber losses.

Each diagram depicts the gradual change in the attenuation coefficient as the load increases, with the most significant changes observed at shorter wavelengths.

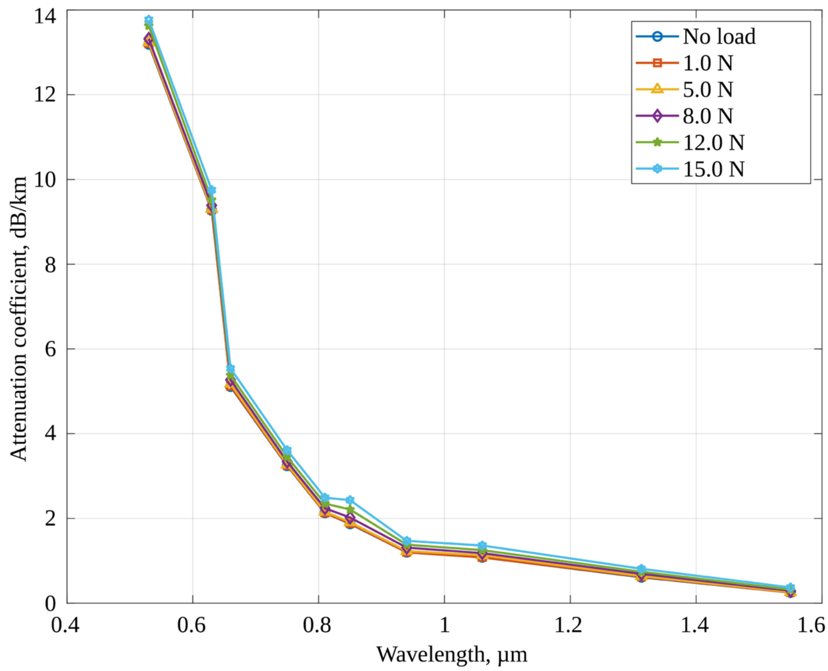

Fig. 3. Dependence of the attenuation coefficient on load for different wavelengths

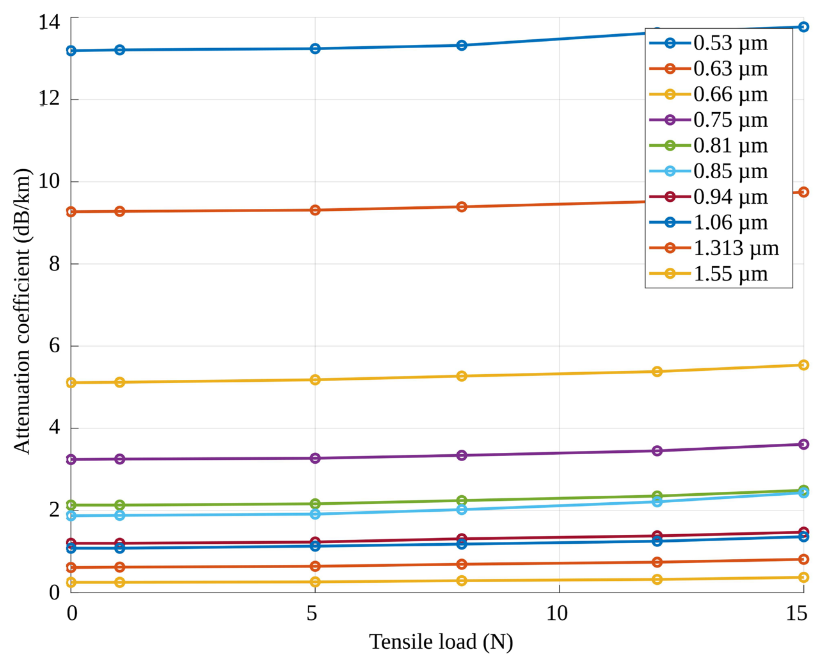

Fig. 4. Dependence of the attenuation coefficient on tensile load for different wavelengths

It is evident that for shortwave regions of the spectrum, such as 0.53 μm, attenuation is significantly higher compared to longwave sections, for example, 1.55 μm. This confirms the assumption that shortwave ranges are more sensitive to mechanical impacts and changes in operating conditions. The diagram illustrates that even minor variations in wavelength can cause noticeable fluctuations in the attenuation coefficient, which is important to consider when designing optical systems and selecting operating wavelengths for data transmission.

Table 1

Spectrum of attenuation coefficients (a, dB/km) of a single MOF as a function of tensile load

l, μm	0.53	0.63	0.66	0.75	0.81	0.85	0.94	1.06	1.313	1.55
No load	13.19	9.27	5.11	3.24	2.13	1.87	1.20	1.08	0.61	0.25
1.0 N	13.21	9.28	5.12	3.25	2.13	1.88	1.20	1.08	0.62	0.25
5.0 N	13.24	9.31	5.18	3.27	2.16	1.91	1.23	1.13	0.64	0.26
8.0 N	13.32	9.39	5.27	3.34	2.24	2.02	1.31	1.18	0.69	0.29
12.0 N	13.63	9.52	5.38	3.45	2.35	2.21	1.38	1.25	0.74	0.32
15.0 N	13.77	9.75	5.54	3.61	2.49	2.43	1.47	1.36	0.81	0.37

Thus, the data presented in Fig. 3 highlight the importance of analyzing spectral characteristics when assessing the performance and reliability of optical fibers in various operating conditions.

5. 2. Reliability assessment of multimode optical fibers under tensile loads

Table 2 presents the research results, demonstrating that prolonged exposure to a tensile force of 16 N significantly increases fiber attenuation. Initially, the attenuation coefficient at a wavelength of 1.06 μm was 1.09 dB/km. However, as the exposure time increased, it reached 5.89 dB/km by the 110^{th} minute, with fiber failure occurring at the 113^{th} minute.

Fig. 4 illustrates a diagram of the MOF attenuation coefficient (α, dB/km) at a wavelength of 1.06 μm, depending on the duration of tensile force application (15 N). The diagram clearly shows how load application time affects the fiber attenuation coefficient, demonstrating that attenuation increases with prolonged exposure. This confirms a direct relationship between the load duration and signal loss in the optical fiber. The data presented in Fig. 5 emphasize the importance of considering mechanical loads when designing and operating optical systems, as prolonged exposure can significantly degrade the fiber's transmission characteristics.

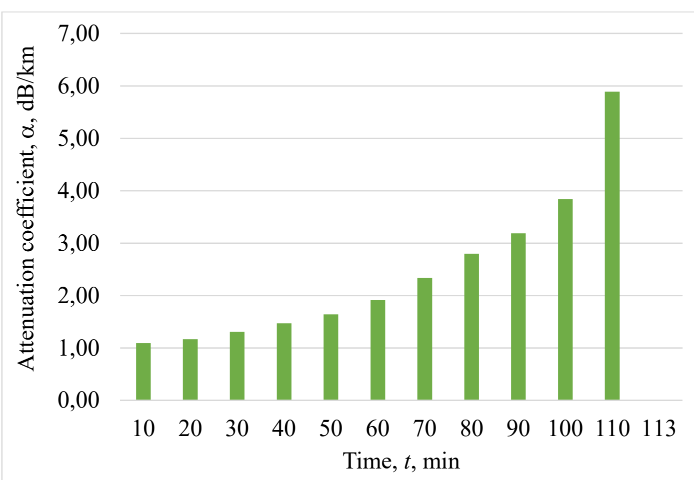

Fig. 5. Illustration of the MOF attenuation coefficient under prolonged tensile load

The primary factors affecting fiber durability are mechanical loads, temperature fluctuations, installation and operating conditions, as well as material quality. Prolonged exposure to tensile and compressive forces leads to increased signal attenuation coefficient and fiber degradation, as confirmed by experimental data. To improve reliability, it is necessary to develop new materials, enhance protective coatings and optimize operating conditions. Research in this field is crucial for advancing technologies and standards, ensuring reliable and long-term operation of fiber-optic systems under various conditions.

Table 2

Attenuation coefficient of a single MOF (a, dB/km) at a wavelength of 1.06 μm depending on the duration of tensile force of 15 N

t, min	10	20	30	40	50	60	70	80	90	100	110	113
α, dB/km	1.09	1.17	1.31	1.47	1.64	1.91	2.34	2.80	3.19	3.84	5.89	—

Thus, while short-term application of significant tensile forces does not cause a substantial increase in the attenuation coefficient, prolonged exposure results in a significant increase in fiber losses. The shortwave range proved to be the most sensitive to tensile loads, which must be considered in the design and operation of optical systems.

6. Discussion of tensile load effects on multimode optical fibers

The experimental results presented in Tables 1, 2 demonstrate a significant dependence of the MOF attenuation coefficient on the applied tensile load and its duration. The increase in the attenuation coefficient in the shortwave range can be explained by the high sensitivity of short waves to mechanical deformations in the fiber structure. For example, at a 15 N load, attenuation at a wavelength of 0.53 μm increased by 0.58 dB/km, which significantly exceeds the corresponding increase for a wavelength of 1.55 μm (0.12 dB/km). This is due to the greater material inhomogeneity of the fiber, affecting the shortwave part of the spectrum. Additionally, prolonged load exposure leads to an increase in the attenuation coefficient: at a 15 N load, attenuation at a wavelength of 1.06 μm increased from 1.09 dB/km to 5.89 dB/km over 110 minutes (Table 2). Fiber failure occurred at the 113th minute, indicating that the ultimate tensile strength had been reached.

Unlike other studies focusing on short-term loads, this experiment examines the dynamics of the attenuation coefficient over time. This allows for assessing the cumulative effect of prolonged mechanical impacts. For example, while [5] focuses on instantaneous changes in the attenuation coefficient, the presented approach demonstrates a progressive growth in the parameter, enabling predictions of fiber durability under real operating conditions. This comparison shows that the proposed method contributes to a deeper understanding of fiber degradation. The results in Fig. 3–5 indicate that tensile loads significantly affect the MOF attenuation coefficient, especially in the shortwave range. At a 15 N load, attenuation at a wavelength of 1.06 μm increased nearly 5-fold over 110 minutes, reaching a critical level before fiber failure (Fig. 3). The shortwave range (0.53 μm) exhibits faster attenuation growth compared to the longwave range (1.55 μm), which is associated with light interaction with material defects (Fig. 4). Comparative analysis (Fig. 5) confirms the increased vulnerability of short waves to mechanical deformations.

The experiment confirmed that increasing the tensile load leads to fiber degradation, particularly in the shortwave range. This was made possible by applying a method of prolonged load exposure with recording of changes in time.

The study was conducted in laboratory conditions, which limits its applicability to real-world operational scenarios where additional factors such as vibrations, temperature fluctuations, and chemical exposure may affect the fiber. Furthermore, the experiments were performed for one type of MOF, requiring caution when extrapolating results to fibers with different parameters. A more complete understanding necessitates considering the impact of complex effects.

The disadvantages of the study include the limited analysis of the fiber material microstructure, which could provide deeper insight into the degradation mechanism. Additionally, cable length can significantly impact defect accumulation and the increase in attenuation coefficient, as increasing lengths have a higher probability of light signal interaction with inhomogeneities and damaged areas. This also amplifies the influence of distributed mechanical loads. To account for this factor, future research could investigate fibers of varying lengths and simulate load distribution along the entire cable.

Further research could focus on developing models that consider complex effects, including mechanical, thermal and chemical factors. This will enable the creation of predictive diagnostic methods for fiber durability. For example, machine learning could be used to analyze experimental data and predict the moment of fiber failure. Additionally, expanding the range of experiments to include different types of fibers and load conditions would provide a more complete understanding of fiber behavior in various operating conditions.

Thus, the obtained results have made it possible to identify key factors affecting the strength and attenuation of MOFs. The problem addressed in this study is to develop a scientifically grounded framework for considering mechanical impacts in the design of optical communication lines. The acquired data are of practical significance for ensuring the durability and reliability of fiber-optic systems under increased mechanical loads.

7. Conclusions

1. The study of changes in the MOF attenuation coefficient under various tensile loads demonstrated that tensile forces significantly affect fiber characteristics, especially the attenuation coefficient. This is due to the increased sensitivity of the shortwave spectrum regions to mechanical impacts. For example, at a 15 N load at a wavelength of 0.53 μm, the attenuation coefficient increased from 13.19 dB/km to 13.77 dB/km. A unique aspect of the obtained results is the identified dependence of the attenuation coefficient on the spectral range and applied load, which helps determine critical operating conditions for fibers in communication systems. These results are explained by the nature of mechanical stress distribution within the fiber structure and can be used in the design of optical systems where fibers are subjected to dynamic or static tensile loads.

2. The impact of prolonged tensile load exposure on the attenuation coefficient revealed a significant deterioration in fiber characteristics under sustained stress. At a 16 N load for 110 minutes, the attenuation coefficient at a wavelength of 1.06 μm increased from 1.09 dB/km to 5.89 dB/km, with fiber failure occurring at the 113th minute. These findings highlight the importance of considering time factors when designing communication systems. The results are explained by the accumulation of residual stresses in the fiber material, leading to structural failure, and can be applied in assessing the operational reliability of optical systems intended for prolonged load conditions.

For higher-order modes, an increase in compressive force, which induces inhomogeneities in MOFs, leads to changes in the attenuation coefficient. The primary cause is most likely birefringence. Another possible reason is the formation of additional inhomogeneities in the MOF core, which result in an increased proportion of higher-order spatial modes.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

The manuscript has data included as electronic supplementary material.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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