

DEPENDENCES OF THE SPECTRUM CENTRAL FREQUENCY SHIFT AND MANDELSTAM – BRILLOUIN SCATTERING POWER ON THE CHANGE IN YOUNG'S MODULUS OF CORE MATERIAL IN TELECOMMUNICATION OPTICAL FIBERS

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Mandelstam - Brillouin scattering in optical fibers is a phenomenon which is commonly used for distributed measurement of deformations and temperature. The study aims at identifying patterns and quantity evaluation of the influence of the core material mechanical properties of the fiber on the backscattering spectrum. The research is of great practical importance for the development of highly sensitive sensors and for monitoring the condition of optic-fiber communication lines. The Brillouin frequency shift and the power of the scattered signal are closely related to the fiber acoustic properties, which are determined by the fiber elastic characteristics. One of the key parameters is the Young's modulus. The paper investigates the fundamental relationships between the shift in the central frequency of the spectrum and the Mandelstam - Brillouin scattering power resulted from a change in the Young's modulus of the core material in telecommunication optical fibers. The findings show that a change in the elastic properties of the fiber described by Young's modulus directly influences the amplitude of acoustic waves produced by electrostriction, which, in its turn, determines the parameters of the scattered signal spectrum. The analysis is done on the basis of the optical and acoustic waves interaction equations. A model is proposed which takes into account changes in the acoustic and optical properties of the fiber resulted from changes in elastic parameters and makes it possible to investigate the relationship between the Young's modulus and the Brillouin scattering characteristics. The study presents the basic mathematical justification for the relationships. Analytical calculations and numerical modeling have been performed to identify the dependences of the shift in the central frequency and the power of scattering signals on deformations produced by changes in the mechanical properties of the optical fiber core material. The research shows the possibility of affecting the Young's modulus by changing the refractive index or density of the fiber core material during manufacturing optic-fiber cables. The results could be used for designing fibers with controlled Brillouin properties in manufacturing a new generation of distributed sensor systems making it possible to monitor fiber-optic communication systems and to detect changes in the elasticity or detect the fatigue signs.

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Introduction

Mandelstam – Brillouin scattering is a fundamental nonlinear optical phenomenon which appears when light interacts with acoustic waves in a material environment. This phenomenon was first theoretically predicted by Leon Brillouin and Leonid Mandelstam at the beginning of the 20th century. It obtained a wide practical application for the development of laser technologies and became the basis for numerous scientific and technological solutions. In telecommunication optical fiber lines, the Mandelstam – Brillouin scattering is detected as a three-wave mixing process which integrates two optical fields and one propagating acoustic wave. This process is characterized by a frequency shift of the backscattered light relative to the incoming radiation, which is determined by the acoustic velocity in the material, the refractive index of the medium, and the pumping wavelength. The Brillouin frequency shift in standard single-mode telecommunication fibers is approximately 10.845 GHz at the room temperature for the pump wavelength of 1550 nm.

The physical properties of the optical fiber core material, specifically the Young's modulus, play a crucial role for resulting spectrum parameters of Mandelstam – Brillouin scattering. The Young's modulus of quartz glass in the core of the single-mode telecommunication fibers is about 73 GPa and can change due to the concentration of alloying impurities, especially germanium. Changes in the elastic properties of the material directly affect the propagation velocity of acoustic waves, which results in a modification in both the frequency shift and the power of the Brillouin scattering spectrum.

The relevance of the research arises from the growing demands for the accuracy and reliability of fiber-optic communication systems and sensor. The analysis of the relationship between the mechanical properties of fiber and the parameters of Mandelstam – Brillouin scattering is of great importance for the designing highly sensitive distributed sensor systems which make it possible to measure temperature and mechanical deformation simultaneously. In addition, it is necessary to control the Brillouin scattering parameters in order to minimize nonlinear effects in high-speed telecommunication systems.

The research is of high scientific significance as it defines quantitative relationships between the Young's modulus of the core material and the main spectrum parameters of Mandelstam – Brillouin scattering. The experimental studies show that a change in the Young's modulus from 73.205 to 73.283 GPa at the temperature of 40 – 47°C results in the noticeable changes in both the frequency shift and the power of the signal scattered. These dependencies are of significant importance for optimizing the parameters of fiber-optic systems and developing new materials with specified optoacoustic properties. Current researches in the field of Mandelstam – Brillouin scattering in optical fibers study a wide range of temperature conditions, from the room temperature to cryogenic operating modes. At extremely low temperatures, new physical phenomena are observed, such as the coherent interaction of acoustic waves with two-level systems in an amorphous material, which allows further investigations in quantum technologies and fundamental research.

The aim of the proposed research is to establish analytical relationships between changes in the Young's modulus of the core material in the telecommunication optical fibers and the main parameters of the Mandelstam – Brillouin scattering spectrum,

such as power and center frequency shift.

The tasks are:

- to derive analytical formula integrating changes in the Young's modulus and a shift in the central frequency and the power of the Mandelstam – Brillouin backscattering spectrum;
- to evaluate the dependency of the main parameters of the spectrum on changes in the Young's modulus;
- to perform mathematical simulations in order to obtain quantitative estimates of the effect from variations in the Young's modulus on the spectrum parameters.

The results of the study will contribute to a deeper understanding of the physical mechanisms of optoacoustic interactions in fiber light guides and create a scientific basis for the development of advanced fiber-optic devices with improved characteristics.

It should also be noted that some methods of forming information leakage channels from optical fiber, based on temperature, mechanical and acoustic actions on the fiber, can be detected using the analysis of Brillouin backscatter parameters.

1 Problem statement

The Brillouin frequency shift ν_B in the optical fiber is a fundamental parameter in distributed sensing systems. It is determined by the acoustic-optical interaction between the incident light and thermally induced acoustic waves propagating along the fiber core. This interaction produces a frequency-shifted back signal, the characteristics of which depend on the optical and mechanical properties of the medium. The main mechanical parameter affecting Brillouin scattering is the Young's modulus E , which directly affects the velocity of the acoustic wave V_A .

The continuum mechanics says that the velocity of a longitudinal acoustic wave in a homogeneous, isotropic material is determined by the expression [1,2]:

$$V_a = \sqrt{\frac{E}{\rho}} \quad (1)$$

where:

E – Young's modulus;

ρ – material density.

Acoustic velocity depends on the elastic properties of the material as is shown in the equation [3]:

$$V_a = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

where:

E – Young's modulus;

ν – Poisson coefficient;

ρ – material density.

Doping the optical fiber core with germanium oxide (GeO_2) has a significant effect on the elastic properties of the glass matrix. An increase in the concentration of GeO_2 leads to:

- a decrease in the velocity of acoustic waves;
- a reduction of the Brillouin frequency shift;
- changes in the temperature coefficients of elastic constants.

It was found that an increase in the concentration of GeO_2 results in a decrease in the Young's modulus, which is shown in Table 1 [4].

Table 1

Dependence of Young's modulus on GeO₂ concentration

GeO ₂ concentration (%)	Young's modulus (GPa)
0 (pure SiO ₂)	72.5 ± 0.3
5	70.2 ± 0.4
10	70.2 ± 0.4

When heating, a decrease in the Young's modulus is observed with an average coefficient of 0.05 GPa/°C [4].

Two main approaches can be used to study the effect of the Young's modulus on the parameters of the backscattering spectrum:

- theoretical analysis is based on the application of the equations of classical elasticity theory and acoustic optics, which relate the Young's modulus to the acoustic resistance of a material and the velocity of sound waves in it;

- numerical modeling based on the development of a computer model using the finite element method, which makes it possible to change the values of the Young's modulus within acceptable technological limits and evaluate the resulting changes in the spectrum parameters.

There are several analytical approaches in theoretical analysis. The most common are the following approaches.

Linear theory of Bragg modes. This theory assumes that there is a linear relationship between the frequency of an acoustic wave and the magnitude of deformations in fiber materials. The models are based on Maxwell's equations and allow calculating the backscattering spectrum based on the basic physical and mechanical parameters of the medium, such as the Poisson's ratio and Young's modulus. However, such models have limitations, since they assume the uniformity of the medium and the absence of internal stresses, which cannot be applied for the common materials.

Nonlinear effects. Nowadays most researches underline the importance of taking into account the nonlinear effects produced by changes in the elasticity of the material under external influences. These effects result in the appearance of an additional component in the distribution of spectrum power, depending on the gradients of Young's modulus along the fiber length. Such nonlinear models are more complicated, but they are in better agreement with the experimental results, demonstrating the dependence of the spectrum line width and a peak shape on the heterogeneity of the material.

Then the expression (1) is inserted into traditional formulae for Brillouin frequency shift [5]

$$v_B = \frac{2nV_a}{\lambda}, \quad (2)$$

where:

n – refractive index of the fiber core;

V_a – velocity of the longitudinal acoustic wave;

λ – wavelength in vacuum.

The following formulae is derived [6]:

$$v_B = \frac{2n}{\lambda} \sqrt{\frac{E}{\rho}}. \quad (3)$$

This dependence means that any changes in E caused by mechanical stress, environment influence, heat treatment or prolonged aging, will be expressed in a measurable change in v_B . Moreover, since the power dissipation of P_B also depends on the acoustic impedance and gain width, it can be expected to be sensitive to changes in E .

Although the dependence of v_B on deformations and temperature is well known, the apparent influence of the Young's modulus as a variable has not yet been sufficiently studied. In real world situations, especially when using composite fibers or under aging conditions, the E value may vary along the length of the fiber. If the Brillouin shift is interpreted only using the deformation or temperature, this can lead to systematic errors if the influence of E is not taken into account.

In this regard, it is necessary to separate and quantify the effect of changes in the Young's modulus on the Brillouin scattering frequency parameters in single-mode telecommunication fibers. For this it is necessary:

- to establish analytical dependencies between E , v_B and P_B ;
- to determine the sensitivity coefficients:

$$\frac{dv_B}{dE}, \frac{dP_B}{dE}. \quad (4)$$

These steps are necessary to build an accurate model of backscattering signal spectrum that takes into account elastic properties and to create a new approach to distributed elasticity monitoring.

2 Analysis of the shift in spectrum central frequency

The Brillouin frequency shift (BFS) is determined by the ratio (3). In quartz fibers it is approximately 10 – 11 GHz for a wavelength of 1550 nm. The value depends on the following factors [7].

- The influence of temperature. The linear dependence of BFS on temperature is used in distributed temperature sensors.
- Mechanical stresses. Fiber deformations lead to a change of V_a and, consequently, BFS. This property is used in strain sensors for monitoring bridges and pipelines.
- Radiation influence. Ionizing radiation causes structural changes in the glass, which can be used for dosimetry.
- The composition of the core (alloying with germanium, fluorine).

BFS measurement methods are described below.

- Heterodyne detection. It is used for accurate BFS measurement with a resolution of up to 0.1 MHz. The method is based on mixing probing and Stokes radiation signals with subsequent spectral analysis.

- Time-domain correlation analysis, which allows high-resolution measurements up to 100 km.

- Coherent detection methods that provide a sub-centimeter spatial resolution, which is critical for monitoring microstructural changes.

Doping the optical fiber core with germanium oxide (GeO₂) has a significant effect on the elastic properties of the glass matrix. An increase in the concentration of GeO₂ leads to:

- a decrease in the speed of acoustic waves;
- a reduction of the Brillouin frequency shift;
- changes in the temperature coefficients of elastic constants.

For a standard telecommunication fiber with a GeO₂ content of ~3 mol.% the Brillouin frequency shift is ~10.845 GHz at the room temperature [8].

The measurements results confirmed that the frequency of the Brillouin shift increases with increasing Young's modulus, as is shown in Table 2 [9, 10].

Table 2

Increase of frequency in Brillouin shift due to increase of Young's modulus

Type of optic fiber	Young's modulus (GPa)	Frequency of Brillouin shift (GHz)
Doped Ge	65	10.60
SMF-28	72	10.85
Photone-cristal fiber	85	11.12

Experimental measurements showed a linear dependence of the BFS on the square root of the Young's modulus. For the fibers with a GeO₂ content from 0 to 8 mol%, a Brillouin frequency shift was from 10.8 to 11.1 GHz when an increase in the Young's modulus was from 71.6 to 73.3 GPa [11]. In telecommunication fibers the Brillouin frequency temperature shift coefficient is usually 1.08 MHz/°C in the central core and may differ slightly in the outer cores in multi-core fibers (1.03 MHz/°C) [12].

The Young's modulus in the quartz glass demonstrates a temperature dependence with a coefficient of approximately – 0.01 GPa/°C, which creates an additional temperature dependence of the Brillouin frequency, which increases the direct thermo-optical effect. This leads to a corresponding change in the Brillouin frequency by ~0.7 MHz/°C, which is critical for temperature monitoring in fiber-optic sensors [13].

The width of the Brillouin gain spectrum also showed a dependence on the elastic properties of the material. For the fibers studied, an inverse correlation was observed between the Young's modulus and the line width [14]:

$$\Delta \nu_B \propto E^{-0.32 \pm 0.05} \quad (5)$$

This is due to a change in the lifetime of acoustic phonons in a material with different elastic properties. The materials which are tougher (with greater Young's modulus) provide less acoustic attenuation and, therefore, narrower spectrum lines.

Taking the derivative of expression (3) with respect to E , a formula for the sensitivity of the Brillouin frequency shift to a change in the Young's modulus can be obtained:

$$\frac{d\nu_B}{dE} = \frac{n}{\lambda} \cdot \frac{1}{\sqrt{E\rho}}, [\text{GHz/Pa}] \quad (6)$$

The proposed expression demonstrates nonlinear dependence of ν_B on E .

3 Analysis of the spectrum power

The power of the Brillouin backscattering depends on the electrostriction coefficient of the material and the acoustic-optical interaction due to the following factors [15]:

- photo elastic effect: a change of refractive index under the influence of mechanical stresses;

- material density: affects the amplitude of acoustic waves;
- acoustic velocity: determines the frequency of interaction.

The core of telecommunication fibers is made of quartz glass doped with germanium oxide (GeO₂). The concentration of GeO₂ varies from 0% (pure quartz) to 30% or more for special fibers. The addition of GeO₂ to quartz glass results in the following changes in physical properties:

- reduction of Young's modulus from 73 GPa for pure quartz to ~64 GPa at 30% of GeO₂;
- increase in density from 2200 kg/m³ to ~2635 kg/m³;
- change of photo elastic constants.

For the quartz glass, used to produce the core of the telecommunication fiber, the Young's modulus is approximately 72 GPa. A change in the Young's modulus leads to the change in the velocity of acoustic waves and, therefore, to the change in the efficiency of the interaction of light with phonons. Increasing the Young's modulus increases the rigidity of the material, which can lead to the increased acoustic-optical dependence and the increase in the power of the scattered signal. The Mandelstam – Brillouin scattering power P_B depends on the efficiency of the photon-phonon interaction, which depends on the elastic properties of the material and is described by the low gain equation [16]:

$$P_B(z) = P_0 \cdot \exp[g_B \cdot P_p(z) \cdot L_{\text{eff}}], \quad (7)$$

where:

- P_0 – power of the probe signal;
- $P_p(z)$ – power of the pump signal;
- g_B – Brillouin gain coefficient;
- L_{eff} – effective interaction length.

The Brillouin gain is determined by the overlap of optical and acoustic modes and is calculated using the formula [17]:

$$g_B = \frac{n^7 p_{12}^2}{\lambda^2 \rho V_a \Gamma_B}, \quad (8)$$

where:

- p_{12} – the photo elastic coefficient;
- Γ_B – the scattering line width at 0.5.

It was experimentally established that for standard silicon fibers with different content of GeO₂, the gain coefficient varies from 2.55×10^{-11} to 3.61×10^{-11} m/Wt [18-20].

The dependences of the gain and sensitivity coefficients on the Young's modulus can be approximated by the expressions:

$$g_B \propto \frac{1}{\sqrt{E \cdot \rho}}, \quad (9)$$

$$\frac{dg_B}{dE} \propto -\frac{1}{2} E^{-3/2}, \quad (10)$$

Therefore, the power scattered is:

$$P_B \propto \exp\left(\frac{C}{\sqrt{E}}\right), \quad (11)$$

where C – some constant.

This shows that even small changes in E can significantly affect the power of the Brillouin signal. This is explained by the following:

- an increase in E leads to an increase in V_a , which enhances the acoustic-optical interaction;
- a tougher core transmits acoustic vibrations more efficiently, increasing the scattering power.

Table 3 shows the values of the nominated power of the backscattering spectrum depending on the Young's modulus of the core [21].

Table 3

Values of nominated spectrum backscattering power depending on the core Young's modulus

Young's modulus E , GPa	Nominated power I/I_{max}
50	1.00
55	0.95
60	0.91
65	0.88
70	0.85
75	0.82
80	0.79

The dependence of the spectrum power on the Young's modulus shown in the Table 3 is determined by the acoustic-optical interaction coefficient. Studies show a nonlinear dependence of the power on the elastic properties of the material, which is due to the change in the efficiency of the optical and acoustic modes interaction.

4 Modeling

The simulation was performed using Python on a simulation model created to analyze the dependence of the shift in the center frequency of the spectrum and the power of the Mandelstam – Brillouin scattering on changes in the Young's modulus of the core material in telecommunication optical fibers. The algorithm flowchart is shown in Fig. 1.

The simulation was performed using the following physical constants:

- quartz glass density $\rho = 2220 \text{ kg/m}^3$;
- refractive index $n = 1.468$;
- photo elastic coefficient $\rho_{12} = 0.27$.

The results of calculations of the frequency shift and the power of the spectrum of the backscattering signal are shown in Fig. 2 and 3, respectively.

Fig. 2. shows a direct relationship between the Young's modulus and the Brillouin frequency shift. An increase in the elasticity of the material leads to an increase in the scattering frequency from 10.6 to 11.1 GHz, which is explained by an increase in the propagation velocity of acoustic waves in a tougher material. The frequency sensitivity to the Young's modulus is 73.5 MHz/GPa. When the Young's modulus is changed by 5 GPa, the frequency changes by 367.5 MHz, which significantly exceeds the typical line width (30 MHz), thus providing high measurement accuracy.

The graph shows the inverse relationship between the Young's modulus of the core material and the normalized spectrum density of the Mandelstam – Brillouin scattering power. As the Young's modulus increases from 70 to 76 GPa, the scattering power decreases by 4.2%.

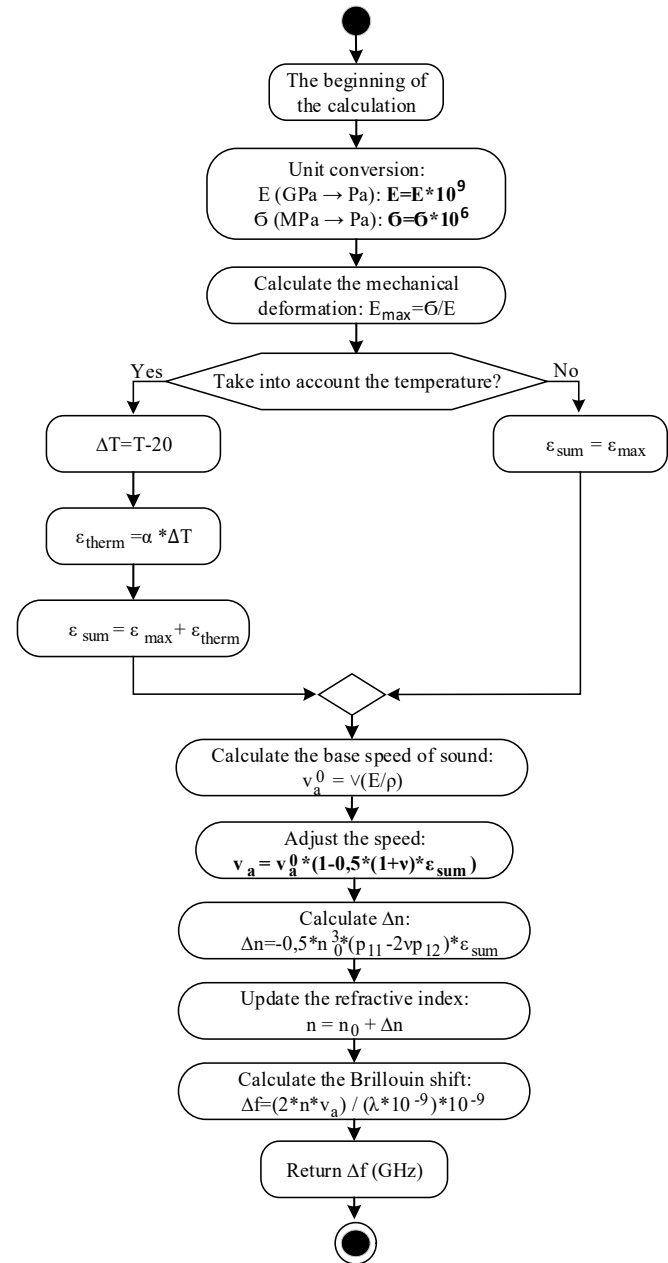


Fig. 1. Algorithm for spectrum parameters calculation depending on Young's modulus

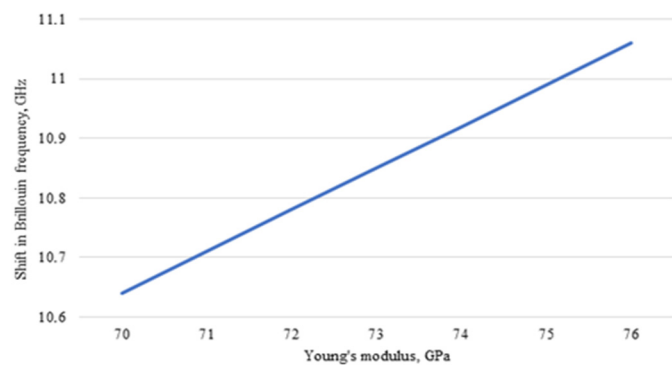


Fig. 2. Dependence of Mandelstam – Brillouin frequency shift on Young's modulus of core material in optic fiber

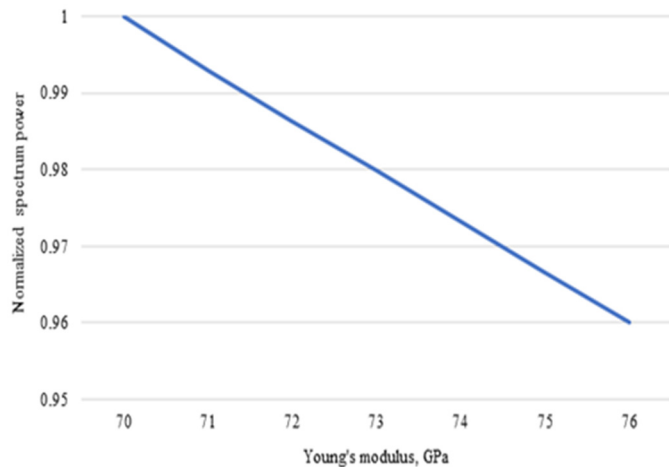


Fig. 3. Graphical representation of dependence of normalized spectrum scattering power on Young's modulus

Statistical analysis reveals strong correlations:

- Young's modulus \leftrightarrow frequency shift: $r = 1.0000$ (ideal direct correlation);
- Young's modulus \leftrightarrow scattering power: $r = -0.9999$ (strong inverse correlation).

5 Practical applications

1. Understanding the dependence of the spectrum parameters on the Young's modulus is important for reducing forced Mandelstam – Brillouin scattering in high-power telecommunication optical systems. Modification of the refractive index profile and elastic properties makes it possible to increase the threshold of stimulated scattering and increase the transmission power capability.

2. The results obtained show the need for careful consideration of changes in the Young's modulus in the design and manufacture of optical fibers. This becomes especially significant in difficult operating conditions, where external stresses result in significant internal stresses that change the local strength of the core.

The dependence of the backscattering signal spectrum parameters on the Young's modulus is used to evaluate the mechanical properties of fibers, detect damage, temperature loads, and internal strain in the fiber. For example, the monitoring of shifts in the central frequency and power of the spectrum makes it possible to monitor the state of optical communication systems and provide reliable operation of fiber-optic communication lines.

3. The research results also make it possible to optimize the design of fiber-optic sensors by selecting the optimal range of Young's modulus of the core material. The use of composites with an adjustable Young's modulus will significantly increase the accuracy of monitoring devices for detecting distributed deformations, temperature areas, and stresses in optical networks.

In addition, understanding the scattering mechanisms can become the basis for the development of innovative methods for compensating losses in communication channels due to the heterogeneity of the fiber core material.

6 Discussion

The analysis of literature data and theoretical models make it possible to form the following regularities:

- a linear dependence: in the area of small deformations, a linear dependence is observed between the change in the Young's modulus and the frequency shift;
- an alloying effect: the content of GeO_2 in the core significantly modifies both elastic and photo elastic properties. The controlled alloying of the core with various oxides makes it possible to purposefully change the elastic properties and, ultimately, change the characteristics of Brillouin scattering;
- feedback: as the toughness of the core increases, the acoustic wave propagates faster, reducing the interaction time with the optical field and reducing the nonlinear gain. It is important to take these results into account when developing fiber sensors, where variations in the Young's modulus due to temperature and mechanical influences can lead to systematic measurement errors.

The influence of the Young's modulus on the parameters of the Brillouin backscattering spectrum is realized through several interrelated mechanisms:

- direct influence on the acoustic velocity;
- photo elastic effect
- geometric changes;
- changes in the refractive index profile.

7 Limitations and prospects

The proposed model is valid in the approximation of weak changes in the elastic properties of the material. With significant variations in the glass composition (more than 20% GeO_2), it is necessary to take into account nonlinear effects and changes in other elastic constants in addition to the Young's modulus.

The influence of mechanical stresses in the fiber that occur during the manufacturing process requires additional research. Residual stresses can change the effective elastic properties of the material and result in the Brillouin line splitting.

A promising direction is the study of backscattering spectra in new types of fibers – multi-core, hollow-core, and polymer. These structures have unique acoustic properties that provide possibilities for designing sensors with absolutely new characteristics.

The development of methods for accurate measuring the elastic properties of small-volume materials will improve the accuracy of predicting spectrum characteristics. The combination of Brillouin spectroscopy with atomic power microscopy and nanoindentation will provide a comprehensive analysis of fiber materials characteristics.

Further research on the functional parameters of fiber-optic sensors should be aimed at:

- studying the effects of other alloying elements, optimizing the refractive index profile, and developing new core materials for specialized applications;
- increasing spatial resolution to centimeters;
- increasing the measuring range to 200 km;
- creation of multiparameter sensors;
- integration with artificial intelligence systems.

8 Conclusion

The proposed research demonstrates the fundamental relationship between the Young's modulus of the optical fiber core material and the characteristics of the Mandelstam – Brillouin backscattering spectrum. The calculation method presented makes it possible to effectively predict the spectrum parameters and select optimal core materials, contributing to an increase in the stability and durability of the fiber-optic devices. The results support the importance of taking into account variations of Young's modulus in high-precision distributed sensing systems, especially under conditions of possible degradation in the elastic properties of fibers due to fatigue, cyclic temperatures or ageing.

The results obtained are of great importance for the development of new-generation distributed fiber-optic sensor systems with enhanced metrological characteristics and improved functionality. Further research will focus on the study of nonlinear effects under large deformations and the development of multiparametric measurement methods using different types of optical fibers.

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ЗАВИСИМОСТИ СДВИГА ЦЕНТРАЛЬНОЙ ЧАСТОТЫ СПЕКТРА И ИНТЕНСИВНОСТИ РАССЕЯНИЯ МАНДЕЛЬШТАМА – БРИЛЛЮЭНА ОТ ИЗМЕНЕНИЯ МОДУЛЯ ЮНГА МАТЕРИАЛА СЕРДЦЕВИНЫ В ТЕЛЕКОММУНИКАЦИОННЫХ ОПТИЧЕСКИХ ВОЛОКНАХ

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Аннотация

Рассеяние Мандельштама - Бриллюэна в оптических волокнах представляет собой широко используемое явление для распределённого измерения деформаций и температуры. Целью исследования является выявление закономерностей и количественная оценка влияния механических свойств материала сердцевина оптического волокна на спектр обратного рассеяния, что имеет важное практическое значение для разработки высокочувствительных сенсоров и мониторинга состояния волоконно-оптических линий связи. Частотный сдвиг Бриллюэна и мощность рассеянного сигнала тесно связаны с акустическими свойствами волокна, которые, в свою очередь, определяются его упругими характеристиками. Одним из ключевых параметров оптического волокна является модуль Юнга. В статье исследуются фундаментальные взаимосвязи между сдвигом центральной частоты спектра и мощностью рассеяния Мандельштама - Бриллюэна от изменения модуля Юнга материала сердцевина в телекоммуникационных оптических волокнах. Показано, что изменение упругих свойств волокна, описываемых модулем Юнга, напрямую влияет на амплитуду акустических волн, генерируемых в процессе электрострикции, что, в свою очередь, детерминирует параметры спектра рассеянного сигнала. Анализ проводится на основе уравнений взаимодействия оптических и акустических волн. Предложена модель, учитывающая изменения акустических и оптических свойств волокна при варьировании упругих параметров и позволяющая исследовать взаимосвязь между модулем Юнга и характеристиками рассеяния Бриллюэна. Представлены основные математические соотношения. Проведены аналитические расчеты и численное моделирование, позволяющие выявить зависимости сдвига центральной частоты и интенсивности сигналов рассеяния от деформаций, вызванных изменением механических характеристик материала сердцевина. Сформулирована возможность вариации модуля Юнга путем изменения показателя преломления сердцевина волокна или его плотности во время производства оптоволоконного кабеля. Полученные результаты могут быть использованы при проектировании волокон с управляемыми бриллюэновскими свойствами для распределённых сенсорных систем нового поколения, способных проводить мониторинг волоконно-оптических линий связи, а также выявлять изменения в упругости материала или признаки усталости конструкции.

Ключевые слова: рассеяние Мандельштама - Бриллюэна, оптическое волокно, модуль Юнга, частота Бриллюэна, волоконно-оптические датчики, обнаружение оптического канала утечки информации.

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