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Simulation of phase conjugation for laser radiation upon nonstationary SBS

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Abstract. **We report the three-dimensional simulation results of phase conjugation upon nonstationary stimulated Brillouin scattering of a focused laser beam. It is shown that in the case of deep focusing of laser radiation in the SBS cell, the phase conjugation quality decreases with increasing laser power and reflection coefficient, in agreement with experimental results. In calculations, the process of Stokes radiation generation is studied in detail, the reasons for a decrease in the phase conjugation quality are explained, and a means of its improvement is proposed.**

Keywords: *stimulated Brillouin scattering, phase conjugation, nonstationary scattering.*

1. Introduction

Investigation of the phase conjugation effect upon stimulated Brillouin scattering (SBS) has a rich history [1 – 4] and still attracts attention of researchers (see review [5]). One of the problems under study in this field is the nonstationary SBS when the pump pulse duration is comparable or smaller than the relaxation time τ of hypersonic oscillations in a SBS medium. In most of the performed researches, starting with papers [6 – 8], main attention was paid to determining the nonstationary SBS threshold and to the degree of the reflected pulse compression, while the phase conjugation quality was poorly studied. At the same time, the problem of the phase conjugation quality uner the nonstationary SBS is of interest both from the fundamental point of view and some applications where the phase conjugation of nanosecond and even shorter pulses is required (see, for example, [9]).

In the case of the quasi-stationary SBS when the pump pulse duration (or coherence time) significantly exceeds τ, the phase conjugation quality of a focused laser beam monotonically decreases with increasing angular pump-radiation divergence at a fixed reflection coefficient, while at a fixed divergence, it monotonically increases with increasing the pump pulse power (energy). This fact, straightening out and summing up the experimental results, was demonstrated in recent calculations [10] with the help of a numerical model [11] allowing one to describe phase conjugation upon SBS in situations close to real. The model can take into account the medium three-dimensionality, hypersonic noise in the medium volume, diffraction, transition processes related to the finite relaxation time of hypersound, SBS saturation, refraction, linear losses and radiation self-action in a SBS medium, i.e. the main known mechanisms accompanying the SBS process.

However, as was experimentally found in early work [12], the dependence of the phase conjugation quality on the laser power (energy) typical of the quasi-stationary SBS changes to the opposite one under the nonstationary SBS. Experiments [12] showed that under the nonstationary conditions, the phase conjugation quality monotonically decreases with increasing pump energy and the range of energies at which effective phase conjugation occurs is small and decreases with pulse shortening. The aim of this paper is to study the reasons responsible for deterioration of the phase conjugation quality with increasing pump energy under the nonstationary SBS by using the calculation method [11] which gives a complete spatiotemporal picture of SBS and makes it possible to observe generation and propagation of a Stokes beam in a SBS medium. This simplifies the analysis of the results obtained in calculations and allows one to explain the experimental data.

2. Fundamentals of calculations

We performed calculations using the calculation model and programme describing the nonstationary SBS process in a tree-dimensional medium [11] by neglecting the parasitic self-action effects. Stimulated Brillouin scattering is described by the system of equations:

$$\frac{n_0}{c}\frac{\partial A_{\rm las}}{\partial t} + \frac{\partial A_{\rm las}}{\partial z} + \frac{\rm i}{2k}\nabla_\perp^2 A_{\rm las} = -\frac{\rm i}{2} p A_{\rm s}, \qquad (1)$$

$$\frac{n_0}{c}\frac{\partial A_{\rm s}}{\partial t} - \frac{\partial A_{\rm s}}{\partial z} + \frac{\rm i}{2k}\nabla_\perp^2 A_{\rm s} = -\frac{\rm i}{2} p^* A_{\rm las}, \qquad (2)$$

$$\frac{1}{2{\rm i}\Omega}\frac{\partial^2 p}{\partial t^2} + \left(1 + \frac{1}{{\rm i}\Omega\tau}\right)\frac{\partial p}{\partial t} + \frac{p}{\tau} = -{\rm i}\frac{g}{\tau} A_{\rm las} A_{\rm s}^* + S, \qquad (3)$$

where $A_{\rm las}$, $A_{\rm s}$, and p are slowly varying complex amplitudes of laser, Stokes, and hypersonic fields, respectively; g is the SBS gain; n_0 is the average refractive index; $k = n_0\omega_0/c$ is the wave number; ω_0 is the laser pump frequency; Ω is the hypersound frequency; S is the Langevin fluctuation force (source of hypersonic noise in the medium volume); $\nabla_\perp^2$ is a Laplacian in the transverse coordinate $\boldsymbol{r}$; z is the longitudinal coordinate. In system of equations (1) – (3) the radiation field amplitudes are normalised so that the flux densities are $J_{\rm las} = |A_{\rm las}|^2$, $J_{\rm s} = |A_{\rm s}|^2$.

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The system of equations (1)–(3) can be solved if we know average and correlation parameters of the hypersonic noise, which would be matched to the observed quantities. Equation (3) should be solved with such random initial conditions for p_0 and $\dot{p}_0$ so that the average level of the hypersound amplitude fluctuations and their correlation time at each point in space remained constant in time in the absence of radiation in the medium. The necessary conditions meet the relations:

$$\langle p_0(\boldsymbol{r}_1, z_1)\, p_0^*(\boldsymbol{r}_2, z_2)\rangle = 4\kappa F_{\rm s}(\boldsymbol{r}_1 - \boldsymbol{r}_2)\,\delta(z_1 - z_2), \qquad (4)$$

$$\langle \dot{p}_0(\boldsymbol{r}_1, z_1)\, \dot{p}_0^*(\boldsymbol{r}_2, z_2)\rangle = 4\kappa \Omega^2 F_{\rm s}(\boldsymbol{r}_1 - \boldsymbol{r}_2)\,\delta(z_1 - z_2), \qquad (5)$$

$$\langle p_0(\boldsymbol{r}_1, z_1)\, \dot{p}_0^*(\boldsymbol{r}_2, z_2)\rangle = 0, \qquad (6)$$

$$\langle S(\boldsymbol{r}_1, z_1, t_1) S^*(\boldsymbol{r}_2, z_2, t_2)\rangle$$
$$= (2/\tau)\langle p_0(\boldsymbol{r}_1, z_1)\, p_0^*(\boldsymbol{r}_2, z_2)\rangle\,\delta(t_1 - t_2), \qquad (7)$$

where κ is the spontaneous laser-radiation scattering coefficient measured in cm^{-1} sr^{-1}; $F_{\rm s}(\boldsymbol{r}_1 - \boldsymbol{r}_2)$ is the dimensionless transverse correlation function which yields a unit axial brightness of Stokes radiation obtained due to spontaneous scattering. The coefficient κ is borrowed from experimental data or estimated from the expression for a gaseous medium as $\kappa = 4\pi^2(n_0 - 1)^2/(\lambda^4 N_0)$, where N_0 is the concentration of gas molecules.

The phase conjugation of laser pulse radiation with the following parameters was studied in calculations: the wavelength is $\lambda = 1.06$ μm, the Gaussian pulse duration is $\tau_{\rm p} = 3$ ns, the Gaussian beam radius is $a = 0.16$ cm. As a scattering medium, we considered liquid Freon C_8F_{18} for which $g = 6.5$ cm GW^{-1}, $\tau = 1$ ns, $\Omega = 8.5$ GHz [13]. The period of hypersonic oscillations is $T = 2\pi/\Omega = 0.74$ ns; therefore $\tau_{\rm p} \sim \tau > T$, i.e. SBS is mainly realised in the nonstationary regime. In this case, the first term in the left-hand side of equation (3) cannot be neglected, unlike [10], where the case $\tau_{\rm p} \gg \tau$ was considered.

Laser radiation was focused into a 150-cm-long cell by a lens with a focal distance $F = 100$ cm. The lens was mounted close to the SBS-cell window ($z = 0$). Thus, in the case under study, the pump beam waist is deeply immersed in the scattering medium and, in addition, its length $z_0 = 4$ cm is significantly shorter than that of the SBS medium.

The spatial structure of the pump field at the cell input did not change in time and, hence, the phase conjugation quality was characterised by conjugation coefficient [2]

$$h(z,t) = \frac{\left|\iint A_{\rm las}(\boldsymbol{r},z,t) A_{\rm s}(\boldsymbol{r},z,t)\,{\rm d}\boldsymbol{r}\right|^2}{\iint |A_{\rm las}(\boldsymbol{r},z,t)|^2 {\rm d}\boldsymbol{r} \iint |A_{\rm s}(\boldsymbol{r},z,t)|^2 {\rm d}\boldsymbol{r}}. \qquad (8)$$

Integrals in (8) were calculated at $z = 0$ (at the input cell window). The average value of the conjugation coefficient was determined by the expression

$$\langle h\rangle = \int h(0,t) P_{\rm s}(t)\,{\rm d}t \Big/ \int P_{\rm s}(t)\,{\rm d}t, \qquad (9)$$

where $P_{\rm s}$ is the Stokes radiation power. The coefficient of laser radiation reflection was determined as $R = E_{\rm s}/E_{\rm las}$, where $E_{\rm las}$ and $E_{\rm s}$ are the laser and Stokes radiation energy at the cell input.

3. Results of calculations and their discussion

It was found in experiments [12] that under nonstationary conditions, the phase conjugation quality decreases with increasing the conjugation coefficient. Figure 1a shows a typical experimental dependence of the reproduction parameter $E_\varphi/E_{\rm s}$ and the reflection coefficient R of laser radiation with a divergence close to the diffraction one on the pump energy from paper [12]. The reproduction parameter $E_\varphi/E_{\rm s}$ in [12] represented a ratio of the energy E_φ in the diffraction angle to the total beam energy $E_{\rm s}$ after reflection and characterised the phase conjugation quality. Figure 1b presents a similar dependence obtained in our calculations. The phase conjugation quality in the calculations was characterised by the integral conjugation coefficient $\langle h\rangle$ (9) with which the reproduction parameter $E_\varphi/E_{\rm s}$ from paper [12] correlates. The main peculiarity follows from Fig. 1b: the higher the pump energy and the laser radiation reflection coefficient, the worse the phase conjugation quality. Thus, the results of our calculations qualitatively agree with the experimental data. To understand why the phase conjugation quality deteriorates with increasing laser energy in this problem, we will consider the typical case when $E_{\rm las} = 8$ mJ, $\langle h\rangle = 0.55$.

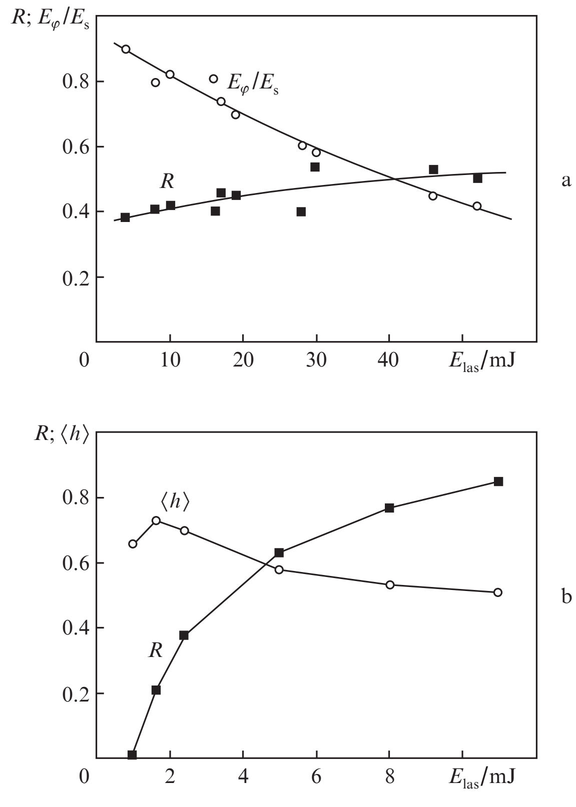

Figure 1. Typical experimental dependence of the reproduction parameter $E_\varphi/E_{\rm s}$ and the reflection coefficient R on the pump energy from paper [12] (a) and the calculated dependence of the integral conjugation coefficient $\langle h\rangle$ and the reflection coefficient R on the pump energy (b).

Figure 2 shows the radiation dynamics at the cell input for $E_{\rm las} = 8$ mJ. Due to SBS, laser radiation is compressed – the duration of reflected radiation becomes 15 times smaller than the pump pulse duration, while the peak power becomes several times greater than the maximum laser pump power. The dynamics of the instantaneous conjugation coefficient h

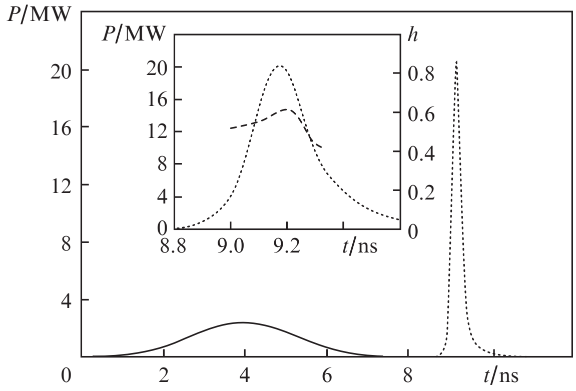

Figure 2. Power dynamics of laser (solid curve) and Stokes (dotted curve) beams; the inset shows also the time dependence of the conjugation coefficient (dashed curve) at the SBS-medium input.

during the Stokes pulse is also presented. One can see that the phase conjugation quality insignificantly increases at the leading edge of the Stokes pulse and decreases at its trailing edge. The intensity profiles of laser and reflected Stokes radiations at the input SBS-cell window clearly illustrating a decrease in the phase conjugation quality are presented in Fig. 3. At the leading edge of the pulse, the Stokes beam is narrower than the pump beam (cf. Fig. 3b and 3a), and at the trailing edge, vice versa, it is broader and has the shape of a torus in this case (see Fig. 3c). Figure 3d shows a time integrated distribution of the energy density of a Stokes beam characterised by a bright and relatively narrow paraxial kernel and a wing with a slower energy density drop. Therefore, the Stokes beam profile does not resemble the pump beam profile, which is confirmed by a relatively low integral conjugation coefficient ($\langle h \rangle = 0.55$).

We will explain the profiles presented in Fig. 3 by considering in more detail the process of Stokes radiation generation inside the cell. Figure 4 demonstrates deformation of the transverse structure of the pump beam in the waist region

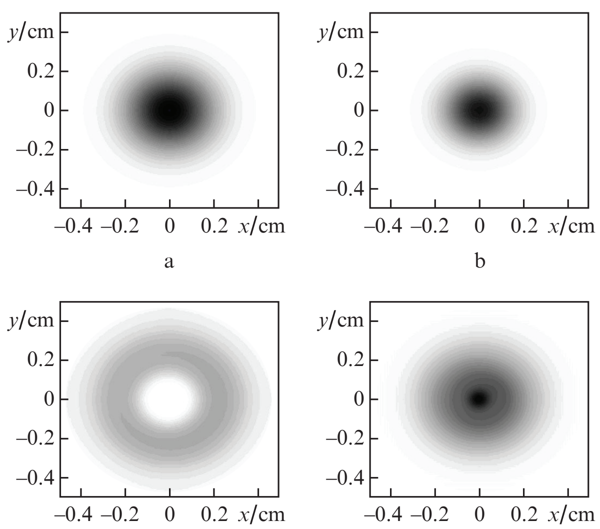

Figure 3. Intensity profiles of laser (a) and Stokes (b–d) beams at instants 9.1 (b) and 9.3 ns (c), and the time integrated distribution (d) at the input SBS-cell window.

($z = 90$ cm). In this case, the process of Stokes radiation generation can be explained as follows. The laser pulse is rather short and as a result, all Stokes radiation is produced mainly in the region of the pump beam waist. Because the total excess of energy over the threshold is great ($R = 0.8$), first there should be a drastic increase in the Stokes radiation amplitude. In this case, amplification of the Stokes beam at the leading edge proceeds in the linear regime under conditions that the pump is still not depleted (Fig. 4a), the Stokes spot (Fig. 4c) resembles the laser spot (although narrower due to the amplification linearity), and the conjugation coefficient insignificantly increases (see Fig. 3). Amplification in the linear regime continues until Stokes radiation is amplified so much that it starts influencing the pump, thereby forming a dip in the latter in the paraxial region (Fig. 4b). The deformed pump profile begins to generate, in turn, Stokes radiation with an intensity, which had a dip at the centre (Fig. 4d). This Stokes distribution is later observed at the input cell window (see Fig. 3c) because Stokes radiation propagates to the SBS-cell window from the waist region without any amplification as it does not interact on its path with the pump of the substantial amplitude. The conjugation coefficient at the cell input decreases because the reflected Stokes beam is absolutely different from the input laser beam.

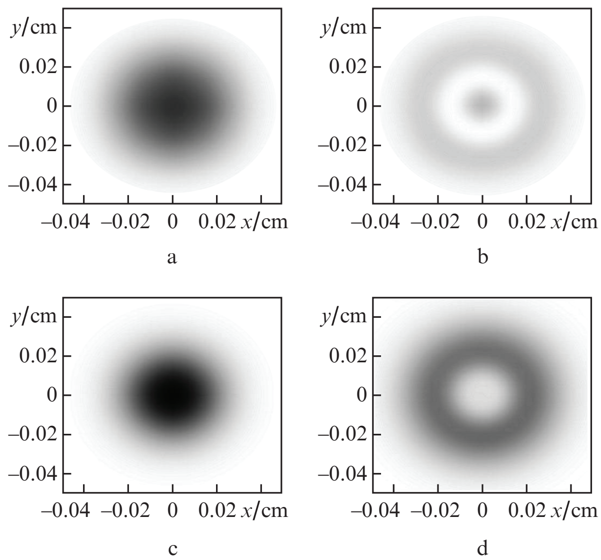

Figure 4. Transverse distribution of the flux density of laser (a, b) and Stokes (c, d) radiations in the section $z = 90$ cm (in front of the waist) at instants 6.1 (a, c) and 6.3 ns (b, d).

Thus, the reasons for a decrease in the phase conjugation quality upon the nonstationary SBS in the saturation regime are explained by the pump beam deformation in the waist region due to the energy transfer to the Stokes beam and by a small length of the interaction region of laser and Stokes beams. In addition, the higher the pump beam energy the faster the Stokes beam amplification undergoes transition from the linear regime to the saturation regime, and the greater the pump beam deformation. Because the Stokes beam traces this deformation, it less resembles the input laser beam. This explains a drop in the conjugation coefficient when increasing the pump energy, i.e. the SBS saturation depth.

The length of the interaction region of laser and Stokes beams can be increased by moving closer the pump beam waist to the input window of the SBS cell. Consider the influence of the pump beam waist position on the phase conjugation quality upon the nonstationary SBS. For this purpose, we will move the SBS cell from the focusing lens. In this case, the pump beam radius at the input cell window decreases. Figure 5 presents the dependences of the conjugation coefficient $\langle h \rangle$ and the reflection coefficient R of laser radiation on the pump energy E_{las} at different distances L between the lens and the SBS cell. One can see that in moving away the cell, the phase conjugation quality increases and the dependence $\langle h \rangle(E_{las})$, instead of decreasing over E_{las}, begins to monotonically increase as in the quasi-stationary regime [10]. Thus, at L = 87 cm, under deep saturation conditions, $\langle h \rangle$ achieves 0.9 for R = 0.76. The reflection coefficient is almost independent of L. This is explained by the fact that Stokes radiation is mainly amplified in the waist region, and the waist in all the cases under study is completely inside the SBS medium.

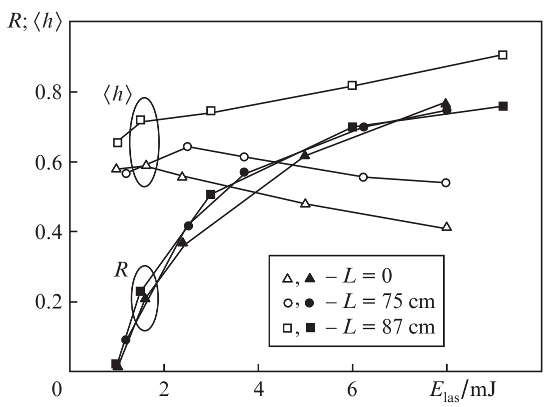

Figure 5. Dependence of the reflection coefficient R and conjugation coefficient $\langle h \rangle$ on the pump energy at distances between the lens and the input SBS-cell window L = 0, 75, and 87 cm.

Figure 6 shows the power dynamics of laser and Stokes radiations at the cell input for L = 87 cm and E_{las} = 9 mJ. One can see that the pump and reflected pulses, unlike the case depicted in Fig. 2, are well overlapped in time, which favours an improvement of the phase conjugation quality. Large values of the conjugation coefficient h are retained during the entire Stokes pulse (Fig. 6).

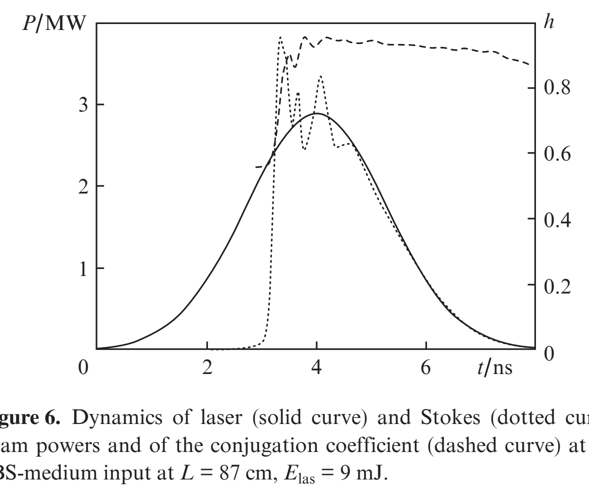

Figure 6. Dynamics of laser (solid curve) and Stokes (dotted curve) beam powers and of the conjugation coefficient (dashed curve) at the SBS-medium input at L = 87 cm, E_{las} = 9 mJ.

Therefore, by moving away the cell from the focusing lens, we can achieve good phase conjugation quality under conditions of deep SBS saturation. However, the radiation load on the input cell window increases in this case. Thus, in the case under study at E_{las} = 9 mJ, the energy density at the input window is 7 J cm^{-2}. The threshold energy density, whose excess leads to irreversible changes in the glass structure, is approximately 10 J cm^{-2}. Therefore, in optimising the SBS-mirror geometry, it is necessary to take into account in the experiment the possibility of damaging the cell window.

4. Conclusions

We have simulated numerically the influence of the nonstationary SBS on the phase conjugation quality. We have studied the phase conjugation of a laser pulse with the diffraction divergence and duration τ_p = 3 ns in liquid Freon C_8F_{18} (the decay time of hypersonic oscillations is τ = 1 ns).

It has been found in the calculations that when pump radiation is deeply focused into the SBS medium, the phase conjugation quality deteriorates with increasing laser energy and reflection coefficient. This agrees with the experimental data [12] and differs from the results typical of the quasi-stationary SBS when the conjugation coefficient increases with increasing laser energy and reflection coefficient [10]. We have explained the reasons for the phase conjugation quality deterioration upon the nonstationary SBS in the saturation regime. We have shown that Stokes radiation is mainly amplified in the pump beam waist, only the leading edge of the Stokes pulse being amplified in the linear regime, which provides the average phase conjugation quality. The next (main) part of the Stokes pulse is formed under the action of the SBS saturation, which leads to a paraxial dip in the pump beam and, as a result, to the corresponding deformation of the Stokes beam. Outside the pump beam waist, pierced Stokes intensity distribution moves to the SBS-cell window, virtually without amplification and changing the profile because it does not meet on its path laser radiation of a higher intensity. In this connection, the intensity distribution profiles of Stokes and laser beams differ substantially at the cell input.

We have shown that a decrease in the conjugation coefficient with increasing the saturation depth of the nonstationary SBS can start increasing, as under quasi-stationary conditions [10], in moving the pump beam waist to the input cell window when the laser and Stokes beams are better overlapped in time and the length of their nonlinear interaction region increases. In this case, it is possible to achieve the conjugation coefficients close to ideal if the problem of radiation resistance of the input SBS-cell window is solved.

References

1. Zel'dovich B.Ya., Popovichev V.I., Ragul'skii V.V., Faizulov F.S. *Pis'ma Zh. Eksp. Teor. Fiz.*, **15**, 160 (1972) [*JETP Lett.*, **15**, 109 (1972)].
2. Zel'dovich B.Ya., Pilipetskii N.F., Shkunov V.V. *Principles of Phase Conjugation* (Springer Series in Optical Sciences) (Berlin: Springer-Verlag, 1985) Vol. 42; *Obrashchenie volnovogo fronta* (Phase Conjugation) (Moscow: Nauka, 1985).
3. Bespalov V.I., Pasmanik G.A. *Nonlinear Optics and Adaptive Laser Systems* (New York: Nova Science Publishers, Inc., 1994; Moscow: Nauka, 1985).
4. Ragul'skii V.V. *Obrashchenie volnovogo fronta pri vynuzhdennom rasseyanii sveta* (Phase Conjugation upon Stimulated Light Scattering) (Moscow: Nauka, 1990).

5. Ostermeyer M., Kong H.J., Kovalev V.I., et al. *Las. Part. Beams*, **26**, 297 (2008).
6. Hagenloker E.E., Minck R.W., Rado W.G. *Phys. Rev.*, **154**, 226 (1967).
7. Hon D.T. *Opt. Lett.*, **5**, 516 (1980).
8. Papernyi S.B., Petrov V.F., Startsev V.R. *Pis'ma Zh. Tekh. Fiz*., **7**, 433 (1981).
9. Andreev A.A., Sutyagin A.N. *Kvantovaya Electron*., **24**, 155 (1995) [*Quantum Electron*., **24**, 150 (1995)].
10. Bogachev V.A., Kochemasov G.G., Starikov F.A. *Kvantovaya Electron*., **38**, 849 (2008) [*Quantum Electron*., **38**, 849 (2008)].
11. Starikov F.A., Dolgopolov Yu.V., Kochemasov G.G., et al. *Proc. SPIE Int. Soc. Opt. Eng*., **3930**, 12 (2000).
12. Yashin B.E., Kryzhanovskii V.I., Serebryakov V.A. *Kvantovaya Electron*., **9**, 1695 (1982) [*Sov. J. Quantum Electron*., **9**, 1086 (1982)].
13. Andreev N., Kulagin O., Palashov O., Pasmanik G. *Proc. SPIE Int. Soc. Opt. Eng*., **2633**, 476 (1995).