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Determination of Sound Speed in Optical Fibers Based on the Stimulated Mandelstam-Brillion Scatering Effect

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Abstract: This work is focused on creating multipurpose device for diagnostics of interferometric measuring systems. Operating principle of such device is based on appearing of a nonlinear effect – stimulated Mandelstam-Brillion scattering (SMBS) which appears because of influence of laser radiation in optical fiber. As a result there were conducted investigations of parameters of nonlinear effect in optical paths under different conditions. There were formulated recommendations for designing device and methods for diagnostics of measuring systems such as Photon Doppler velocimetry (PDV), velocity interferometer system for any reflector (VISAR), and Fabry-Perot. The purpose of this work is to determine the technical capabilities of the implementation of the diagnostic method for velocity measuring systems such as PDV, VISAR and Fabry-Perot. For this purpose, in this work, the thresholds for the appearance of the SBS effect were determined, experimental measurements of the spectral shift were carried out, and the ultrasound velocity in various media was calculated from the data obtained.

Keywords: Stimulated Mandelstam-Brillion scattering, nonlinear effects, sonic wave, sound speed, Stokes wave.

1. Introduction

In experiments on studying shock-wave loading using diagnostics of the speed of motion of accelerated objects based on laser interferometric systems, to increase the level of the useful signal, it is necessary to use high-power laser radiation sources. At the same time, to increase the number of recording channels, time division multiplexing with extended signal delay lines is often used, which can lead to the manifestation of nonlinear optical effects [1]. In this work, it is proposed to use one of such effects - stimulated Mandelstam-Brillouin scattering (SMBS) - in order to create equipment for verifying velocity measurement systems such as Photon Doppler velocimetry (PDV), velocity interferometer system for any reflector (VISAR), and Fabry-Perot.

The creation of a universal stand for diagnostics of laser-interferometric instrumental systems is an urgent task, which will provide the possibility of calibration by measuring the spectral shift of the signal reflected back due to the SBS effect in an optical fiber.

SMBS is a nonlinear process that can occur in optical fibers at a radiation power much lower than that required for other nonlinear effects [2]. It manifests itself in the form of generation of a Stokes wave propagating in the opposite direction and containing the largest part of the initial energy. The magnitude of the spectral shift depends on the speed of the ultrasonic wave generated in the optical fiber. Since the speed of sound in a medium is measurable and known with a high accuracy, this can be used for calibration and verification of laser-optical speed meters.

2. Review of Studies on Nonlinear Effects in Optical Fibers

Studies of the maximum achievable parameters of fiber-optic systems for the transmission of laser radiation began a long time ago and this was due to the improvement in the quality and transmission of the created samples of fiber products, which, as a result, made it possible to increase the length of fiber-optic lines and create a new class of laser emitters and amplifiers - the so-called fiber-optic lasers and amplifiers with diode pumping.

Analyzing the material of the studies performed on the problem of limiting the capabilities of fiber-optic systems for transmitting laser radiation, it is clear that there are the following main limiting factors:

- Radiation resistance of optical fibers;
- The phenomenon of stimulated Mandelstam-Brillouin scattering (SMBS);
- Stimulated Raman scattering (SRS);
- Four-wave displacement (FWD).

With an increase in the power of laser radiation obtained in such devices, developers and researchers faced physical limitations, which were caused by such effects as SMBS [3-5], SRS [4, 6], FWD [6, 7], the result of which was a decrease in quality radiation, damage to elements of the optical schemes, the appearance of parasitic spectral components. The study of the indicated parasitic phenomena was carried out both within the framework of theoretical concepts about the processes accompanying the propagation of radiation in optical waveguides, and experimentally. As a result, the basic relationships were determined, which make it possible to perform accurate calculations and approximate estimates of the limits of the occurrence of nonlinear phenomena, the power of scattered waves, emerging harmonics and other components resulting from the interaction of light with the environment. Researchers from various scientific groups carried out a large amount of experimental research, as a result of which the nature and numerical characteristics of the arising nonlinear phenomena at various parameters of radiation (wavelengths, spectral width) and optical fibers (core diameters, lengths, dispersion) were determined, the limits of their occurrence and efficiency.

It should be noted that the research carried out has a peculiarity associated with the fact that most of the work is aimed at solving problems associated with the provision of traditional telecommunication problems: the exchange of information over a long distance with the maximum possible speed. Existing works devoted to the study of the onset thresholds and characteristics of SMBS, SRS, and other nonlinear effects practically do not consider the propagation of narrow-band radiation (with a line width in the range of tens, hundreds, and units of kHz) in optical fibers up to 3 km long. As a result, the coverage of experimental results, for example, for SMBS, looks as shown in Fig. 1.

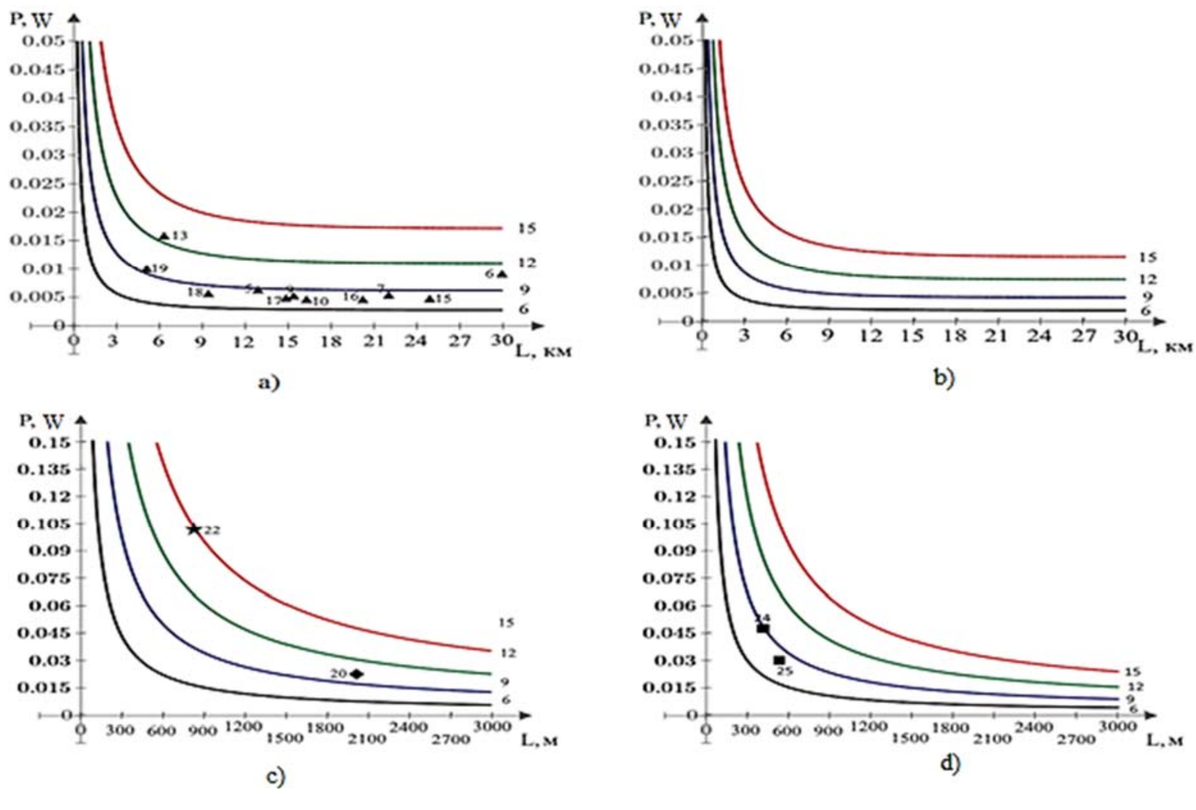

Fig. 1. Comparison of the results of experimental studies based on the data of [5-7, 9] with the calculated dependence of the threshold SMBS power on the fiber length for a given core diameter for the spectrum width (labels with numbers correspond to the results works with serial numbers according to Table 1: a), c) 10 MHz, b), d) 10 kHz.

Table 1. Ultrasound speed and SMBS threshold.

No.	Fiber type	Ultrasound speed, m/s	SMBS threshold, mW
1.	SMF-28 (25 km)	5450±180	4
2.	GeO_2 fiber (47 m)	4970±190	134

Since the effect of lowering the threshold for the occurrence of SMBS for such radiation is obvious, and the existing data for the formation of a full-fledged picture are not enough, the problem of experimental determination of the characteristics of nonlinear effects for narrow-band radiation used in interference optical fiber techniques with short optical fibers is urgent.

Table 2. Summary table on the existing experimental data on the thresholds of SMBS.

№	Fiber length, m	Losses, dB / km	Core diameter, µm	Fiber type	Wavelength, µm	Line width, MHz	Threshold power, W (dBm)
1.	5.8	20	3.8	SMF	0.535	100	2.3 (33.6)
2.	4000	4	3.5	SMF	0.71	30	0.03 (13)
3.	13000	0.41	9	SMF	1.32	22	0.0056 (7.5)
4.	30000	0.46	10	SMF	1.3	22	0.01 (10)
5.	22000	0.2	8	SMF	1.55	20	0.004 (6)
6.	396	0.4	9	SMF	1.064	0.01	102 (20)
7.	500	1	4.5	HNLF	1.55	0.01	0.0298 (14.7)
8.	900	0.8	4	HNLF DS	1.55	0.01	0.0232 (13.65)
9.	200	17	10	MSF	1.55	0.01	1.29 (31.1)
10.	100	30	10	MSF with acetone	1.55	0.01	0.521 (21.17)
11.	10	0.3 [8]	1.5	MSF with CS_2	1.55	0.01	0.005 (7)

3. Estimation of the Threshold for the Onset of Stimulated Scattering of Mandelstam-Brillouin

In the event of SMBS occurrence, acoustic phonons are involved in the process of interaction of radiation with matter, while the interaction at a wavelength of 1.55 µm occurs in a narrow frequency band $\Delta f_b = 20 \cdot 10^6$ Hz [1]. Therefore, in SMBS, wavelengths with an interval of more than 20 MHz between them do not interact. Within this width, SMBS can cause significant distortions of the original signal, which is expressed in the appearance and amplification of a reverse directional frequency-shifted signal (Stokes wave). In applications involving the use of fiber-optic components in measuring complexes, SMBS leads to a decrease in the level of the useful signal and a decrease in the signal-to-noise ratio, which entails a loss of information content of the received data. Some of the forward propagating light is scattered backward by the refractive index waves with a frequency shift. This leads not only to a weakening of the signal transmitted along the fiber in the forward direction, but also to the appearance of additional variations in the frequency and amplitude of the radiation source when reflected radiation hits it.
Shown in Fig. 2 families of curves characterize the dependence of the threshold power on the length and diameter of a single-mode fiber at spectral widths of 10 kHz and 100 MHz.

The SMBS process can be described classically as a parametric interaction between pump, Stokes and acoustic waves. Due to electrostriction [9], the pump generates an acoustic wave, which leads to periodic modulation of the refractive index. The induced refractive index grating scatters the pump radiation as a result of Bragg diffraction.

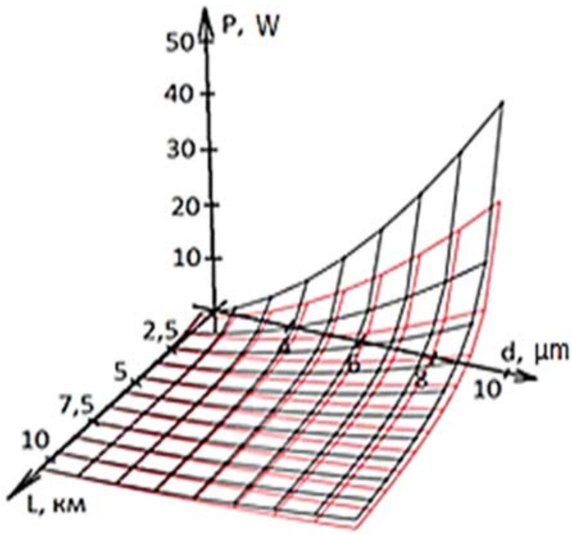

Fig. 2. Dependence of the threshold power of SMBS occurrence on the length and diameter of the waveguide core at a signal wavelength of 10 kHz (red (lower) grid) and 100 MHz (black (upper) grid), L is the length, d is the diameter of the fiber core.

Since the grating moves with a sonic velocity ν_A, the frequency of the scattered radiation undergoes a Doppler shift towards the region of longer wavelengths. The speed of sound in a medium is expressed by the formula [1].

$$\nu_A = \frac{\upsilon_B \lambda_p}{2n_p}, \quad (1)$$

where υ_B is the frequency shift at SMBS, λ_p is the pump wavelength, n_p is the effective refractive index at the pump wavelength λ_p.

Since the speed of sound in a medium is measurable and known with a high accuracy, it can be used for diagnostics of laser-optical speed meters.

4. Experiment Setup and Results

In this work, the thresholds for the onset of the SMBS effect were determined, experimental measurements of the spectral shift were carried out, and from the data obtained, the ultrasound velocity in various media was calculated. The diagram of measurements and equipment location is shown in Fig. 3.

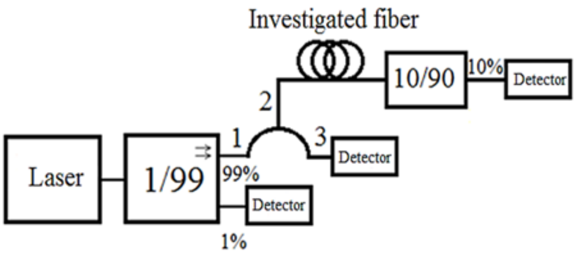

Fig. 3. Measurement scheme for determining the ultrasound velocity.

To calculate the threshold signal power at which the power output signal is compared with the wave scattered in the opposite direction, taking into account the width of the radiation spectrum, use the expression [2]:

$$P_{SMBS} \approx \frac{21 b S_e}{g_B L_e}\left(1 + \frac{\Delta f_S}{\Delta f_B}\right), \quad (2)$$

where b takes values from 1 to 2, depending on the state of polarization of the initial wave and the Stokes wave (in the worst case, when the radiation of both waves is linearly polarized b = 1), S_e - is the cross-sectional area of the fiber core along which the signal propagates, $L_e = \frac{1-e^{-\alpha L}}{\alpha}$ - is the effective fiber length, $g_B = 4.5 \cdot 10^{-11}$ - is the typical SMBS gain for silica fiber, Δf_S - is the line width signal radiation, Δf_B - is the SMBS gain frequency band (20 MHz).

Graphs of the dependence of the transmitted and reflected power of laser radiation on the input power were plotted for the optical fiber SMF-28 and GeO_2-fiber. The obtained experimental curves were used to determine the thresholds for the occurrence of SMBS in the studied fibers, which manifests itself in the form of a significant increase in the intensity of the reflected signal.

The experimental curves for optical single-mode fiber SMF-28 and GeO_2-fiber are shown in Fig. 4 and Fig. 5, respectively.

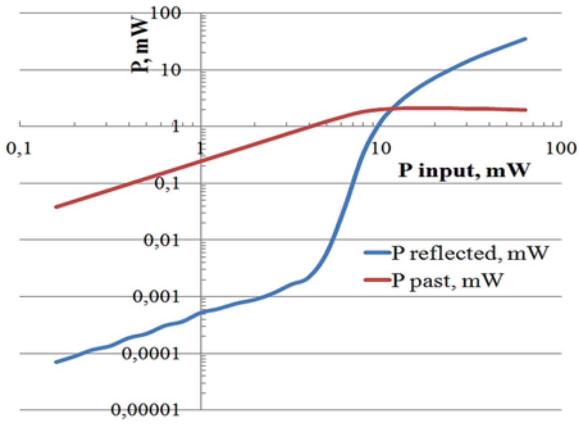

Fig. 4. Dependences of the transmitted and reflected power of laser radiation on the input power for an SMF-28 optical single-mode fiber with a length of 25 km and a core diameter of 9 µm.

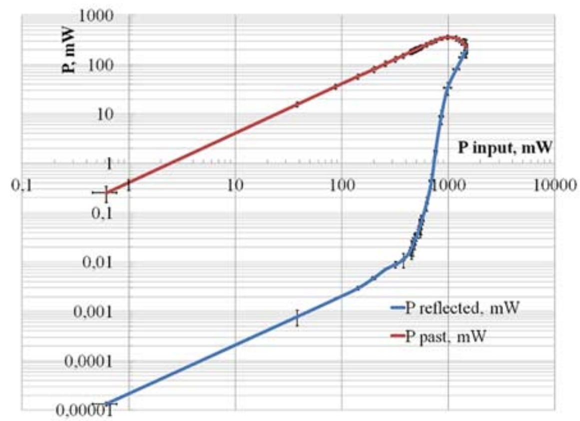

Fig. 5. Dependence of the transmitted and reflected power of laser radiation on the input power for an optical single-mode fiber doped with GeO_2 with a length of 47 m and a core diameter of 4 µm.

Fig. 6 shows a schematic diagram for determining the spectral shift for SMBS in optical fibers. Experimental determination of the spectral shift is possible in two ways: using a spectrometer or using a photodetector and oscilloscope instead of device 7, as shown in Fig. 6.

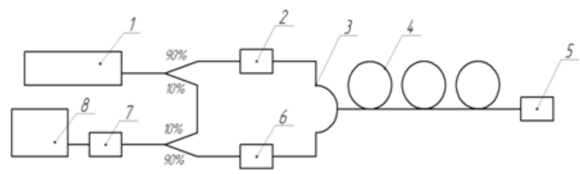

Fig. 6. Scheme for determining the speed of sound in an optical fiber based on the SBS effect (1 - laser, 2 - pass-through power meter, 3 - circulator, 4 - SMF-28 fiber optic 25 km, 5.6 - power meters, 7 - photodetector, 8 - oscilloscope).

Using a spectrometer, we obtain spectrograms of signals (transmitted and reflected) spaced from each other at a certain distance characteristic of a given sample. Fig. 7 and Fig. 8 show spectrograms for SMF-28 and GeO_2 optical fibers, respectively.

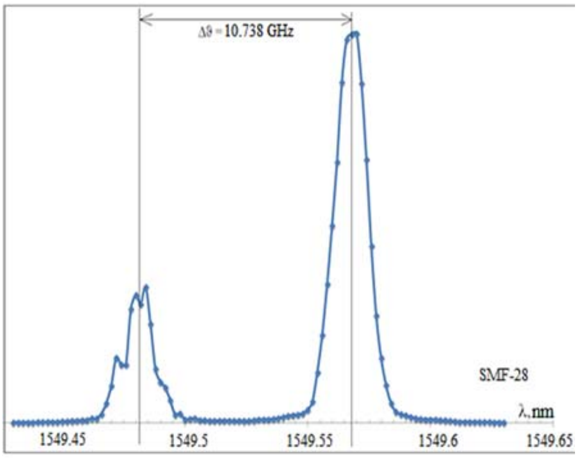

Fig. 7. Spectrograms of the output laser radiation for an SMF-28 single-mode optical fiber 25 km long and 9 μm in diameter.

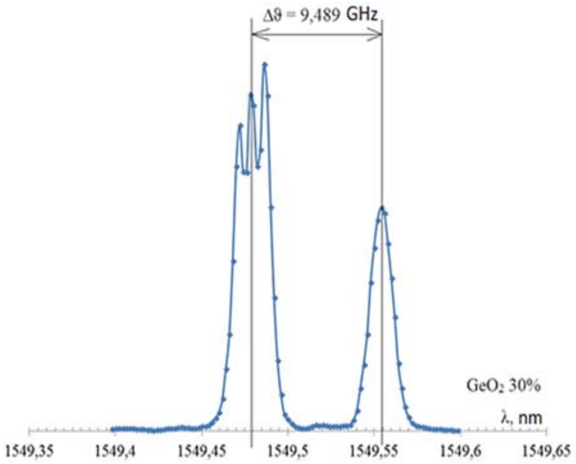

Fig. 8. Spectrograms of the output laser radiation for an optical single-mode GeO_2 fiber with a length of 47 m and a core diameter of 4 μm.

The second method is based on the use of PDV technology. Fig. 9 and Fig. 10 show the processed oscillograms of the frequency beats for the SMF-28 optical fiber and for the GeO_2-doped fiber, respectively. With the help of Fourier transforms, it is possible to determine how much the frequency of the reflected signal has shifted from the transmitted one.

Thus, the spectral shift was determined for two fibers: SMF-28 with a length of 25 km and GeO_2 fiber with a length of 47 m. For the case with SMF-28 at a power of 4 mW, the spectral shift corresponds to a speed of 5450 m/s, and for the case with a germanium doped fiber at a power of 130 mW the spectral shift corresponds to a speed of 4970 m/s.

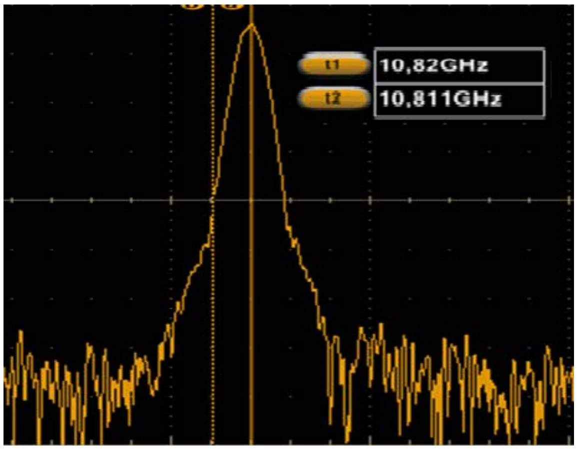

Fig. 9. Oscillogram of the output laser radiation for an SMF-28 single-mode optical fiber with a length of 25 km and a core diameter of 9 μm.

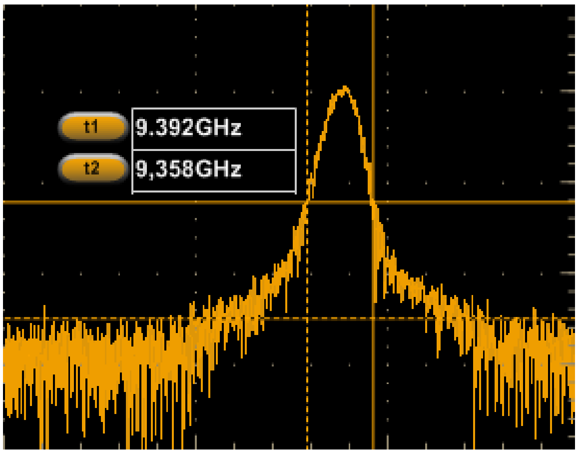

Fig. 10. Oscillogram of the output laser radiation for an optical single-mode GeO_2 fiber with a length of 47 m and a core diameter of 4 μm.

5. Conclusions

In this work, we present the results of experimental development of an optical scheme for observing the SMBS effect under various conditions when measuring the spectral shift based on the heterodyne principle. Estimates are made for the speed of sound for optical fibers with a core of various types of materials. The data obtained are compared with the calculated values of the speed of sound in optical fibers.

In this work, we determined the threshold powers at which stimulated Brillouin scattering is excited, measured the ultrasound velocity in an SMF-28 single-mode optical fiber 25 km long with a core diameter of 9 μm and in a GeO_2 fiber 47 meters long with a core diameter of 4 μm with the use of narrow-band laser radiation with a line width of 1 kHz.

The results obtained demonstrate the fundamental possibility of implementing a device that allows diagnostics of measuring complexes based on laser heterodyne interferometers using the SMBS effect.

Having large experimental data (wavefront reversal, SMBS onset threshold) in various types of fibers and in various media of laser radiation propagation, we are able to diagnose a PDV-based device in different spectral regions.

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