Phase conjugation of light fields as a result of nonlinear interaction in saturable media

E. V. Ivakin, V. G. Koptev, A. M. Lazaruk, I. P. Petrovich, and A. S. Rubanov
Institute of Physics, Belorussian Academy of Sciences

(Submitted 14 August 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **30**, No. 10, 648–651 (20 November 1979)

The formation of a wave, which is phase conjugated (inverted) with respect to the pumping field as a result of interaction of colliding light beams with a saturable dye solution, was observed experimentally.

PACS numbers: 42.65.Jx

We show in this paper that an inverted wave can be formed in dynamic bulk structures (reference-free holograms) induced in saturable resonant media by pumping radiation with a broad angular spectrum. In contrast to the related effect of wave-front inversion due to SMBS,[1] SRS,[2] and superluminescence,[3] this effect, which is attributed to anomalously low absorption of a phase-conjugate wave rather than to amplification, proceeds effectively when the frequency of the signal wave coincides with that of the inverted wave.

To illustrate the difference between the absorption of an inverted wave and any other spacial configuration of a bucking field, which is not correlated with pumping, let us examine the following model problem. Suppose that a pumping field $\mathscr{E}_L(\mathbf{r}_\perp,z)e^{+ikz}$ is a superposition of many plane waves with random phases and in every cross section $z=\text{const}$ has a uniform statistical Gaussian distribution with an average energy density $\langle W_L\rangle$. The local absorption coefficient of a weak probing field $\mathscr{E}_S(\mathbf{r}_\perp,z)e^{-ikz}$ is described in terms of a two-level model of a resonant medium by the expression

$$g(W_L)=\frac{g_0}{(1+aW_L)^2}, \tag{1}$$

where g_0 is the linear absorption coefficient and α is the saturation parameter. By analogy with Refs. 4 and 5, averaging the value $g(W_L)|\mathscr{E}_S|^2$ over the cross section gives an estimate of the absorption coefficient of the inverted $(\mathscr{E}_S\sim\mathscr{E}_L^*)G_c$ and the uncorrelated $(\int d^2r_\perp,\mathscr{E}_S\mathscr{E}_L=0)G_u$ configurations of the reading field

$$G_c(\langle W_L\rangle)=\frac{g_0}{a^2\langle W_L\rangle^2}\left[\left(1+\frac{1}{a\langle W_L\rangle}\right)\exp\left(\frac{1}{a\langle W_L\rangle}\right)E_1\left(\frac{1}{a\langle W_L\rangle}\right)-1\right],$$

$$G_u(\langle W_L\rangle)=\frac{g_0}{a\langle W_L\rangle}\left[1-\frac{1}{a\langle W_L\rangle}\exp\left(\frac{1}{a\langle W_L\rangle}\right)E_1\left(\frac{1}{a\langle W_L\rangle}\right)\right];$$

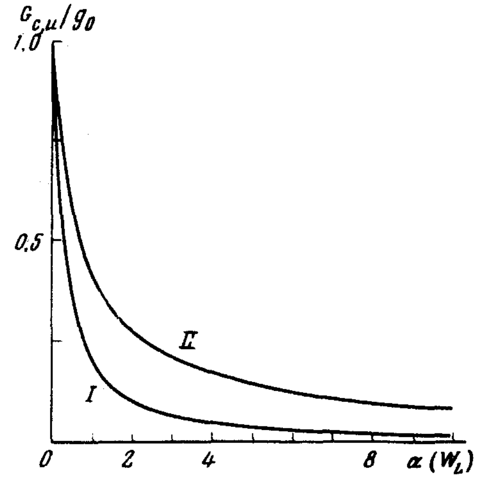

FIG. 1. Dependence of the averaged absorption coefficients G_c (I) and G_u (II) on the density of the pumping energy.

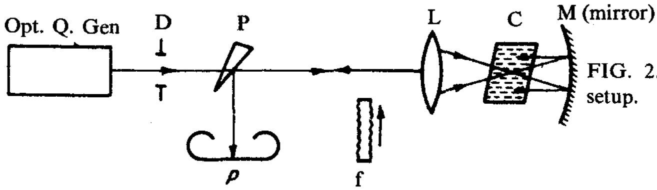

FIG. 2. Schematic of the experimental setup.

where $E_1(\ )$ is an integral exponential function. At any density of the pumping energy $G_c > G_u$ (Fig. 1), and the inverted wave is separated out as a result of suppression of the uncorrelated part of the probing field in the layer of the nonlinear material with sufficiently large integral absorption.

In the experiment the pumping was accomplished by using the second harmonic ($\lambda = 532$ nm) of a single-mode yttrium-aluminum garnet laser beam with pulse duration of ~ 20 nsec. A diaphragm D 1.2 mm in diameter cut out the central part of the beam with an angular divergence of 1 mrad. After passing through the elements of the optical system (Fig. 2), the beam was focused by a lens L ($F = 35$ mm, 20-mm aperture) into a cell C (18-mm length filled with a standard solution of rhodamine-6G ($g_0 = 12$ cm^{-1}). To suppress luminescence of the dye, we introduced a quencher *KJ* into the solution. The phase-conjugate wave was formed from pumping radiation that passed through the cell and was reflected by a mirror 3 in the opposite direction. The backward-propagated radiation was diverted by a glass wedge П to the recording system. The pumping power (~ 10 kW) was lower than the threshold of the onset of the SMBS. The backward-directed signal was missing without the mirror.

The dye solution was clarified by focusing the undistorted laser beam into the cell and the pumping transmission was $\sim 20\%$. The direction of propagation and divergence of ~ 1-mrad backward radiation did not depend on the location or the radius of curvature of the mirror 3, which indicates that the backward-propagating wave has been inverted. The same results were obtained when a diffusely reflecting screen was

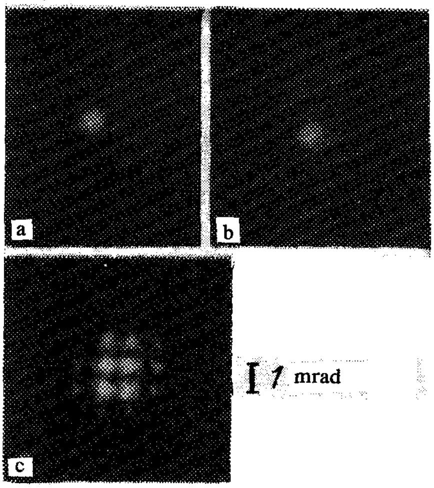

FIG. 3. Photographs of the far zone of the inverted light beam in the absence of the phase plate (a) and in its presence (c); (b) reconstructed image of the screen.

substituted for the mirror. In the experiment we reconstructed not only the divergence but also the structure of the laser field. By introducing a screen (0.25-mm mesh) into the laser beam, its image could be reconstructed by the inverted wave (Fig. 3b). Within the limits of the experimental error, all the backward radiation had an inverted wave front.

A nonuniform phase plate P distorted the wave front of the laser beam and the divergence increased by a factor of ~ 30. In this case only a fraction of backward radiation (of the order of several percent) has an inverted wave front, which, after passing the phase plate in the backward direction, is converted into a beam with the original divergence (Fig. 3c). The uncorrelated part of the radiation was scattered uniformly at an angle of about 30 mrad, forming a diffuse background of low luminosity. As in superluminescence,[3-5] the relatively low discrimination of the uncorrelated component of the probing field is attributed to the saturating nature of the dependence $g(W_L)$ in Eq. (1).

A qualitative experiment, in which the same setup was used with a nonsaturable absorber ($\dot{J}_2$ solution in ethanol), showed that nonsteady-state stimulated thermal scattering[6] under these conditions contributes negligibly to the formation of a phase-conjugate wave. This is borne out, in particular, by the presence of a strong background produced as a result of inversion of the undistorted laser beam. When the cell C contained pure ethanol, the inverted wave could not be isolated from the noise.

In conclusion, we note that the examined effect has a number of advantages—low threshold, absence of a frequency shift, etc.—over the other nonlinear-optical wave front inversion methods. The unit used in the experiment—a lens, a cell with a saturable resonant medium and a mirror—which has the properties of a passive valve in addition to those of a phase-conjugate mirror, can apparently be used in laser systems.

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