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Conjugation and transformation of the wave front by stimulated Brillouin scattering of vortex Laguerre–Gaussian laser modes

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Abstract. **We study experimentally stimulated Brillouin scattering (SBS) of vortex laser beams, namely, the LG_1^1 and LG_0^1 Laguerre–Gaussian modes. The wave front transformation is experimentally demonstrated in the case of SBS of the LG_1^1 laser mode, directly focused into the SBS cell, when the fundamental Gaussian mode LG_0^0 rather than the conjugate mode is selected from the Stokes beam. It is shown that optical vortices become phase conjugate by destroying the laser mode structure in the SBS cell. Phase conjugation (PC) of the LG_0^1 and LG_1^1 modes is obtained in the SBS mirror using a regular aberrator (microlens raster) in the system of laser beam focusing into the SBS cell.**

Keywords: *optical vortex, stimulated Brillouin scattering, phase conjugation.*

1. Introduction

Laser beams with the screw dislocation of the wave front (optical vortices), whose phase surface is a helicoid, are widely investigated in relation with their potential application in communication systems, optical information processing systems, and high technologies [1]. A well-known example of optical vortices is provided by Laguerre–Gaussian laser modes LG_n^m.

One of the important optical transformations of a laser beam is phase conjugation (PC) [2]. As well as any control of the optical vortex phase, PC is difficult to implement using a flexible mirror in linear adaptive optics devices because of discontinuity of the phase surface. That is why it is rather interesting to obtain PC by one of the well-known nonlinear mechanisms – stimulated Brillouin scattering (SBS). Note that the classical PC upon SBS in focused beams is due to the fact that the gain for the conjugate Stokes mode is 50% higher than the gain of the nearest Stokes modes, thereby providing efficient selection of the conjugate mode [2].

Theoretical analysis and calculations of stationary [3] and nonstationary [4] SBS of Laguerre–Gaussian modes, directly focused into the bulk SBS medium, revealed new phenomena. It was shown that no PC of vortex modes is observed, and this fact is due to the absence of the conjugate Stokes mode selection. This occurs because the gains of the conjugate Stokes mode LG_n^m and the analogous mode with the inverse helicity LG_n^{-m} are similar. Therefore, (e.g., in the case of the simplest toroidal mode LG_0^1) the Stokes beam is a random combination of several modes, including the conjugate one. For a wide enough class of vortex beams (e.g., in the case of the laser mode LG_1^1 having two intensity rings), one can observe a phenomenon that may be called wave front transformation (WFT) in the SBS process. Its essence is that in the Stokes beam the fundamental Gaussian mode rather than the conjugate one (as in the classical PC [2]) is selected. The gain of the fundamental mode is 20% higher than that of the conjugate mode LG_1^1 and the mode LG_1^{-1}, i.e., a certain selection of this mode exists [3, 4].

The absence of phase conjugation of the LG_0^1 mode under the conditions of direct focusing of laser radiation into the SBS medium is confirmed experimentally [5, 6]. The aim of the present paper is, firstly, to check experimentally the predicted WFT effect for the focused laser mode LG_1^1, and, secondly, to determine the conditions for implementing PC upon SRS of vortex beams by using a more complex SRS mirror that incorporates a microlens raster.

2. Experimental setup

In the optical scheme for studying SBS of vortex beams (Fig. 1), we used the laser system that included a laser source and an astigmatic $\pi/2$-convertor. The laser source was designed following the scheme, similar to that described in Ref. [7], and consisted of a master oscillator and a double-pass amplifier. The phosphate Nd glasses GLS-23 (λ = 1.053 μm) with the dimensions $\varnothing 5 \times 100$ mm and $\varnothing 8 \times 150$ mm were used as an active medium in the oscillator and the amplifier.

The Hermite–Gaussian modes HG_{01} or HG_{21} were produced using spatial selectors (thin wires, placed on the axis of a plane-spherical resonator) in the master oscillator. Passive Q-switching of the master oscillator resonator was implemented using a $YAG:Cr^{4+}$ crystal. The duration of the laser pulse was 40 ns.

The Laguerre–Gaussian modes LG_0^1 or LG_1^1 were produced at the output of the master oscillator by means of a tunable astigmatic $\pi/2$-convertor based on a so-called optical quadrupole [7].

The SBS was excited in the 150-cm-long cell, filled with liquid freon C_8F_{18} (the SBS gain, g = 6.5 cm $GW^{-1;}$ the hypersound decay time, τ = 1 ns [8]). The laser mode radiation could be focused into the SBS cell by the single lens (*8*). The

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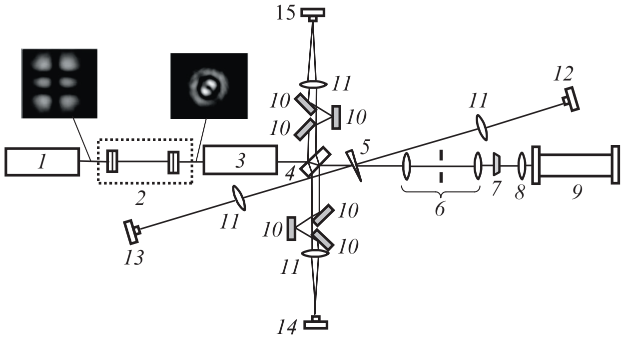

Figure 1. Optical scheme of the experiment: (*1*) master oscillator; (*2*) $\pi/2$-convertor; (*3*) amplifier; (*4*) plane-parallel beamsplitter; (*5*) wedge; (6) angular selector; (*7*) lens raster; (*8*) focusing lens; (*9*) SBS cell; (*10*) mirrors; (*11*) lenses; (*12–15*) CCD-cameras.

optical system consisting of the angular selector (*6*), regular aberrator (*7*) in the form of a raster of identical microlenses and the lens (*8*) could be used for the same purpose.

In the experimental studies of the PC of optical vortices under the conditions of SBS, it is necessary to compare not only the intensity distributions of the laser and Stokes modes, but also the phase distributions of the beams. To study the phase structure of radiation, use was made of a special interferometer scheme, where the reference beam was produced from a part of the original Laguerre–Gaussian mode LG_0^1 or LG_1^1 (see Fig. 2, which is a fragment of Fig 1). As a result, each of the modes interfered with a similar one, but having the topological charge of the opposite sign (the opposite helicity), i.e., with LG_0^{-1} or LG_1^{-1}. The interference fringe density depended on the thickness of the plane-parallel plate (*4*) and could be additionally varied by inclining the mirrors (*10*).

Figure 3 shows the experimentally observed intensity distributions of the laser modes LG_0^1 and LG_1^1 in the far-field zone and the patterns of their interference with an oblique wave having the form of a LG_0^{-1} or LG_1^{-1} mode, respectively.

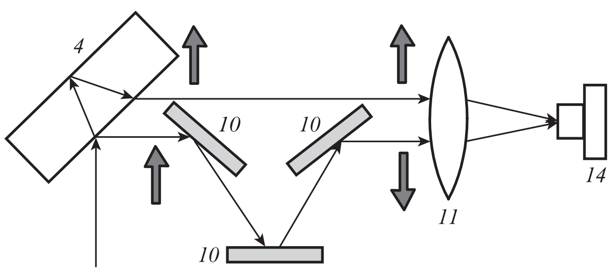

Figure 2. Optical scheme for measuring the laser beam phase: (*4*) plane-parallel beamsplitter; (*10*) mirrors; (*11*) lens; (*14*) CCD-camera.

The peculiarity of the interference of two Laguerre–Gaussian modes having the opposite helicity of the phase manifests itself in branching of a fringe in the middle of the beam and formation of a characteristic 'fork' with an additional fringe appearing in the centre, as compared with the case of a vortex mode interfering with a plane reference wave [1]. Such branching of fringes indicates the vortex nature of the beam investigated, while the absence of branching is a manifestation of the regular character of the beam phase surface.

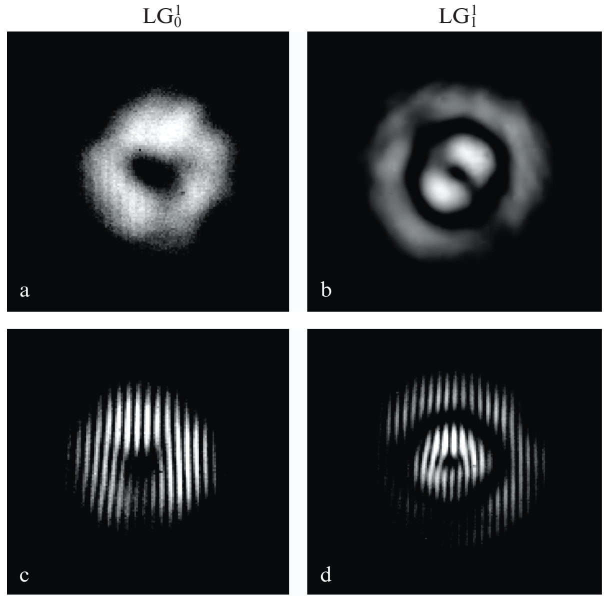

Figure 3. Experimental intensity distributions (a, b) and phase portraits (c, d) of the modes LG_0^1 (a, c) and LG_1^1 (b, d).

3. SBS of the LG_1^1 laser mode and transformation of its wave front

Earlier, it was shown theoretically [3, 4] and experimentally [5, 6] that in the case of direct focusing of the laser mode LG_0^1 by a lens, the Stokes beam is a random superposition of vortex modes LG_0^1 and LG_0^{-1}, and no PC is observed under these conditions. The specific features of the SBS induced by a higher-order laser mode (LG_1^1) are experimentally investigated in the present paper.

In the experiments, radiation of the LG_1^1 mode was focused into the SBS cell by the lens (*8*) with the focus length 50 cm [the angular selector (*6*) and the lens raster (*7*) were removed from the scheme]. The length of the interaction region in the nonlinear medium amounted to a few waist lengths of the laser beam. In each laser shot the intensity and the phase portrait were registered for the laser and Stokes radiation using four CCD cameras (see Fig. 1). The peculiarities of the LG_1^1 mode were investigated in two regimes, namely, near the Stokes excitation threshold and in the SBS saturation regime.

Near the SBS threshold (the reflection coefficient for the Stokes radiation being at the level 1%–5%) in most laser shots we observed the regime that can be called a wave front transformation upon SBS [3, 4]. Its essence is that the fundamental Gaussian mode LG_0^0, orthogonal to the laser mode and having a regular phase front, is selected from the Stokes beam (Figs 4a, b, e, and f). According to [3, 4], the gain of the LG_0^0 Stokes mode is 20% greater than that of the LG_1^1 conjugate mode and the LG_1^{-1} mode. This excess is not so high as the 50% excess in the case of the classical PC in focused beams [2]; therefore, in a number of laser shots the Stokes beam consists of two off-axis spots (Fig. 4c) that repeat bright spots in the distribution of the laser intensity in Fig. 3b. However, in any case the singularity, characteristic for Fig. 3d, is absent in the phase portrait of the Stokes beam (Figs 4e–g).

In the case of SBS, excited in the saturation regime, when the reflection coefficient amounts to 50%–60%, the intensity

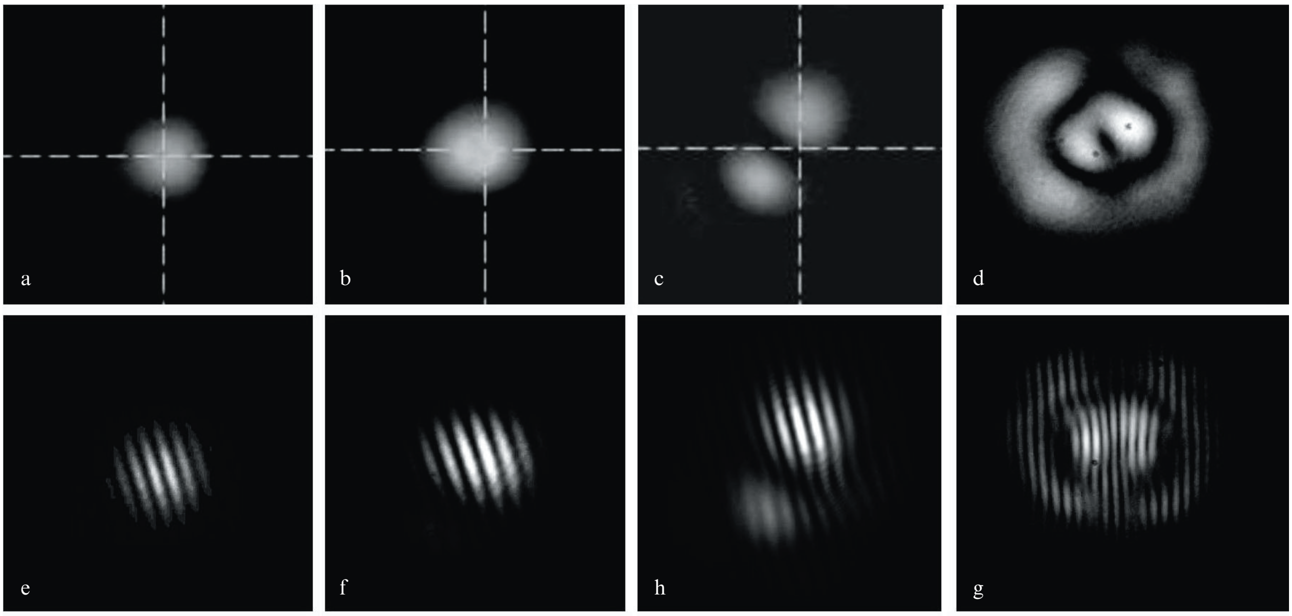

Figure 4. Intensities (a – d) and phase portraits (e – h) for the Stokes beam near the SBS threshold (a – c, e – g) in three laser shots and in the saturation regime (d, h) in the case of direct focusing of the LG_1^1 laser mode into the SBS cell.

distribution for the Stokes beam in the far-field zone (see Figs 4d, h) repeats the laser mode distribution, consisting of two rings (compare Fig. 4d and Fig. 3b), as shown in earlier calculations [4]. However, in correspondence with [4], the axial branching of fringes, present in the laser beam (Fig. 3d), is absent in the interferogram of the Stokes mode (Fig. 4h).

Thus, both in linear regime and under SBS saturation, no PC of the laser mode LG_1^1 is observed, i.e., there is no axial vortex in the Stokes beam, so that the beam has a regular phase distribution. The smaller the influence of the SBS saturation, the closer the structure of the Stokes beam to that of the fundamental Gaussian mode LG_0^0.

It is worth noting that a more stable TWF effect may be obtained by increasing the mode index n, because the degree of selection of the fundamental Gaussian mode increases in this case [3, 4, 9]. The TWF can be observed also for nonvortex beams with $m = 0$ and without the on-axis dip in the intensity distribution. The analysis shows the possibility of transforming the wave front of a vortex laser mode into that of a more complex (not fundamental) Gaussian mode in the regime of a SBS-amplifier, when the Stokes beam is produced not from the noise, but from an input Stokes signal consisting of a single particular mode.

4. Use of kinoform optics in the scheme, focusing Laguerre – Gaussian modes into the SBS cell to obtain PC

Work [5, 9], by means of calculations, shows that a vortex beam can become phase conjugate by destroying the beam structure in the SBS medium, e.g., in an SBS mirror with a microlens raster [10]. Such an SBS mirror allows efficient angular filtration of the nonconjugate Stokes component, reduction of local light loads and avoiding undesirable accompanying nonlinear effects. The scheme of the SBS mirror, including an ordered phase plate representing a raster of small diffractive Fresnel lenses and an angular selector, is shown in Fig. 5, which is a fragment of Fig. 1. According to the theory and calculations [11, 12] and also the experiments [12 – 14], optimal geometry of the SBS mirror exists that stably provides the PC coefficient greater than 90 % – 95 % for the transmission coefficient of the angular selector being 50 % – 70 % and for any SBS saturation level, i.e., for any reflection coefficient. Such a focusing scheme proved to be optimal for obtaining high-quality PC in SBS of laser beams with regular phase distortions [11 – 14]; therefore, it was interesting to apply it also to studying the PC in vortex beams.

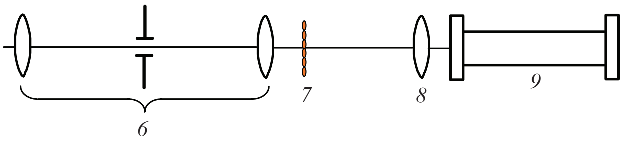

Figure 5. Optical scheme of an SBS-mirror: (*6*) angular selector; (*7*) microlens raster; (*8*) focusing lens ($f = 50$ cm); (*9*) SBS cell.

In the performed experiments, use was made of an eight-level raster (*7*) with square packing of microlenses having the size 1 mm and the focal length 200 mm. The use of such a raster provided the minimal threshold energy for exciting SBS. The distance between the raster (*7*) and the lens (*8*) was chosen such that both bright zones of the laser beam intensity, namely, the focal plane of the lens (*8*) and the image of the focal plane of the raster microlenses, were located inside the cell with appropriate separation between them. From the cell the reflected radiation of the Stokes component passed through the angular selector (*6*), after which its distribution in the far-field zone and phase portrait were compared with respective characteristics of the laser mode (Fig. 6). The coefficient of light reflection from the SBS cell was about 15 %.

One can see from Fig. 6 that the transverse intensity distribution of the Stokes modes in the far-field zone and their phase portraits coincide with the respective distributions and

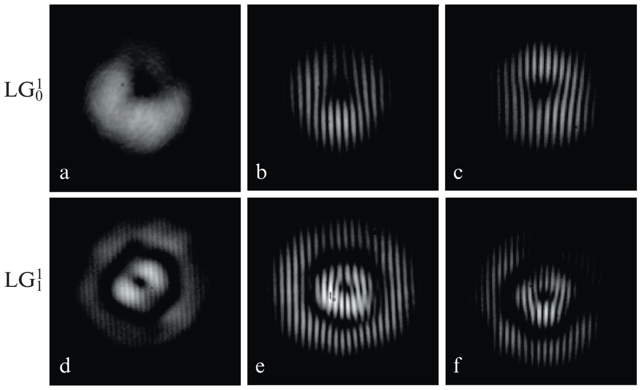

Figure 6. Intensity distributions in the Stokes beam (a, d), phase portraits of the Stokes beam (b, e) and phase portraits of the laser radiation, reflected by a plane mirror (c, f), in the case of the laser mode LG_0^1 (a–c) and LG_1^1 (d–f).

phase portraits of the laser modes LG_0^1 and LG_1^1 in Fig. 3. This is an evidence of high-quality PC. To get an extra evidence that the Stokes beam is phase conjugate with respect to the laser one, we performed special experiments, in which the SBS mirror was replaced with a common plane mirror, and in the same measurement scheme the phase portrait was recorded for the radiation, reflected from the mirror (Figs 6c, f). In the latter case the orientation of the 'fork' in the interferogram was opposite to that of the laser mode. This indicates the fact that using the raster in the scheme focusing the laser radiation into the SBS cell results in complex conjugation of the phase of the laser pump wave front.

Thus, we have experimentally demonstrated for the first time that the optimal geometry of the SBS-mirror, found earlier [11–14], allows high-quality PC of laser radiation for beams with screw dislocations as well.

5. Conclusions

We have studied experimentally SBS of vortex laser beams (Laguerre Gaussian modes LG_0^1 and LG_1^1) under different conditions of focusing and at different energies of the pump pulse.

It has been experimentally demonstrated that in the case of SBS of a vortex laser Laguerre–Gaussian mode LG_1^1, directly focused into the SBS cell, wave front transformation is observed instead of phase conjugation. The Stokes beam has no vortices and in the near-threshold regime often presents the fundamental Gaussian mode, which agrees with predictions of theory and calculations.

Phase conjugation of a vortex laser beam is experimentally shown to be achieved by destroying the mode structure in the SBS cell. High-quality PC of LG_0^1 and LG_1^1 modes is obtained using a complex SBS mirror, incorporating an ordered microlens raster in the laser beam focusing system.

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