On the possibility of a complete compensation for nonlinear distortions of a light beam by means of an inversion of its wave front[1)]

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It was established experimentally and theoretically that wave-front inversion (WFI) generally prevents nonlinear distortions of a light beam, but under certain conditions a complete compensation for nonlinear distortions and suppression of self-excitation of the bucking waves are possible by means of WFI.

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The mutual influence of self-focusing and wave-front inversion (WFI) is now extremely important because of the ever-expanding area of applications of the WFI effect.[1–3] This is especially critical in experiments on the formation of light beams in high-power laser devices. In addition, the crucial question of the degree of reproduction, when a condensed medium possessing generally a cubic nonlinearity is used as the Brillouin mirror (BM) for WFI, has no been discussed in the literature, so far as we know, although it was observed experimentally[4] that under certain conditions self-focusing of the Stokes wave as a result of SRS prevents image reconstruction.

In order to separate in the experiment the influence of self-focusing on WFI from other possible wave-front distortions in the BM, it is advisable to investigate the relationship of these effects in a scheme (Fig. 1) where the WFI is achieved in the liquid CCl_4 with a small nonlinearity (cell C_3), and the nonlinear distortions occur as a result of passage of the incident wave E_+ and reflected wave E_- through the cell C_2 containing a highly nonlinear substance CS_2. In the experiments we investigated the inversion of an image of the hexagonal grating G with a 1-mm period and 60% transparency. The high-power laser beam was modulated by the grating, passed through

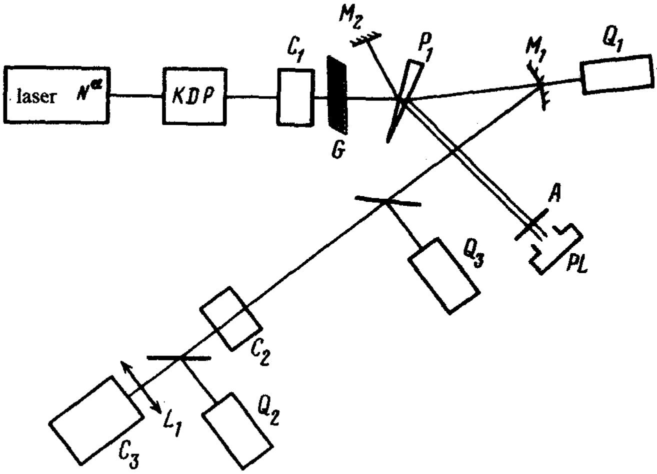

FIG. 1. Schematic of the experimental set-up. The neodymium-glass laser was comprised of a master oscillator that operated in the passive, Q-switching regime (30-nsec flash duration) in a longitudinal and transverse mode, and a six-stage amplifier with an output energy of ~ 10 J. The neodymium laser radiation was converted into the second harmonic in the KDP crystal. The second-harmonic radiation, with an energy of up to 2 J, passed through the cell C_1 with copper sulfate solution and entered the measurement circuit. G is a hexagonal grating, M_1 is a 100% mirror with a 3-m radius of curvature, M_2 is a plane mirror, Q_1, Q_2, Q_3 are calorimeters, C_2 is a CS_2 cell with length $L = 2$ cm, C_3 is a CCl_4 cell with length of 20 cm, P_1 is a glass wedge, A is a set of light filters, PL is camera for recording the intensity distribution in the near zone. The distance between cells C_2 and C_3 did not exceed 10 cm; therefore, the wave interaction in cell C_2 can be considered stationary.

the nonlinear medium C_2, was reflected from the BM (C_3, L_1), passed through the nonlinear medium again, and was directed to the photographic plate PL. The SMBS [stimulated Mandelstam–Brillouin scattering] in the cell C_2 was monitored by comparing the readings of the calorimeters Q_2 and Q_3, and none was excited in the experiments described below. Figure 2 shows the intensity distribution in the near zone without the nonlinear medium (in the absence of the cell C_2), with the image structure being completely preserved as the pumping power was varied from 4 to 25 MW. When cell C_2 is present, the image structure is strongly dependent on the pumping power and the reflection coefficient of the BM $R = |E_-|/|E_+|$. In a weak pumping field (Fig. 3a) with a decomposition integral $B = k(n_2/2n_0)|E_+|^2 L = 0.2$ slight nonlinear distortions of the image structure are noticeable. With an increase in the power (Fig. 3b) and a corresponding increase in B to 0.5 the image structure disappears in the beam intensity distribution. However, with a further increase in pumping intensity (and reflection efficiency of the BM), at R values close to one, the image structure of the central part of the beam is re-established (Fig. 3c). In this case the energy reflection coefficient (measured from the readings of the calorimeters Q_1, Q_2, Q_3) amounted to 40%. Measurements of the duration of the laser pulse ($\tau_L \sim 20$ nsec) and the Brillouin pulse ($\tau_s \sim 8.5$ nsec), which were performed on a S-8-12 high-speed oscilloscope, give a reflection coefficient of ~ 1 at the pulse maximum.

In order to analyze the given experimental results, we shall write the system of known quasi-optical equations which describe the nonlinear distortions in the cell C_2:

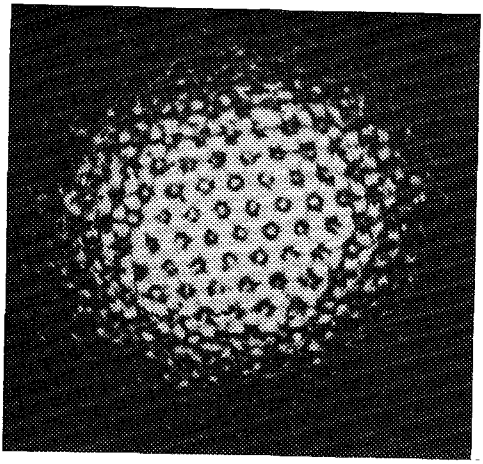

FIG. 2. Intensity distribution of SMBS light in the near zone in the absence of CS_2 cell.

$$\pm 2ik \frac{\partial E_\pm}{\partial z} + \Delta_\perp E_\pm + k^2 \frac{n_2}{n_0} (|E_\pm|^2 + p|E_\mp|^2) E_\pm = 0 . \quad (1)$$

(2)

Here, the refractive index is $n = n_0 + (\frac{1}{2})n_2|E|^2$ and k is the wave number in the medium. The difference between the wave numbers of the E_+ and E_- waves can be ignored along the interaction length, $p = 0$, in the case of nonoverlapping pulses in the medium; the quantity $p = 1$ characterizes the relative contribution of the fast nonlinearity mechanism in n_2, as compared with the frequency shift of the E_+ and E_- waves. The nonsymmetry of the nonlinear polarizations in (1) and (2) is due to parametric wave excitation, which is important if a periodic modulation of the refractive index due to interference of the waves can be established. The equations for E_+ and E_- are identical for $p = 1$ [see (1) and (2)]; therefore, if $E_- = RE_+^*$ even if in one plane, say, at the exit from the nonlinear medium, then this equality is satisfied in all planes, including the entrance to it. Thus, if E_- occurs as a result of WFI, the nonlinear distortions are completely compensated for any R. For $p \neq 1$ (in particular, for $p = 0$ and for $p = 2$) this symmetry of the equations exists only for complete inversion of the wave front with $R = 1^2$. The symmetry of Eqs. (1) and (2) for $R = 1$ can qualitatively explain the restoration of the image due to an increase of the pump power (Fig. 3c); here, however, the stability of the complete nonlinear distortion compensation regime in the presence of a deviation in R and reproduction from unity must be proved.[3] Since most of the beam energy behind the grating is contained in the zero order, the system of equations (1) and (2) can be linearized with respect to small perturbations u and v introduced into E_+ and E_-, respectively, which in turn can be replaced by plane waves for $B \sim 1$ and $kL/a^2 \ll 1$. In this case each plane component of the perturbations $\propto \cos \vec{\kappa} r_\perp$ or $\sin \vec{\kappa} r_\perp$ develops independently. The fundamental difference from known formulations[6,7] of the problem lies in the specific relationship between perturbations of the forward and backward waves that arrive at the aperture of the device for the WFI (the BM in our experiment):

$$\mathbf{v}(L) = M\mathbf{u}(L) + \mathbf{N} \quad (3)$$

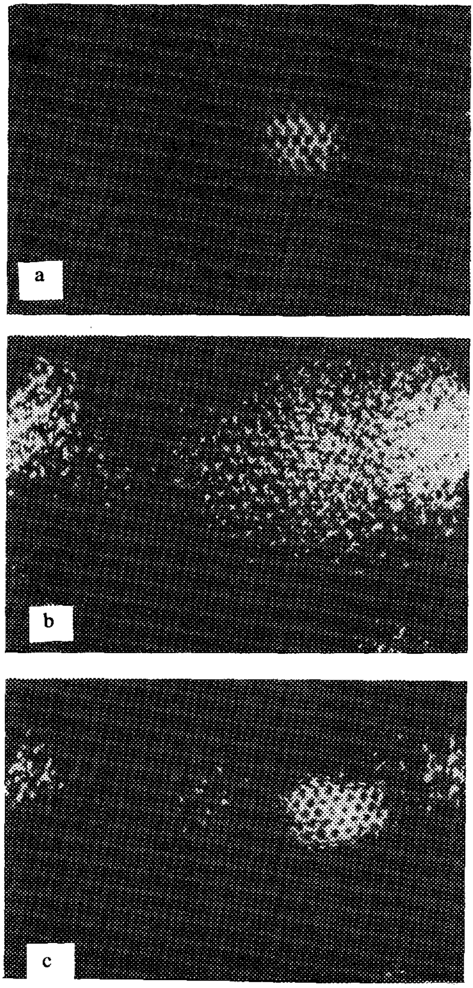

FIG. 3. Dependence of the grating image structure in the near zone on the pumping intensity and reflection coefficient of BM. a, Pumping intensity $W_L = 5.6$ MW, decomposition integral $B = 0.2$, BM reflection coefficient $R \approx 0.22$; b, $W_L = 12.6$ MW, $B = 0.5$, $R \approx 0.35$; c, $W^L = 17$ MW, $B = 0.7$, $R \approx 0.9$.

Here the real and imaginary parts of the perturbations are represented in the form of two-component vectors. The matrix $M = \left[\begin{smallmatrix}\alpha & 0\\ 0 & -\alpha\end{smallmatrix}\right]$ describes the reflection from the BM[4]. The vector **N** describes the rescattering of perturbations that do not enter the BM aperture in a given plane component, as well as the perturbations that appear because of imprecise reproduction in the BM. As a result of solving the linearized Eqs. (1) and (2) with the boundary condition (3), $\mathbf{v}(0)$ is expressed in terms of $\mathbf{u}(0)$ and **N**. At $M = 0$ the answers are the same as those in Ref. 7; however, at $M \neq 0$ the results differ significantly. At $\mathbf{N} = 0$ and $\alpha = R = 1$ we obtain the relation $\mathbf{v}(0) = \mathbf{u}^*(0)$, which follows directly from the symmetry of (1) and (2). The linearized equations (1) and (2) have an additional symmetry at $R \neq 1$ and $\alpha = \alpha_0 = [(1 + R^2)^2 + 4(p^2 - 1)R^2 + R^2 - 1]^{1/2}/2pR$, so that $\mathbf{v}(0) = \alpha_0 \mathbf{u}^*(0)$, regardless of the transverse structure of $\mathbf{u}(0)$, which allows us to fully compensate for the small distortions even when $R \neq 1$. In studying the stability of both compensation regimes, whose details will be published separately, the evolution of small-angle perturbation[7] $(\kappa/k)^2 \sim n_2|E|^2$ must be distinguished from that of the wide-angle perturbation $(\kappa/k)^2 \gg n_2|E|^2$. For wide-angle components the stability region of the complete compensation regime in the least favorable situation $2B = \pi/p$ (corresponding to self-excitation of the bucking waves[6]) can be estimated from the asymptotic $[(1-R) \ll 1]$ expression $\mathbf{v}(0) \backsim N\{[(1-R)/p] + \alpha\}^{-2}$.

Even for $R = 1$ the presence of a finite reproduction prevents self-excitation.[5] For the small-angle components the requirements for reproduction are more stringent. At $R = \alpha_0$ the inequality $|\alpha - \alpha_0| \lesssim e^{-(p+1)B}$ must be satisfied in order to prevent the distortions from increasing significantly and to eliminate self-excitation.

We note that in a multichannel laser system consisting of amplification stages and beam-splitting schemes it is apparently possible, as follows from the results obtained by us, to compensate nonlinear distortions by means of WFI, for example, while maintaining the average power level along the path of each beam. In fact, if the nonlinear distortions in each state are small then the gain coefficient can be averaged along the beam path, and the compensation for the distortion will be similar to that in our experiment. Large reflection coefficients apparently can also be achieved through nonresonance, four-photon inversion of the wave front, since it was shown to be possible to supress self-excitation of the bucking waves that prevents their realization.

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1) The results of this work were first reported at the All-Union Conference "Laser Optics 80", Leningrad, January 3–7, 1980.

2) The symmetry of Eqs. (1) and (2) in a linear medium ($n_2 = 0$) in connection with the WFI problem was pointed out in the pioneer paper.[5]

3) This symmetry is preserved when the terms, which describe amplification of the Stokes wave E_- (and attenuation of the pumping wave E_+) due to stimulated scattering ($\pm ikg|E_{\mp}|^2E_{\pm}$), are taken into account.

4) The quantities α and R can be controlled independently by using in addition to any, say, four-photon WFI scheme, the linear amplifiers or attenuators of the different angular components and at the same time achieve the regime.

5) The bright spots in Fig. 3c apparently are due to self-excitation of the perturbations that do not enter the BM aperture.

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