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Study of Brillouin scattering in a phosphosilicate optical fibre and its influence on a Raman laser operation

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***Abstract*. Stimulated Brillouin scattering (SBS) of single-frequency radiation in an AllWave® telecommunication fibre and a phosphosilicate fibre is studied. The frequency shift and stimulated Raman gain are measured. The emission spectrum of a phosphosilicate Raman fibre laser is studied in the near-threshold regime. It is shown that SBS does not broaden the output emission spectrum of the Raman laser.**

Keywords: *stimulated Brillouin scattering, Raman fibre laser, spectral broadening.*

1. Introduction

A Raman fibre laser belongs to promising near-IR radiation sources [1]. The pump radiation is converted in this laser to the Stokes components due to stimulated Raman scattering (SRS), which provides lasing at any wavelength in the spectral region between 1.1 and 1.7 μm. The use of fibres doped with GeO_2 at high concentrations allows one to extend the upper boundary of the emission wavelength of Raman lasers up to 2.2 μm [2].

Raman fibre lasers have found wide applications in wavelength-division-multiplexing (WDM) telecommunication systems as multiwave signal sources [3] and multiwave pump sources for fibre amplifiers [4]. They are also promising for long-distance remote sensing [5], supercontinuum generation [6], and applications in optical tomography [7].

Recent studies have been mainly concerned with the extension of possibilities of Raman lasers by changing their spectral parameters and controlling them. In particular, attempts have been made to develop tunable Raman fibre lasers (see, for example, [8]). Of current interest is the development of Raman fibre lasers emitting in the visible range between 550 and 770 nm [9, 10].

The spectral parameters of a Raman fibre laser determine its practical applications. It is well known that the emission spectrum of a Raman laser broadens with increasing power; however, the reasons for this broadening, which is commonly attributed to nonlinear effects, are still not elucidated conclusively [11].

Stimulated Brillouin scattering is the strongest of the nonlinear effects. For example, SBS noticeably restricts the power of light propagating through an optical fibre: in the case of a typical spectral radiation power density of ~ 1 kW nm^{-1}, the pump radiation propagating in the fibre begins to experience stimulated backscattering and exhibits the frequency shift (see, for example, [12]). The SBS threshold can be most easily achieved in the case of narrowband radiation, and for this reason SBS is the main factor limiting the efficiency of single-frequency fibre amplifiers [13]. It was pointed out in some papers that SBS may cause the broadening of the emission spectrum of a Raman laser, especially in the near-threshold regime when the laser spectrum can be narrow [14]. However, this hypothesis neither was confirmed nor refuted experimentally so far.

To study the influence of SBS on the spectral parameters of a Raman fibre laser, it is necessary to know the SBS threshold and gain, which depend first of all on the composition and geometrical parameters of the fibre, in particular, its length and should be determined for each particular fibre. A phosphosilicate fibre is one of the most promising active media for Raman lasers. The large Stokes shift in this fibre (~ 1330 cm^{-1}) is three times greater than that in a standard germanosilicate fibre (~ 440 cm^{-1}), which allows one to reduce the number of SRS stages for pump-radiation conversion for obtaining the required laser wavelength, thereby simplifying the system [15]. Unfortunately, SBS in phosphosilicate fibres has not been investigated so far.

In this paper, we studied the SBS of narrowband radiation in a phosphosilicate fibre and a standard AllWave® telecommunication fibre. The measurements with the latter fibre were mainly preformed to verify the method. We measured the frequency shift of the scattered wave and the SBS gain. Also, the formation of the output spectrum of a Raman laser was studied experimentally at powers close to the threshold. The results obtained in our study show that SBS does not affect the spectral parameters of the medium-power Raman phosphosilicate fibre laser.

2. Experimental

Stimulated Raman scattering in the fibre was studied on the setup shown schematically in Fig. 1. The fibre was pumped by a single-frequency, 1064-nm, 1-W Mephisto (InnoLight)

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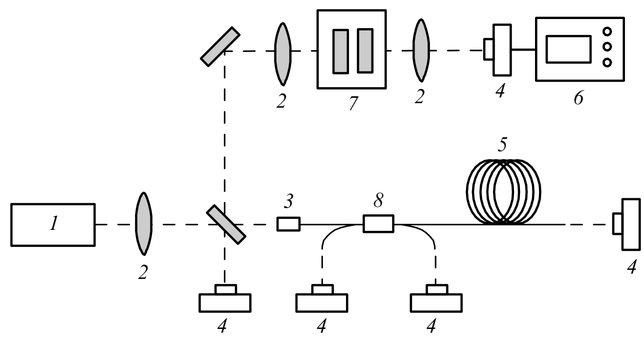

Figure 1. Scheme of the experimental setup for measuring the SBS parameters in a phosphosilicate fibre: (*1*) single-frequency Nd : YAG pump laser; (*2*) lens; (*3*) collimating lens; (*4*) photodiode; (*5*) fibre; (*6*) oscilloscope; (*7*) scanning Fabry–Perot interferometer; (8) 90 : 10 coupler.

Nd : YAG laser. The laser linewidth ~1 kHz was much narrower than the width of the SBS spectrum (~ 20 MHz) [12]. The laser radiation was coupled into the fibre with a collimator based on a gradient lens. The coupling efficiency achieved 70 %, the radiation power coupled into the fibre was measured with a 90 : 10 fibre coupler.

To the coupler output an AllWave™ fibre or a phosphosilicate fibre with 12 % molar concentration of P_2O_5 in the fibre core (with the mode field diameter 6.3 μm at 1064 nm) was spliced. The backscattered radiation spectrum was recorded with a scanning Fabry–Perot interferometer with the free spectral range variable between 0.1 and 50 GHz, or with an ANDO AQ6317 optical spectrum analyser used instead of the interferometer. The scattering spectrum exhibited the main and shifted peaks. The shift of the scattered wave was measured from the position of the latter peak. To avoid the influence of radiation reflected from the fibre ends on the parameters of the pump laser and scattered wave, all fibre ends were cleaved at a small angle (~ 10°). We measured in experiments the input pump power, transmitted power, and scattered wave power. The SBS gain in the fibre was calculated from the dependences of the transmitted and scattered waves on the incident wave power.

Figure 2 shows the results obtained for the AllWave™ fibre. In the fibre of length 100 m, the SBS of the pump wave only begins: the scattered wave power is low and increases exponentially, while the transmitted pump power saturates at a level of ~ 0.5 W. In the fibre of length 1300 m, SBS rapidly saturates, the scattered wave power increases linearly, and the transmitted pump power saturates at a level of ~ 40 mW. The frequency shift $\Delta\nu$ of the scattered wave, measured with the scanning interferometer, is 16 ± 1 GHz.

Note that a considerable difference in the saturation levels in short and long fibres can be simply qualitatively explained. The longer is the interaction length of radiation with a fibre, the greater part of pump radiation is converted to the reflected wave and the greater is the pump-wave depletion. Thus, the pump-wave power transmitted through the fibre of length 1300 nm is much lower than the radiation power transmitted through the fibre of length 100 m.

In a phosphosilicate fibre of length 370 m, the pump power saturates at 100 mW (Fig. 3). The frequency shift of the scattered wave is 14 ± 1 GHz at a wavelength of 1064 nm.

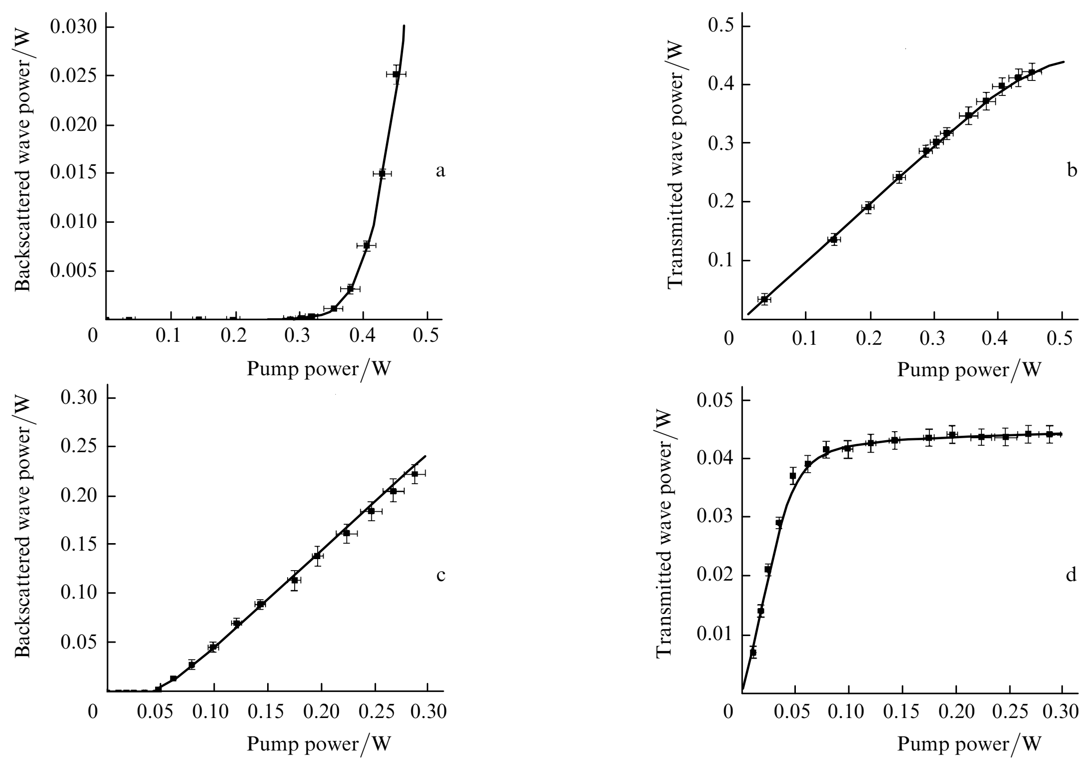

Figure 2. SBS in the AllWave™ fibre of lengths 100 m (a, b) and 1300 m (c, d): dependences of the power of the reflected (a, c) and transmitted (b, d) waves. Points are experiment; curves are approximations by experimental data by the method of least squares.

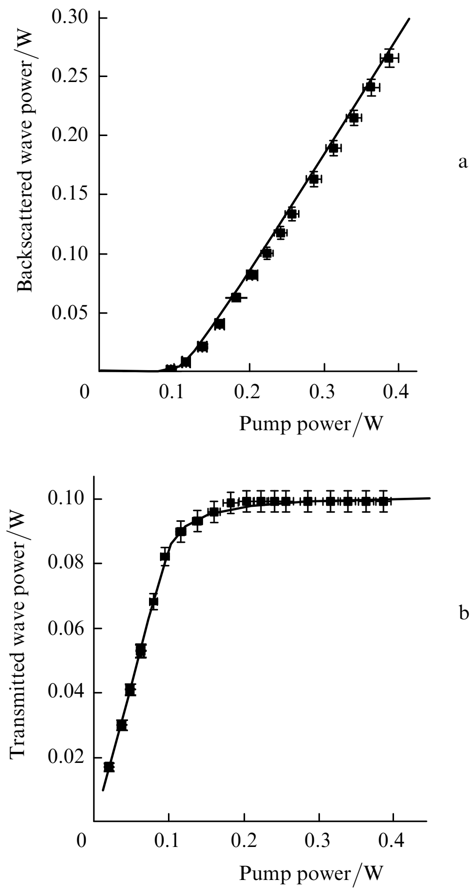

Figure 3. SBS in the phosphosilicate fibre of length 370 m: dependences of the power of the reflected (a) and transmitted (b) waves. Points are experiment; curves are approximations by experimental data by the method of least squares.

3. Determination of the SBS gain

To find the SRS gain from experimental data, it is necessary to consider this effect analytically. It is known that SBS is described by the system of equations [12]

$$\frac{dP}{dz} = -g_B IP - \alpha_P P, \tag{1}$$

$$\frac{dI}{dz} = -g_B IP + \alpha_I I, \tag{2}$$

where I is the scattered radiation power; P is the pump-wave power; α_P and α_I are the damping coefficients for the pump and scattered waves, respectively ($\alpha_P \approx \alpha_I$); g_B is the SBS gain; and z is the coordinate along the fibre length. This system should be supplemented with the two boundary conditions: $P(0) = P_0$ (the pump power at the fibre input is equal to the supplied power) and $I(L) = I_{sp} \to 0$ (the absence of a stimulated scattered wave at the fibre output). Here, I_{sp} is the power of a spontaneously scattered wave and L is the fibre length.

The system of nonlinear equations (1), (2) has no exact analytic solution in the general case. However, it is possible to obtain the approximate analytic solution by using the condition $\alpha_I I \ll g_B PI$, which is valid when the pump power greatly exceeds the scattered-wave generation threshold. In this case, the term $\alpha_I I$ describing losses for the scattered wave can be neglected in (2). The losses for the pump wave cannot be neglected because the condition $\alpha_P P \ll g_B IP$ is not fulfilled. To obtain the approximate analytic solution, taking into account the decay of the pump radiation in the fibre, the term $+\alpha_I I$ in (2) should be replaced by the term $-\alpha_P I$ of the same smallness. When the condition $\alpha_{I,P} \ll g_B P$ is fulfilled, i.e. above the threshold, the accuracy of this approximation remains the same as in the case of a complete neglect of losses, namely, $\sim\alpha L/A \leqslant 3\,\%$. A standard dimensionless quantity A defined by the expression $A(L) = \ln[A(L)/(g_B L I_{sp})] \sim 10 - 20$ characterises the power of scattered radiation (see, for example, [12, 16]).

The analytic solution in the accepted approximation has the form

$$P(z) = \frac{b\exp(-\alpha_P z)}{1 - \exp\{-g_B b(a + [1 - \exp(-\alpha_P z)]/\alpha_P)\}},$$
$$I(z) = \frac{b\exp(-\alpha_P z)}{\exp\{g_B b(a + [1 - \exp(-\alpha_P z)]/\alpha_P)\} - 1}, \tag{3}$$

where constants b and a are determined from the boundary conditions

$$b = \exp(\alpha_P L)[P(L) - I_{sp}] \simeq \exp(\alpha_P L) P(L),$$

$$\exp(-g_B ba) \simeq \frac{I_{sp}}{P(L)} \exp[g_B P(L) L_{eff}].$$

Here, $L_{eff} = [\exp(\alpha_P L) - 1]/\alpha_P$ is the effective length.

We can obtain from solution (3) the relations between $P(0)$, $P(L)$ and $I(0)$:

$$P(0) = P(L)\exp(\alpha_P L) \times \left\{1 - \frac{A(L)}{g_B L P(L)} \exp[g_B L_{eff} P(L) - A(L)]\right\}^{-1}, \tag{4}$$

$$I(0) = P(0) - P(L)\exp(\alpha_P L). \tag{5}$$

By using Eqns (4) and (5), we can approximate the experimental dependences of powers of the transmitted and scattered waves on the pump-wave power by using the method of least weighted squares and find the SBS gain g_B. The approximation was performed by the gain g_B and constant $A(L)$.

The result of the approximation for AllWave™ fibre pieces is shown by the curves in Fig. 2. We used in the approximation the experimental value of the damping coefficient in the fibre $\alpha_P = 0.69 \pm 0.02$ dB km^{-1}. As a result, we obtained the SBS gain $g_B = 400 \pm 180$ km^{-1} W^{-1} in the fibre of length $L = 100$ m and $g_B = 220 \pm 10$ km^{-1} W^{-1} for $L = 1300$ m. The difference between these values and a large error of measuring g_B in the 100-m fibre are due to the lack of experimental data on the scattered-wave power in the region of radiation power saturation. To measure g_B more accurately, the experimental data are needed both in the linear and saturation regions. The gain $g_B = 220 \pm 10$ km^{-1} W^{-1} obtained in the 1300-m fibre well agrees with the standard value $g_B = 250 \pm 10$ km^{-1} W^{-1} for telecommunication fibres [12]. By substituting the experimental gain g_B to the condition of applicability of the analytic solution $\alpha_I I \ll g_B P_P I$, we obtain that Eqns (4) and (5) are valid for pump powers exceeding 10 mW, i.e. over the entire range of our measurements.

Thus, we showed by the example of a standard telecommunication fibre that the method for measuring and approximating experimental data developed in our work allows us to determine accurately the SBS gain in the optical fibre of length of a few hundred meters pumped by radiation powers of tens of milliwatts. This means that this fibre can be used for measuring the SBS parameters in phosphosilicate fibres.

Figure 3 presents the experimental data obtained for a phosphosilicate fibre of length 370 m and their approximation by the method of least squares by using expressions (4) and (5). The SBS gain was measured to be 610 ± 65 km^{-1} W^{-1}, which is approximately three times higher than that in a standard telecommunication fibre.

4. Influence of SBS on the parameters of a Raman phosphosilicate fibre laser

To estimate the influence of SBS on the spectral parameters of a Raman fibre laser, we studied a single-stage Raman phosphosilicate fibre laser shown schematically in Fig. 4. The laser was pumped by a 1.06-μm cw ytterbium-doped fibre laser. The high-Q resonator for the Stokes component generated at 1.24 μm was formed by two fibre Bragg gratings with the maximum reflectivity exceeding 99 %.

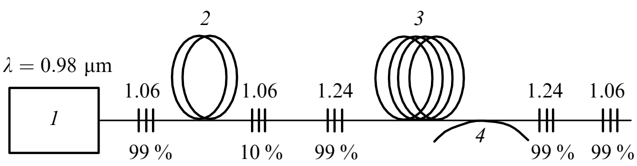

Figure 4. Ytterbium fibre laser-pumped single-stage Raman fibre laser: (*1*) diode laser; (*2*) ytterbium fibre; (*3*) phosphosilicate fibre; (*4*) 1.24-μm, 99 : 1 coupler.

Knowing the SBS in a phosphosilicate fibre, we can estimate the influence of SBS on the formation of the emission spectrum of the Raman phosphosilicate laser. The fibre was pumped by a 3-W, 1.06-μm power with line of width ~ 0.1 nm, which greatly exceeds the typical SBS gain linewidth (~ 10^{-4} nm at 1064 nm). Therefore, the maximum spectral density of the pump power (~ 30 W nm^{-1}) is much lower than the spectral power density (~ 1 kW nm^{-1}) required for the SBS of the pump radiation in a phosphosilicate fibre of length 370 m (see Fig. 3).

In the case of high-power (up to 1.8 W) Stokes radiation propagating in the fibre, the situation can be different. Because the Stokes wave propagates in the resonator, the SBS of this wave should be described by introducing the effective length of the fibre, i.e. the fibre length multiplied by the number of round trips of radiation in the resonator. Because the resonator has a high Q factor for the Stokes component, the effective length will be much greater than $L = 370$ m, and, hence, the SBS threshold will be considerably lower. Let us estimate the minimal possible SBS threshold. The stimulated scattering of the Stokes wave can occur only when the gain of the scattered wave exceeds the total losses of the wave. Therefore, the minimal spectral threshold power P_{th} can be determined from the expression $g_B P_{th} = \alpha$, where $\alpha \simeq 1$ dB km^{-1} is the coefficient of linear losses for the Stokes wave. It follows from this that for the typical width of the SBS spectrum ~ 10^{-4} nm (at a wavelength of 1 μm) and the measured SBS gain ~ 2650 dB km^{-1} W^{-1}, the minimal spectral power density is ~ 4 W nm^{-1}. Except linear losses, there also exist lumped losses (splice losses and fibre Bragg grating losses), which achieve in our case 2×0.45 dB per round trip in the resonator. Thus, the minimal spectral power density of the Stokes wave at which the stimulated scattering of the wave can occur is ~ 8 W nm^{-1}. The maximum spectral power density of the Stokes wave measured in our experiments did not exceed 2 W nm^{-1}, which is several times lower than P_{th}.

The spectral power density of the Stokes component does not achieve the SBS threshold due to broadening of the emission spectrum of the Raman laser. Direct measurements of the intracavity lasing spectrum (the main peak in Fig. 5) show that the spectrum is initially broadened up to ~0.1 nm even in the near-threshold region. The minimal width of the emission spectrum of the Raman laser (the main peak in Fig. 5) is determined by the spectral width of the multimode pump radiation due to transfer of intensity fluctuations from the pump wave to the Stokes component, which corresponds in the frequency scale to the four-wave mixing of the longitudinal modes of the pump and Stokes waves [17]. Note, in particular, that the single-frequency generation of the Stokes component, which should be expected due to the homogeneous saturation of the SBS gain [18], was not observed in experiments.

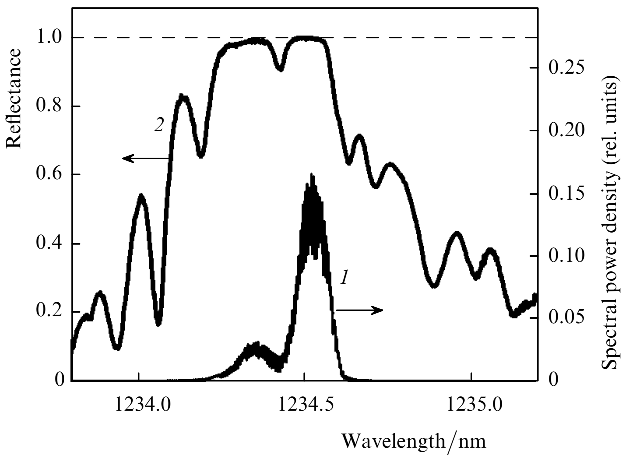

Figure 5. Intracavity emission spectrum of the Stokes component in the near-threshold region (*1*) and effective 'total' reflectance of FBGs per round trip of radiation in the Raman laser resonator (*2*).

As the pump power is increased, the emission spectrum of the Raman laser broadens, and its shape 'duplicates' qualitatively the spectral dependence of the resonator reflectance (Fig. 5), which can be interpreted as the independent generation of different modes [19]. In this case, it is due to the broadening of the laser spectrum that the spectral power density of the Stokes wave does not achieve the SBS threshold, and thus the spectral parameters of the Raman fibre laser are independent of the SBS threshold.

5. Conclusions

We have presented the method for measuring SBS parameters in optical fibres. The SBS parameters have been measured for the first time in a phosphosilicate fibre. The frequency shift of the scattered wave at 1064 nm was 14 ± 1 GHz and the SBS gain of single-frequency radiation was 610 ± 65 km^{-1}W^{-1}. This gain g_B is approximately three times higher than that in the AllWave™ fibre, which can be explained by a smaller diameter of the mode in the phosphosilicate fibre.

We have studied the influence of SBS on the spectral parameters of the Raman phosphosilicate fibre laser. It has been shown that the spectral power density of the Stokes component in the Raman phosphosilicate laser is insufficient for SBS because the emission spectrum of the laser is broadened even near the lasing threshold. Despite the homogeneous saturation, the emission spectrum of the laser is formed as in the case of independent generation of different longitudinal modes, i.e. it is determined by the spectral shape of losses in the resonator. Experimental data [20] demonstrate the influence of four-wave mixing on the broadening of the spectrum of the Raman laser.

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