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Spatial coherence of the Stokes component of stimulated Raman scattering excited in a long multimode fibre

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Abstract. **The mode structure of the Stokes component of stimulated Raman scattering (SRS) in a multimode fibre excited by a pump field with statistics corresponding to a narrowband Gaussian noise model is theoretically analysed. The relation is obtained between the number of spatially coherent radiation modes of the Stokes wave and fibre parameters and SRS excitation conditions. It follows from this relation that the degree of spatial coherence of the Stokes radiation at the fibre output is determined by the number of spatial modes of pump radiation and the averaged gain of the Stokes radiation over the interaction length. It is established that there exists the threshold gain at which the number of spatially coherent radiation modes of the Stokes component increases infinitely and, therefore, its spatial coherence tends to zero. The estimates of the number of spatially coherent radiation modes of the Stokes component showed that already at the Raman scattering excitation threshold their number is so great that the degree of spatial coherence of the Stokes component radiation corresponds to the degree of coherence of a thermal source radiation. The measured dispersion of spatial intensity fluctuations of the Stokes component separated by using an interference filter (with the transmission bandwidth ~1 nm at 620 nm) proved to be approximately three times higher than the dispersion of radiation intensity fluctuations of a luminescent lamp. The large dispersion of spatial intensity fluctuations of the Stokes component is caused most likely by individual intensity spikes in a small-scale (unresolved by a detector with a spatial resolution of ~14 μm) speckle pattern produced in the detection plane by monochromatic Stokes radiation.**

Keywords: *stimulated Raman scattering, spatial coherence, multimode optical fibre.*

1. Introduction

Stimulated Raman scattering (SRS) leads to the efficient nonlinear transformation of exciting radiation energy in an active medium to the energy of light waves at frequencies representing combinations of the incident radiation frequency and characteristic frequencies of microparticles of their ensembles in the medium [1 – 3]. Converters based on SRS produce radiation at frequencies covering a broad spectral range from the UV to IR region [4], which opens up prospects for their applications in various applied and scientific purposes.

One of the promising media for SRS transformations is an optical fibre [5]. The distinct features of SRS in fibres are a broad frequency conversion range, the high conversion efficiency, and a low enough excitation threshold. Fibre SRS converters can find applications in medicine (as light sources for the high-quality colour imaging of endocavitary structures) and optical communications. SRS radiation used for these purposes should satisfy a number of requirements imposed on spectral, energy, and spatial characteristics. To obtain high-resolution images in endoscopy and a high signal-to-noise ratio in long optical communication lines with SRS amplifiers, the converted radiation should have a low spatial coherence. In this connection the study of spatial correlation properties of SRS radiation in multimode fibres is of current interest. The properties of conversion of the spatiotemporal structure of scattered radiation, in particular, SRS have been studied in many papers [6 – 8]. Most of the papers were devoted to the analysis of conditions of the reconstruction and phase conjugation of the beams formed upon SRS and only some papers considered the spatial dynamics of the amplitude – phase characteristics of SRS waves [9 – 13]. The coherent characteristics of Stokes waves have been investigated in more detail both theoretically and experimentally for compressed gases at small interaction lengths [11 – 13]. SRS in a long multimode fibre has specific features. One of them is that it is excited by pump radiation whose spatial coherence considerably changes due to self-phase modulation [14]. This fact should undoubtedly affect the spectrum of angular frequencies of SRS radiation.

The aim of our study is to develop a statistical SRS model for long optical fibres, to estimate the degree of spatial coherence of converted radiation obtained in model conditions and to compare the obtained results with experimental data.

2. The theoretical model

Consider the case of stationary SRS in a multimode optical fibre in the absence of the pump-wave depletion. It is known that the amplitude of the Stokes component under these conditions can be written in the form [3]

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$$A_s = A_{s0}(\boldsymbol{r}, z=0)\exp\frac{g|A_{p0}(\boldsymbol{r}, z=0)|^2 z}{2}, \qquad (1)$$

where A_{s0} is the amplitude of the probe Stokes wave for $z = 0$; $\boldsymbol{r}$ is the radius vector in a plane perpendicular to the fibre axis; g is the gain increment; $|A_{p0}|^2$ is the pump wave intensity; and z is the length of interaction of pump radiation with the medium.

Let us determine the correlation function of Stokes radiation

$$B_s(\boldsymbol{r}_1, \boldsymbol{r}_2, z) = \langle A_s(\boldsymbol{r}_1, z)A_s^*(\boldsymbol{r}_2, z)\rangle$$

$$= \left\langle A_{s0}A_{s0}^* \exp\frac{g|A_{p0}(\boldsymbol{r}_1, z=0)|^2 z}{2}\exp\frac{g|A_{p0}(\boldsymbol{r}_2, z=0)|^2 z}{2}\right\rangle \qquad (2)$$

and perform statistical averaging in (2) by assuming that spatial amplitude–phase fluctuations of the probe Stokes wave and pump are independent and obey the Gaussian statistics [15]. We also assume that the statistics of probe Stokes radiation is caused only by phase fluctuations, while the pump statistics is also determined by amplitude fluctuations appearing due to the nonstationary self-phase modulation of individual modes in the fibre and their interaction. By using the expression for the two-dimensional probability density for the amplitudes and phases of input radiation corresponding to the model of a narrowband normal noise [16], we obtain after some transforma-tions

$$B_s(\boldsymbol{r}) = \frac{B_{s0}(\boldsymbol{r})}{2\{1 - \varphi[1 + (b_{p0}^2(\boldsymbol{r}) - 1)\varphi]\}}, \qquad (3)$$

where $\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2$; $B_{s0}(\boldsymbol{r})$ is the mutual coherence function for the probe Stokes radiation; $b_{p0}(\boldsymbol{r})$ is the modulus of the degree of spatial coherence of pump radiation; $\varphi = g\langle I_{p0}\rangle z$ is a parameter characterising the averaged amplification of Stokes radiation over the interaction length; and $\langle I_{p0}\rangle$ is the average pump radiation intensity.

We will analyse the coherent properties of radiation of Stokes components by estimating the number of spatially coherent modes contained in this radiation [17]:

$$N \simeq (\Delta\nu_s)^2 s. \qquad (4)$$

Here,

$$\Delta\nu_s = \left(-\frac{\{d^2|b_s(\boldsymbol{r})|/\mathrm{d}r^2\}_{r=0}}{\{|b_s(\boldsymbol{r})|\}_{r=0}}\right)^{1/2}$$

is the width of the angular spectrum of Stokes radiation waves; $|b_s(\boldsymbol{r})| = |B_s(\boldsymbol{r})/B_s(\boldsymbol{r}=0)|$ is the modulus of the degree of spatial coherence of Stokes radiation; and s is the light-beam cross section at the fibre output.

The parameter N can be determined in practice by measuring the contrast C of a speckle pattern formed by the Stokes component transmitted through a random phase screen,

$$C = \frac{\sigma}{\langle I\rangle} = \frac{1}{\sqrt{N}}, \qquad (5)$$

where $\langle I\rangle$ is the mean intensity of the speckle pattern and σ is its root-mean-square deviation.

Because the Fresnel number of the active waveguide of an optical fibre is small, we can assume that only one mode of the probe Stokes wave is amplified [13]. Then, by using (3), we obtain according to (4) for the case of the initially completely spatially coherent probe Stokes wave the expression

$$N = \frac{2N_{p0}\varphi^2}{1 - \varphi}. \qquad (6)$$

It follows from (6) that the degree of the spatial coherence of the Stokes component radiation at the fibre output is determined by the number N_{p0} of pump radiation modes and the averaged gain of Stokes radiation over the fibre length. For $\varphi = 1$, the parameter N increases infinitely and the spatial coherence of SRS radiation tends to zero

3. Experiment

Figure 1 shows the optical scheme of the experimental setup used for measuring the degree of spatial coherence of the Stokes component to compare them with theoretical predictions. The 532-nm second harmonic of pulsed Nd:YAG laser (*1*) passed through a set of calibrated neutral filters (*2*), was coupled through microobjective (*3*) into a short piece (~1 m) of multimode fibre (*4*) and then

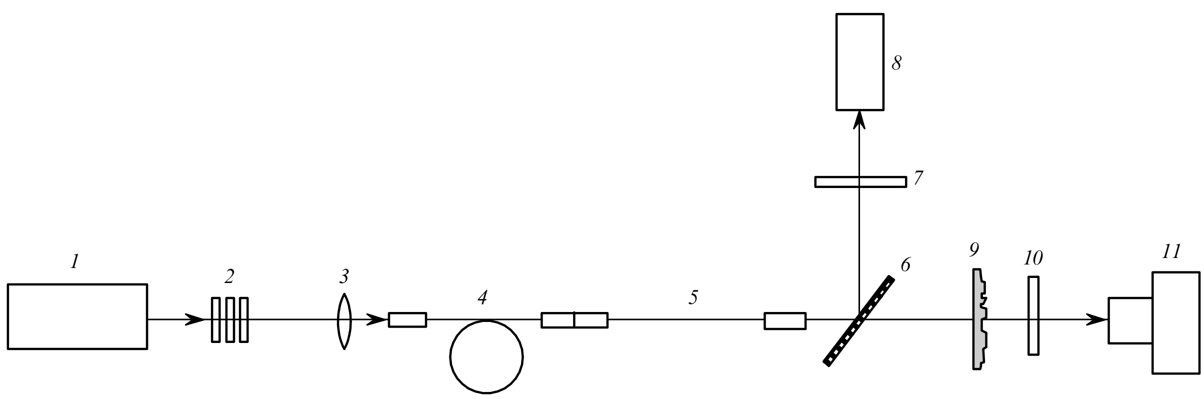

Figure 1. Optical scheme of the experimental setup: (*1*) pulsed solid-state laser; (*2*) set of calibrated neutral filters; (*3*) microobjective; (*4*) piece of a multimode fibre; (*5*) main fibre; (*6*) beamsplitter; (*7*) mirror with $R = 90\,\%$; (*8*) spectrum analyser; (*9*) mat plate; (*10*) filter; (*11*) CCD linear array.

into main step-index fibre (*5*) of length ~ 100 m and a core diameter of $\sim 60 - 100$ μm. A part of radiation coming from the fibre was directed with beamsplitter (*6*) through mirror (*7*) ($R = 90$ % at 532 nm) to spectrum analyser (*8*). Radiation propagated through the beamsplitter was incident on mat plate (*9*), scattered in it, passed through filter (*10*) with the 620-nm transmission band of width ~ 1 nm and then was detected with 2048-pixel CCD linear array (*11*) (with a spatial resolution of ~ 14 μm). A short fibre piece wound on a coil is used in the scheme to form the guided modes in the fibre and to measure the radiation energy coupled to the main fibre.

We recorded SRS spectra and the Stokes radiation intensity distributions behind the mat plate at 620 nm for different pump radiation powers and the invariable degree of the spatial coherence of pump radiation. The contrast of produced speckle patterns and the related number N of spatially coherent modes were determined from these distributions.

Figure 2 presents Stokes components typical for a silica fibre [18], which were recorded for the two values of the parameter M equal to the ratio of the pump power to its threshold value (which was ~ 200 W). One can see that as the pump power is increased, cascade SRS is realised, when the energy of the first SRS components is almost completely transferred to higher-order Stokes components. In this case, the spectral shift with respect to the pump wavelength can achieve ~ 100 nm. The spatial intensity distributions of the Stokes component corresponding to these pump powers detected behind optical filter (*10*) are shown in Fig. 3 by curves (*1*) ($M = 1.9$) and (*2*) ($M = 3.9$). The intensity distributions were recorded at a distance from the mat plate providing a great number of speckles observed upon irradiation of the plate by radiation coupled to the fibre. Curve (*3*) gives the radiation intensity distribution of a luminescent lamp recorded with a CCD linear array through a diffusely scattering plate. The relative depth of random intensity fluctuations of the recorded intensity distributions averaged over several realisations, or the so-called contrast of speckle noise (5), was 0.12, 0.1, and 0.03, respectively. The radiation intensity fluctuations of a luminescence lamp are mainly determined by the nonuniformity of the energy sensitivity of individual pixels of the CCD camera. Therefore, the amplitude of these fluctuations can be treated as the relative measurement error of the contrast of speckle structures of the Stokes component radiation.

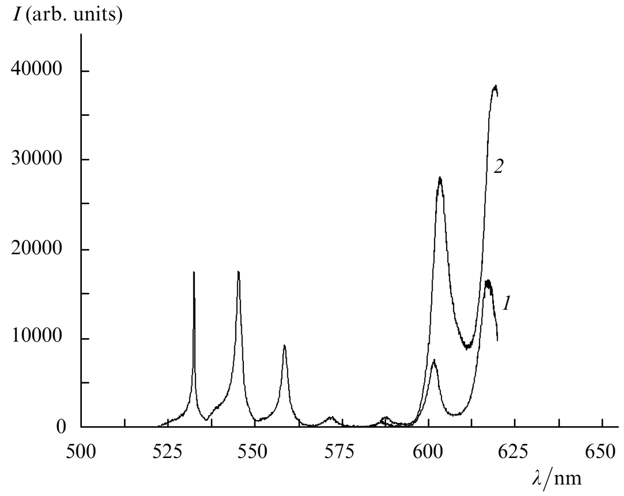

Figure 2. SRS spectra in a multimode fibre with $M = 1.9$ (*1*) and 3.4 (*2*).

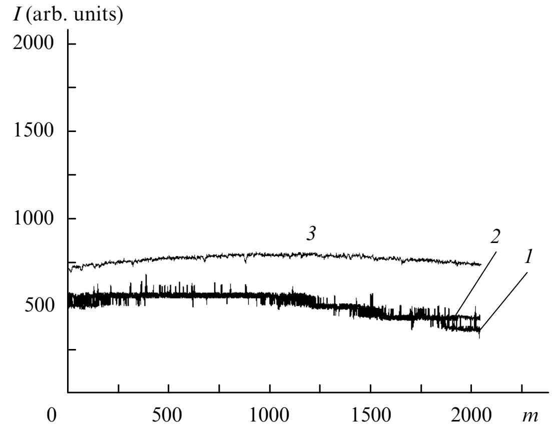

Figure 3. Spatial intensity distributions of the SRS Stokes component for different pump powers (*1*, *2*) and of a luminescent lamp (*3*); m is the pixel number in the CCD linear array.

The estimates of the parameter φ (6), which most considerably affects the degree of the spatial coherence of Stokes components, show that already at the threshold SRS excitation power its value exceeds by more than an order of magnitude the value of φ at which the number of radiation modes of the Stokes component infinitely increases. This means that the Stokes waves excited in a multimode fibre by a noise-like pump field with power exceeding their generation threshold should be certainly spatially incoherent. One can see from Fig. 3 that in practice the spatial intensity distributions of Stokes components [curves (*1*) and (*2*)] somewhat differ from this distribution for a polychromatic light source [curve (*3*)]. The dispersion of spatial intensity fluctuations of the SRS Stokes component is determined to a great extent by individual intensity spikes caused by diffraction-interference effects manifested in the case of highly monochromatic radiation.

4. Conclusions

We have developed the statistical model of SRS in a multimode long fibre. For pump radiation in the form of the narrowband Gaussian noise, the relation has been obtained between the number of spatially coherent radiation modes of the SRS Stokes component and the fibres and SRS excitation conditions. The energy, spectral, and spatial characteristics of SRS radiation have been studied experimentally depending on the pump properties. Theoretical estimates of the degree of the spatial coherence of the SRS Stokes wave and experimental data are in qualitative agreement.

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