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Nonlinear optical effects in optical waveguides play an important role in the development of fiber and integrated optics systems for optical communication and information processing. On the one hand, nonlinear effects impose restrictions on the radiation power that can be transmitted through an optical fiber or light guide.

In this paper, the problem of the occurrence of the phenomenon from the stimulated Brillouin scattering (SBS) effect is investigated using two optical sources of rays in a single-mode optical fiber at joint waves of 1310 nm and 1550 nm. Due to the fact that in all trunk fiber-optic lines, the intensity and energy of input signals is limited due to the influence of SBS, methods are currently being sought to reduce the influence of this phenomenon.

It was found that the energy of the input beam in the combined propagation of the compound did not reach the value of the threshold of SBS in the values of 25 dBm and 27 dBm due to the discrepancy between the experimental results and the results of the model. The SBS effect was not observed when the threshold threshold of 15 dBm and 27 dBm – SBS was reached when combining a dual beam along a single optical fiber in one direction. As a result, by double integration, the value of the SBS threshold was raised, and the direction for future scientific research was determined. If the possibility of increasing the threshold of SBS is proved, then increasing the distance of amplifiers in the main networks, respectively, its economic effect increases. In addition, it can be noted that there are no scientific papers devoted to the study of the effects of optical nonlinear effects by combining and distributing these two compounds along a single optical fiber.

This article discusses the issues of improving the capacity and determination of the threshold for stimulated Brillouin scattering. To increase the power threshold is invited to consider the dependence of the phase modulation frequency of the spectral width of the laser radiation.

In addition, the fact that the SBS threshold did not reach the value at an energy of 27 DB in the case of the double-beam distribution can be proved by discrepancies in comparison with the results of experimental studies and the results of the model that determines the SBS effect

Keywords: Non-linear effects, stimulated Brillouin scattering (SBS), fiber-optics, single-mode fiber, communication lines

MODELING THE METHOD FOR DETERMINING THE STIMULATED BRILLOUIN SCATTERING THRESHOLD IN A SINGLE-MODE OPTICAL FIBER

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1. Introduction

Currently, with the use of DWDM technology, the problem of increasing the compaction of information transmitted

over an optical fiber has been solved. However, due to the influence of the SBS effect, it is impossible to increase the information compaction to the required level when transmitting over a single-mode fiber. The problems of the influence

of the SBS effect identified in the sixties of the twentieth century have now been activated by a new wave due to a sharp increase in channel densification. This is due to the fact that it is currently possible to transmit information over advanced optical fibers using multimode laser beam sources.

In this paper, the problem of the occurrence of the phenomenon from the SBS effect is investigated using two optical sources of rays in a single-mode optical fiber at joint waves of 1310 nm and 1550 nm. Due to the fact that in all backbone fiber-optic lines, the intensity and energy of input signals is limited due to the influence of SBS, methods are currently being sought to reduce the influence of this phenomenon.

The main aim of this work is to collect additional data on changes in this phenomenon under the influence of various external factors and to present the main conclusions based on the study.

To date, the problems of increasing the intensity of the information given in the sources of technical literature of the threshold of SBS for power values at 1310 nm above 15 dBm, 1550 nm above 27 dBm have not been solved.

Currently, without solving the problem of the SBS threshold, information compaction is performed in an extensive form by increasing the number of fibers.

Therefore, studies of the SBS effect, the presentation of a method for determining the SBS threshold and the search for solutions to the tasks are relevant.

2. Literature review and problem statement

[1] Similar scientific studies have used beams with very small frequency distances between the two beams. In the study, the distance difference between the two waves did not exceed 10–50 nm. Such limitations may be due to the fact that for a single-mode optical fiber, one transparency window is preliminarily set, for example, 1310 nm, 1550 nm, 1640 nm.

The paper [2] presents the results of experimental studies of the nonlinear SBS process in a single-mode fiber, which occurs during the generation of higher-order phonons. Experimentally demonstrated TPI-SBS, which occurs at half the usual Brillouin frequency, it is proved that this indicates a modification of the standard theory of electrostriction. It is shown that such nonlinear processes can be observed in the case of harmonics of the usual Brillouin shift with the correct phase matching conditions.

In the paper [3], the authors demonstrated a Q-switched Yb-doped fiber laser in a single-mode multimode single-mode structure to inhibit fiber nonlinear effects. Nonlinear optics of waveguide systems are characterized by a high field intensity due to the spatial confinement of the beam, and a large nonlinear interaction length, which can be obtained in low-loss fibers or optical fibers.

The results showed that the SMS-switchable laser completely suppresses stimulated raman scattering and significantly reduced phase self-regulation, but the issues related to SBS compression remained unresolved.

Special attention is paid to the analytical calculation of the power of back reflection and the threshold of SBS in optical fibers with different refractive index profiles. To do this, the acousto-optic interaction in the guide geometry was considered and a modal overlap integral was derived describing the dependence of the Brillouin gain on the refractive index

profile of the optical fiber. An analytical approach to calculating the gain of Brillouin fiber amplifiers in the pumping depletion mode is also considered. In the mode with a high gain, fiber losses cannot be neglected, and they must be taken into account along with pumping depletion [4].

The paper [5] analyzes physical patterns in which the stimulated scattering excited by individual light rays can be connected through a common electrostatic wave, and physical factors affecting the spectrum of backscattered light. Modeling of the SBS in a golden cylindrical hohlraum excited by two-color light with a distance between wavelengths of 0.3 nm shows that: the SBS is effectively suppressed by two-color light, the SBS spectrum is split into two peaks with a distance of 0.3 nm. The SBS light corresponding to the incident light of longer wavelength receives a higher gain, however, in order to get the best number of beamlets to suppress SBS, the total intensity and bandwidth of the lasers must be fixed.

In the paper [6], using a general noise model, namely the Gaussian process, simple expressions are obtained for reducing the gain coefficients depending on the length. Both cases were analyzed when the power level and fiber parameters are constant or vary along the length of the fiber. Let's also consider the modulation of phase and intensity and demonstrated that the gain reduction coefficient does not depend on the modulation scheme.

The expansion of the lasers line width by noise is a simple and common method used to increase the threshold of SBS. In this paper, there is an unresolved issue based on the lack of effect for long fibers. The reason for this may be due to the stochastic nature of the noise, the resulting gain of the SBS threshold is less than ideally expected from the spectral power density of the optical signal.

All the methods described above are taken into account in [7], several methods have been developed to reduce the effects of SBS, each of which affects the SBS threshold by manipulating one of several parameters. These methods fit into several free categories, including increasing the effective area of the mode, expanding the pumping spectrum beyond, the Brillouin gain band, changing the Brillouin gain band along the fiber length. The reduction of SBS was achieved by combining several of these methods into a single system.

To study the nonlinear effect [8] in the article, the authors experimentally measured the input, output and reverse reflected radiation capacities at the specified wavelengths in an experimental work to control the SBS effect by sending light in one direction along a single modulated optical fiber with wavelengths of 1310 Nm and 1550 nm. On the basis of the practical results of this work, the author registered a change in the values of intensity of rays of different wavelength at passing along the fiber in the straight direction and at being reflected back. The article discusses the types of nonlinear processes that occur along the fiber. Therefore, one of the main objectives of the research was to determine the level of Brillouin scattering in results registered in the laboratory. The time of beginning the SBS is set out in the question.

In all scientific works aimed at studying the properties of optical fibers, the basic structure of scientific laboratories has similarities. There are also similarities in the work on the registration of spectral, energy and other characteristics received by an optical fiber, passed through the fiber and reflected rays. All this suggests that it is expedient to conduct a study on increasing the threshold of SBS in optical fiber.

3. The aim and objectives of the study

The aim of the study is to simulation of the method for determining the stimulated Brillouin scattering threshold in a single-mode optical fiber. The results of the study will improve the reliability of fiber-optic communication lines.

To achieve this aim, the following objectives are set:

- to study the features of the interaction of waves of different frequencies in single-mode optical fibers;
- determination of the values of nonlinear processes along the optical fiber at the starting points;
- to identify the method of SBS threshold.

4. Materials and methods

The main purpose of the organized scientific experimental research was to record changes in the SBS effect as a result of the transmission of signals over long distances together with double-beam. After discussing the results of the study, some of the achievements and shortcomings of organized experimental studies were revealed. The advantage is that for the first time, double-frequency beams, widely used at large lengths, were distributed along a single-modulated optical fiber. Since it is a prerequisite for sending radiation of only one frequency at a base along a single modal fiber, scientific interest has been aroused by what nonlinear effects occur when transmitting two beams. One of the disadvantages of the practice is the lack of tools for testing nonlinear processes other than SBS effect. Due to the lack of spectral analyzers with very high sensitivity, it was not possible to determine the proportion of the nonlinear effect of "Phase self-modulation". The study of the effect of Phase self-modulation caused by the expansion of the width of the spectral forms of incident, passed and reverse reflected rays with the help of a high-sensitivity spectral analyzer requires inclusion in the plan of future work.

The reliability and validity of the results of the work is based on the full compliance of the obtained experimental studies with modern theoretical methods used for fiber optics.

To solve the tasks set in the process of conducting experimental studies, the results obtained are verified using mathematical modeling.

To conduct experimental research, a circuit was assembled containing: radiation sources at 1.31 microns and 1.55 microns; intensity modulators controlled by an electric pulse generator; optical radiation power amplifiers at wavelengths of 1.31 microns and 1.55 microns. The results obtained are the measurement of pulse energy during propagation in the form of separate rays with wave dynamics of 1310 nm and 1550 nm, joint transmission and in the case of reflection, the organization of a practical laboratory for the study of the SBS effect based on the determination of the dependence of the measured energy values were reflected in the scientific article of the authors [8].

5. Results of simulation of the method for determining the stimulated Brillouin scattering threshold in a single-mode optical fiber

5.1. Investigation of the features of the interaction of waves of different frequencies in single-mode optical fibers

By modulating light sources of 1310 nm and 1550 nm at a frequency of 155 MHz and transmitting pulse signals, the energies of the input, output and reverse reflected rays were recorded. In principle, the maximum energy value for 1310 nm will be 15 dB (7 MW), and for 1550 nm – 27 dBm (10 MW). These values are considered the SBS threshold for these frequencies, so all measurements were made without exceeding these values. In addition, during the combined propagation of the double beam, the sum of the energy of each beam at the same value was carried out without exceeding the SBS threshold of 27 dBm.

5.2. Interpretation of the obtained results by the method of direct processing using the results recorded in experimental work

Thus, according to the results recorded in the experiments, the dependence of the points of deviation from the straight line was determined by the method of direct processing of the results on the graphs of the dependence of the energy of reflected light waves at all lengths on the length of the fiber [9].

At fiber's every 150 m, 1000 m, 3000 m, 8000 m, 20000 m length the deviation of ray of 1310 nm wavelength were registered as values 12, 10.5, 9.3, 8, 7.3 dBm, and nonlinear process was determined (Fig. 1).

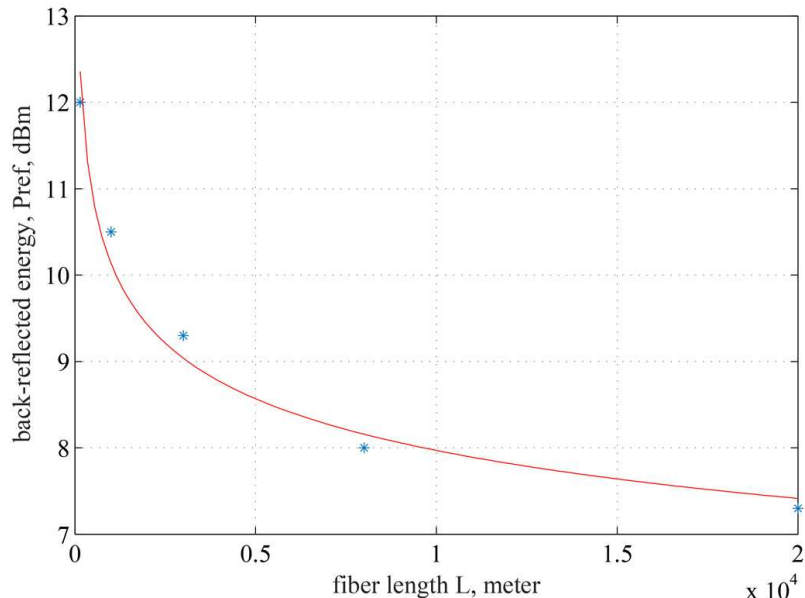


Fig. 1. Dependence of values of energy amplification of waves, reflected along the fiber, on fiber length in the points of deviation from the straight line

As it was determined that dependence of points where SBS effect starts on fiber length is described by law:

$$P_{ref} = A * L^a. \quad (1)$$

And as during the measurements the power values in logarithmic scale were registered in dBm, in order to find

the relations in converting to direct power, the formula for converting from logarithmic to ordinary scale was used:

$$\log_L P_{ref} = a + \log_L A. \quad (2)$$

$$Y = a + X. \quad (3)$$

By considering as a straight line and converting by the method of least squares, one can find a relation (Fig. 2).

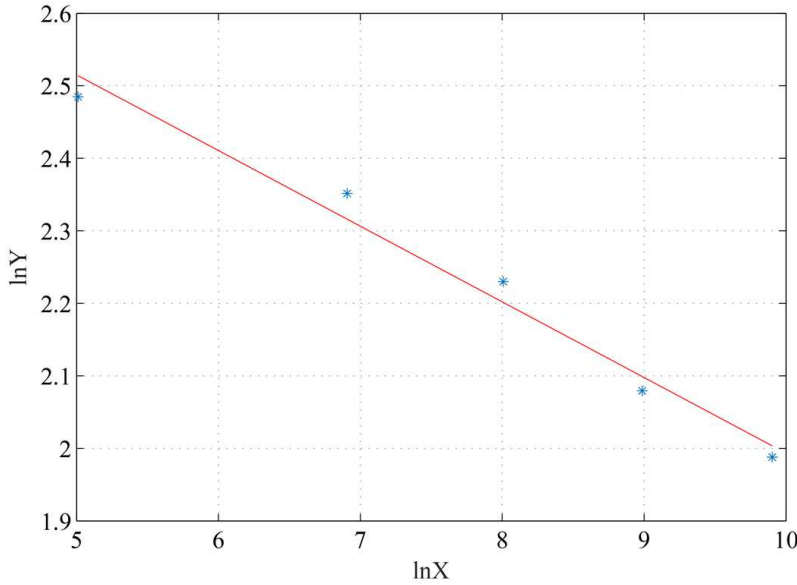


Fig. 2. Straight linear change of the reflected wave energy at converting from logarithmic scale to direct scale

A fragment of a program written in the Matlab programming environment:

```
clear all;
clc;
L = [150 1000 3000 8000 20000];
P1310 = [12 10.5 9.3 8 7.3];
figure; %1
plot(L,P1310, '*');

LnX = log(L);
LnY = log(P1310);
%LnY = A + B*LnX
Xor = mean(LnX);
Yor = mean(LnY);
B = (sum((LnX - Xor).*LnY)) / (sum((LnX - Xor).^2));
A = Yor - B*Xor;
X(1) = LnX(1);
X(2) = LnX(end);
Y(1) = A + B*X(1);
Y(2) = A + B*X(2);
figure; %2
plot(LnX, LnY, '*', X,Y, 'r')
```

In order to prove in advance that the results obtained from experimental measurements correspond to the theory and to determine the correctness of the work carried out, mathematical processing was made to the results obtained using the least square error method. To verify the of the calculations correctness, calculations based on the Student

coefficient of at least 5 points were used, and at least 5 results were used for each point of the study.

In order to explain the nonlinear process in the fiber, it is possible to describe by method of linked modes the change along the z -axis of pump I_p (source of direct waves) and reflected back Stokes wave I_s in the following way:

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s, \quad (4)$$

$$\frac{dI_p}{dz} = -g_B I_p I_s + \alpha I_p, \quad (5)$$

where g_B is a gain coefficient of Brillouin back scattering, α is the signal energy loss coefficient along the fiber. This loss coefficient was regarded as stable at all measurements at all lengths and at all points, since this value was set as $\alpha=0.22$ dB/km for 1550 nm and $\alpha=0.35$ dB/km for 1310 nm in the factory passport of the investigated optical fiber. However, at accounting these results in the computations, this value converted to Watt/km was used.

If to designate the rays entering the fiber in the direct way by $I_p(0)$, the rays leaving the fiber in direct way by $I_p(L)$, Stokes waves entering the fiber in the inverse direction by $I_s(0)$, Stokes waves leaving the fiber in the inverse direction by $I_s(L)$, then change of direct and Stokes waves along the fiber as a result of solving differential equations (4), (5) can be considered as mathematical model of this work (Fig. 3).

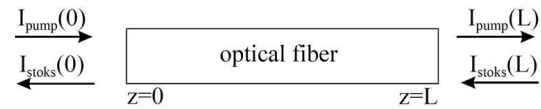


Fig. 3. Conditional designation of the rays entering the optical fiber

$$I_s(z) = \frac{b_0(1-b_0)}{G(z)-b_0} I_s(0) \exp(-\alpha z), \quad (6)$$

$$I_p(z) = \frac{(1-b_0)G(z)}{G(z)-b_0} I_s(0) \exp(-\alpha z). \quad (7)$$

In work [9] it is shown that gain coefficients change according to the law:

$$G(z) = \exp\left\{(1-b_0)(g_0\alpha)[1-\exp(-\alpha z)]\right\}, \quad (8)$$

$$b_0 = \frac{I_s(0)}{I_p(0)},$$

$$g_0 = g_B I_p(0), \quad (9)$$

where b_0 (Brillouin scattering effectiveness parameters) indicates what part of power of the initial radiation source is converted to power of Stokes wave, g_0 is gain coefficient of the weak signal.

The equations (6) and (7) characterize the change in the intensity of radiation waves and Stokes waves along the

fiber length at gaining the area of entering the fiber during Brillouin at radiation points $z=0$ and $z=L$ corresponding to $b_{in}=I_s(L)/I_p(0)=0.001$ and 0.01 . Losses in fibers are equal $\alpha L=0.1$. The Brillouin scattering gain coefficient $g_0 L=10$ corresponds to the gain of the passage in one direction $\exp(10)=2.2 \cdot 10^4$.

It is impossible to apply the equation (7) of the mathematical model proposed by [9] in this work. The reason is that the magnitude of the Stokes wave $I_s(0)$ entering the fiber in the opposite direction was not recorded in experimental work. Therefore, in experimental works, it is possible to determine whether the data after the points of deviation from the straight line in the results obtained correspond to the SBS effect only by applying G. Agraval's equation (7) as here it is possible to determine all the coefficients and parameters. Since in the selected (7), (8) and (9) mathematical models Brillouen amplification coefficient g_B was determined by the equation (5) where the value of the average width Δv_B was unknown, since the acoustic wave coefficient P_{12} and the input radiation spectrum were not measured. Since the spectral forms and values of input, output and reverse reflected rays were not recorded in the experimental works, it was not possible to determine the most important ones among the nonlinear phenomena that occurred along the optical fiber – the phenomenon of Phase self-modulation and the phenomenon of Phase cross-modulation.

Among the coefficients of the equation (9), only Brillouin gain coefficients $g_B=0.1995=0.2$ is obtained from practical results, namely based on results of measuring output power values in 3 km long optical fiber at input power 25 dBm of direct rays of wavelength 1550 nm (Fig. 4).

When applying the obtained coefficient value for all other fiber lengths and wavelengths obtained by experimental studies, it was possible to prove the correctness of the chosen mathematical model. The results of experimental studies were repeated by G. Agraval (Fig. 5) with a percentage accuracy of 90 % [9].

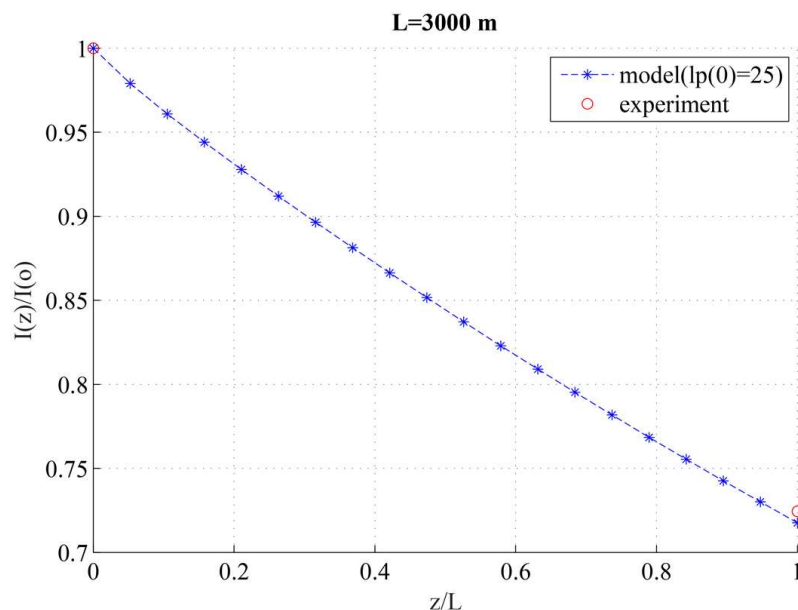


Fig. 4. Red dots are values of power of direct rays entering and leaving the fiber of length 3 km, and dashed blue line is law of change of power of direct rays along the fiber

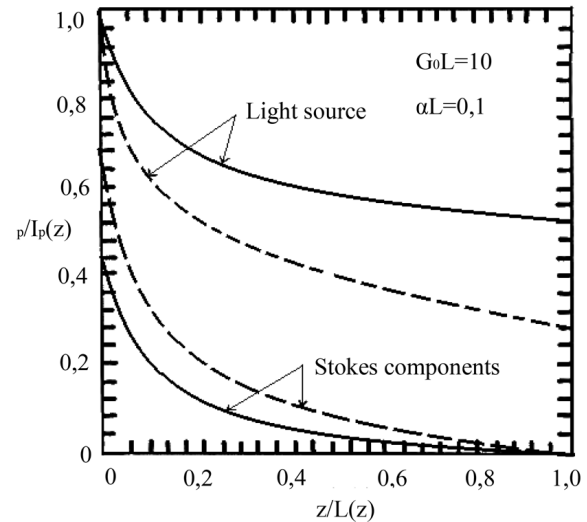


Fig. 5. Changes in the intensity of direct radiation waves and Stokes waves according to the results obtained by G. Agraval. Stokes waves with input intensity 0.001 (solid lines) and 0.01 (strikethrough lines) along the fiber ($z=L$) (normalized to the radiation output intensity)

If to determine the saturated and unsaturated gains in the way shown above, saturation of Brillouin scattering gainers in fiber is described by the following equation:

$$G_s = \frac{I_s(0)}{I_s(L) \exp(-\alpha L)} = \frac{b_0}{b_m}. \quad (10)$$

$$G_A = \exp(g_0 L_{eff}).$$

Thus, using the results recorded in the experimental work, the dependence of the points of deviation from the straight line on the fiber length in the graphs of the dependence of the energy of reverse reflected radiation waves on the input wave energy at all lengths by the method of direct processing of the results was initially established. Interpretation is given for the purpose of analytical explanation of the obtained laboratory results by means of direct analysis of the results.

5. 3. Determination of stimulated Brillouin scattering threshold

For a beam with a wavelength of 1550 nm, checking the points at which the SBS effect began using the model $\alpha=0.22$ dB/km (Fig. 6, 7).

For a beam with a wavelength of 1310 nm, checking the points at which the SBS effect begins using the model $\alpha=0.35$ DB/km (Fig. 8, 9).

In the calculation results, it is shown in the graphs below that when distributing the double-beams, nonlinear effects occur starting from the points at which the SBS threshold is formed (Fig. 10).

Using the SBS threshold power equation, the dependence of the threshold power P_{SBS} on the spectral width of the wave radiation source is obtained. The MATLAB software environment is used to calculate the power values of the SBS threshold and plot graphs.

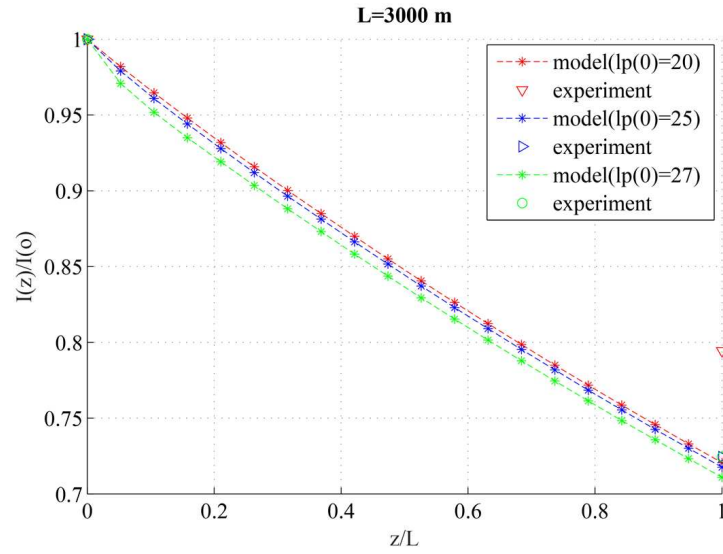


Fig. 6. Points where the SBS effect begins at different input power, optical fiber length $L=3000$ m. Dependence of direct beam power on fiber length

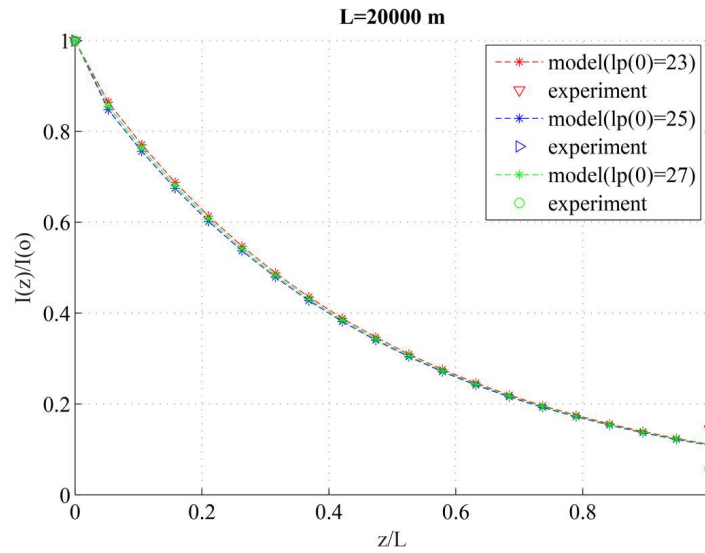


Fig. 7. Points where the SBS effect begins at an optical fiber length of $L=20000$ m. Dependence of direct beam power on fiber length

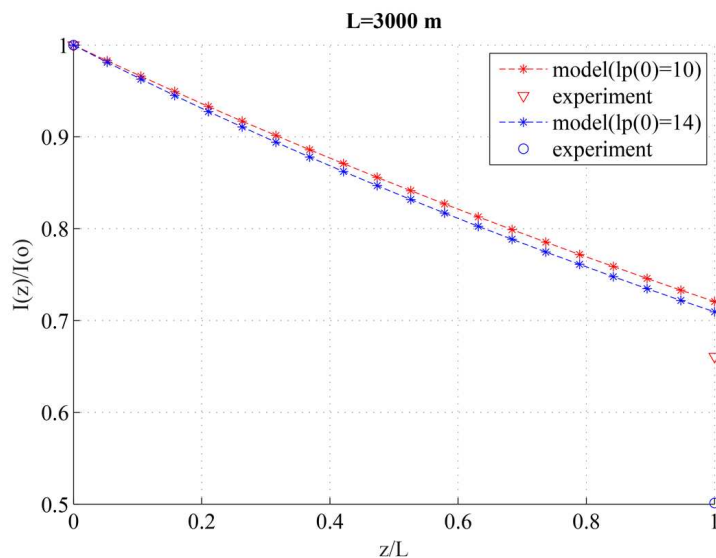


Fig. 8. Points where the SBS effect begins at an optical fiber of length $L=3000$ m. Dependence of direct beam power on fiber length

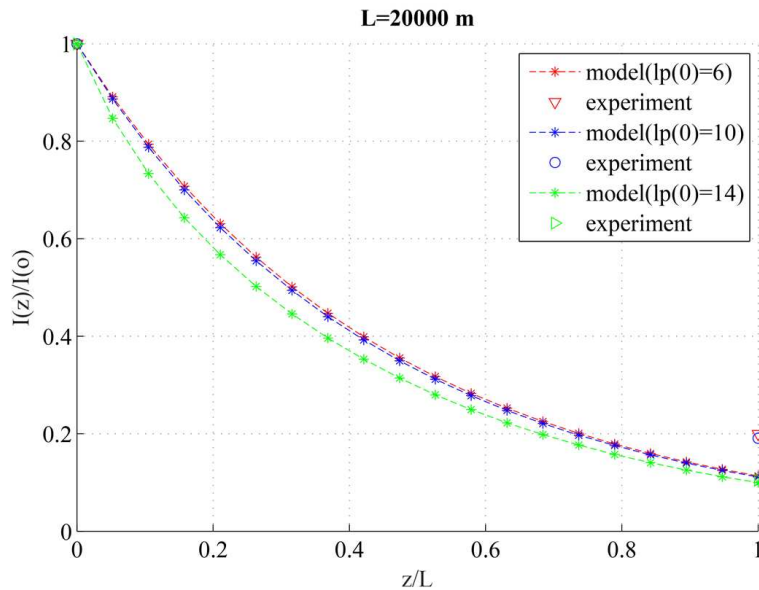


Fig. 9. Points where the SBS effect begins at an optical fiber of length $L=20000$ m. Dependence of direct beam power on fiber length

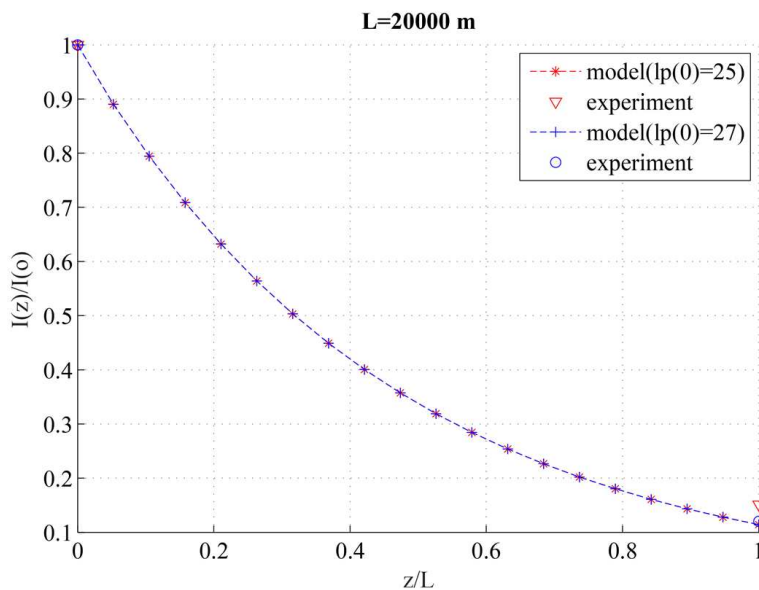


Fig. 10. Points where the SBS effect begins at an optical fiber of length $L=20000$ m. Dependence of direct beam power on fiber length

6. Discussion of experimental results

Thus in Fig. 1, 2, 4, the results below are obtained by use of mentioned above model by considering only points deviating from a straight line at lengths 3 km, 20 km as values where Brillouin scattering starts. Despite measuring optical fibers in lengths of 150 m and 1000 m in the laboratory, it was complicated to register nonlinear processes in points where Brillouin scattering starts after those points.

Therefore, for these lengths, the SBS effect has not been tested. These deviations were observed when checking the input and output values of the radiation power for 1310 nm.

In Fig. 6–9, as a result of the calculations made on the basis of the proposed model, experimental measurements and model compliance studies were carried out to check the

points where the SBS effect began when the wavelengths were $\alpha=0.35$ dB/km for 1310 nm radiation and $\alpha=0.22$ dB/km for 1550 nm radiation. Although the accuracy of matching most measurements with the model is very high, it can be concluded that discrepancies in some measurements may be related to a different type of nonlinear process. Using the results of experimental measurements, it was determined that the proportion of the SBS effect is higher using the model, because when comparing the results of the model with the results of the study, the values of the input at the beginning of the optical fiber and the output at the other end are marked with red dots, and the model shows by what patterns the energy loss decreases at each point along the optical fiber – crossed blue stripes. It is found that the two mentioned designations are crossed at one point at the other end of the fiber – proof that the model for the SBS effect is working correctly, in addition, the fixed nonlinear effects in experimental measurements are the SBS effect.

In Fig. 10 it is shown that in the calculation results, when distributing the double-beams, nonlinear effects occur starting from the points at which the SBS threshold is formed.

It should be noted that from the dependence for waves with lengths of 1550 nm and 1310 nm, with an increase in the value of the spectral width of the radiation source, an increase in the power value of the SBS threshold occurs

The computations hold allowed to achieve the main objective of the study to determine the effect of Brillouin scattering and determine its share in other non-linear effects. Furthermore, it is proved by the comparison of the actual calculations and the results of the study that Brillouin scattering threshold in case when two beams together cannot reach the value of the Brillouin scattering threshold in case when the two beams distributed separately.

One of the disadvantages of the study is the lack of tools in the chain to test nonlinear processes other than SBS effects. Due to the lack of spectral analyzers with very high sensitivity, it is not possible to determine the proportion of the nonlinear effect of «Phase self-modulation».

The study of the effect of Phase self-modulation caused by the expansion of the width of the spectral forms of incident, passed and reverse reflected rays with the help of a high-sensitivity spectral analyzer requires inclusion in the plan of future work.

7. Conclusions

1. When stimulated Brillouin scattering propagates in one direction in a single-mode optical fiber at wavelengths of 1310 nm and 1550 nm, a narrowing of reflected Stokes rays is observed.

2. In order to prove in advance that the results obtained from experimental measurements correspond to the theory and determine the correctness of the work carried out,

mathematical processing of the results obtained using the least square error method and comparisons with the laws in previous scientific works are made. The dependence of the values of nonlinear processes along the fiber at the starting points on the length of the fiber is determined by the method of direct processing of measurement results, and the inverse character in the mathematical model corresponded to the changing results with the degree law.

3. The effects of SBS on single-model optical fibers by sending optical rays at wavelengths of 1310 Nm and 1550 nm in the same direction and the effects of their

interaction with each other of the acoustic hypersounds caused by them are studied, and the reduction of reverse reflected stockpiles is observed. The laws of dependence of the energies of reflected and past Rays on changes in the modulation frequencies of pulses sent individually and jointly at each of the two mentioned wavelengths were measured. In the results obtained, as a result of the interaction of two waves on a combined wave path, a decrease in the threshold of the reflected and passing rays was observed, and a comparison of this effect was made using mathematical modeling.

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