COMPENSATION FOR PHASE DISTORTIONS WITH A STIMULATED BRILLOUIN SCATTERING MIRROR

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The effect of a stimulated Brillouin scattering PC mirror on the quality of compensat ion for phase distort ions of a laser beam has been investigated numerically and experimentally. The character of the angular spectrum distort ions has been analyzed in the case of phase conjugation with a stimulated Brillouin scattering mirror. It has been shown that the distorting factors that influence on the reversed wavefront wave, namely, diffract ion by the aperture of the mirror of limited radius and limited accuracy of phase conjugation due to stimulated Brillouin scattering are interdependent. We established that in the case in which the stimulated Brillouin scattering mirror has a constant radius, the parameter for the correct ion accuracy decreases when the distance between the phase distorting medium and this mirror increases. This effect is observed for complete and partial intercept ion for a beam incident on the mirror.

The use of phase conjugation mirrors for correction of phase distortions of laser beams propagating through the atmosphere is one of the promising subfield in the atmospheric adaptive optics.[1–4] The quality of compensation for phase distortions using phase conjugation may significantly deteriorate due to lack of information on the reversed wavefront wave. The character of distortions of the spatial spectrum of the reversed wavefront wave has been studied experimentally in Ref. 5 with an account of the aperture losses in a PC mirror fabricated using the phenomenon of nonthreshold reflection by the Brillouin nonlinearity. The effect of the PC mirror radius on the correction accuracy of phase distortions of an optical beam propagating through a randomly inhomogeneous medium was theoretically studied in Refs. 1, 6, and 7. In these papers it was assumed that within a limited mirror area the phase conjugation was ideal. The results of Refs. 5–7 implied, in particular, that with increase of the beam divergence induced by a phase distorting medium, the correction accuracy with a PC–mirror of limited radius deteriorates. Mirrors more often used to compensate for phase distortions are those in which the phase conjugation is observed in stimulated Brillouin scattering of a beam focused on optically active medium (the so–called stimulated Brillouin scattering mirrors). The phase conjugation then obtained significantly differs from the expected one according to the studies performed in Refs. 1 and 5–7.

The present paper describes the numerical simulations and experimental measurements of the effect of the radius of stimulated Brillouin scattering mirror on the quality of compensating for phase distortions of an optical beam.

MATHEMATICAL SIMULATION

We modeled the propagation of the initially Gaussian pump beam along the z axis. The beam was incident on an inhomogeneous medium located at $z = z_1$. It was assumed that the medium takes the form of a phase screen with the transparency coefficient $e^{i\varphi}$, where φ is the phase change. The beam after passage of the phase screen propagated through the free space in the region $z_1 < z < z_2$. At $z = z_2$ the beam was transmitted through the receiving aperture of the PC mirror and focused with an ideal lens on the nonlinear medium. That medium was located at $z_2 < z \le z_3$. Stimulated Brillouin scattering was excited in this region. The Stokes wave propagated in a direction opposite to the pump wave.

The system of equations for the complex amplitudes of pump waves A_{pump} and the Stokes component A_s that takes into account only the transverse coordinate x in the Cartesian coordinates (x, z) takes the form

$$\left[2ik_0 \frac{\partial}{\partial z} - \frac{\partial^2}{\partial x^2}\right] A_{pump} = 0, \quad 0 \le z \le z_2, \tag{1}$$

$$\left[2ik \frac{\partial}{\partial z} - \frac{\partial^2}{\partial x^2}\right] A_{pump} = 0, \quad z_2 < z \le z_3, \tag{2}$$

$$\left[2ik \frac{\partial}{\partial z} + \frac{\partial^2}{\partial x^2} + ikg|A_{pump}|^2\right] A_S = 0, \quad z_2 < z \le z_3, \tag{3}$$

$$\left[2ik_0 \frac{\partial}{\partial z} - \frac{\partial^2}{\partial x^2}\right] A_S = 0, \quad 0 \le z \le z_2, \tag{4}$$

where $\kappa_0 = 2\pi/\lambda$ is the wave number in vacuum, λ is the radiation wavelength, $\kappa = \kappa_0\sqrt{\varepsilon}$ is the wave number in the active medium, ε is the dielectric permittivity of this medium, and g is the amplification coefficient due to the stimulated Brillouin scattering. The complex amplitude distribution of the initially Gaussian beam at $z = 0$ takes the form:

$$A_{pump}(x, 0) = \sqrt{I_0}\,\exp(-2x^2/a_0^2), \tag{5}$$

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where a_0 and I_0 are the effective radius of the beam and the axial intensity of the beam.

The functions $A_{pump}(x, z)$ and $A_s(x, z)$ at points $z = z_1$ and $z = z_2$ undergo discontinuity and can be represented in the form:

$$A_{pump}(x, z_1) = A_{pump}(x, z_1 - 0)\ \exp(i\varphi), \tag{6}$$

$$A_S(x, z_1) = A_S(x, z_1 + 0)\ \exp(i\varphi), \tag{7}$$

$$A_{pump}(x, z_2) = A_{pump}(x, z_2 - 0)\ f(x)\ \exp\left[ik_0 \frac{x^2}{2z_f}\right], \tag{8}$$

$$A_S(x, z_2) = A_S(x, z_2 + 0)\ f(x)\ \exp\left[ik_0 \frac{x^2}{2z_f}\right], \tag{9}$$

The value z_f in Eqs. (8) and (9) denotes the focal length, and $f(x)$ is the transmission of the receiving aperture of the PC mirror. In what follows this function is taken in the form $f(x) = \exp[-(2x/b)^{-10}]$, where b is the effective radius of the receiving aperture.

The Stokes component, which is induced by noise, may be taken at $z = z_3$ to be

$$A_s(x, z_3) = \tilde{A}\,(x), \tag{10}$$

where $\tilde{A}$ is a random field. The standard deviation of $|\tilde{A}\,|$ (i.e., the seed signal for the Stokes component) is

$$\sigma = 10^{-m}\sqrt{I_0}, \tag{11}$$

where m is approximately 4–6.[8,9]

The system of equations (1)–(4) with boundary conditions (5)–(10) was solved numerically for a specific model of the phase screen[10] of the form $\varphi = \varphi_0 \cos(2\pi x/d)$, where φ_0 is the degree of modulation of the optical path, and d is the period of the regular phase grating. Our computations were made for the following parameter values of pump radiation: wavelength $\lambda = 1.06$ μm and the initial beam radius $a_0 = 0.6$ cm. The focal length $z_f = 12$ cm. The rest of the parameters of the problem were varied. The complex amplitude distributions of the pump wave $A_{pump}(x, z)$ and the Stokes component $A_s(x, z)$ were computed along with the angular spectra of the functions $A_{pump}(x, z)$ and $A_s(x, z)$

$$F_{pump}(k_x, z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} A_{pump}(x, z)\ \exp(-ik_x x)\ dx, \tag{12}$$

$$F_S(k_x, z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} A_S(x, z)\ \exp(-ik_x x)\ dx, \tag{13}$$

as well as the accuracy parameters W_2/W_1 for correction of the phase distortions with the stimulated Brillouin scattering mirror, where W_1 is the total energy of the Stokes component, and W_2 is the portion of the energy which has passed through the phase screen within a diffraction angle of the initial pump beam.

The squared moduli of the angular spectrum of the pump radiation and of the Stokes component, normalized by their peak values, are shown in Fig. 1 computed in the plane of the receiving aperture of the PC mirror. The component of the angular vector κ_x normalized to the width of the pump beam angular spectrum κ_0 at $z = 0$ is plotted on the horizontal axis and the normalized squared moduli of the angular spectrum are plotted on the vertical axis. Two cases are considered: complete interception of the pump radiation by the mirror with aperture of radius $b = 20$ cm (Fig. 1*a*), and when only a certain portion of radiation falls within the mirror of $b = 0.3$ cm (Fig. 1*b*). The distance between the phase screen and the plane of the receiving aperture is $\rho_0 = z_2 - z_1 = 50$ cm. The period of the phase grating is $d = 150$ μm, and the degree of modulation is $\varphi_0 = 1$. The squared modulus of the angular spectrum of pump radiation is shown by curve 1 in Figs. 1*a* and *b* before the radiation passage through the receiving aperture of the mirror. Curve *2* in Fig. 1*b* shows the same function after the radiation has passed through the receiving aperture of the mirror in the region between this mirror and the lens. Curve *3* shows the normalized squared modulus of the angular spectrum of the Stokes component after radiation passage of the lens in the region between the lens and the receiving aperture and, finally, curves *4* in Figs. 1*a* and *b* show this function after the radiation passage through the aperture.

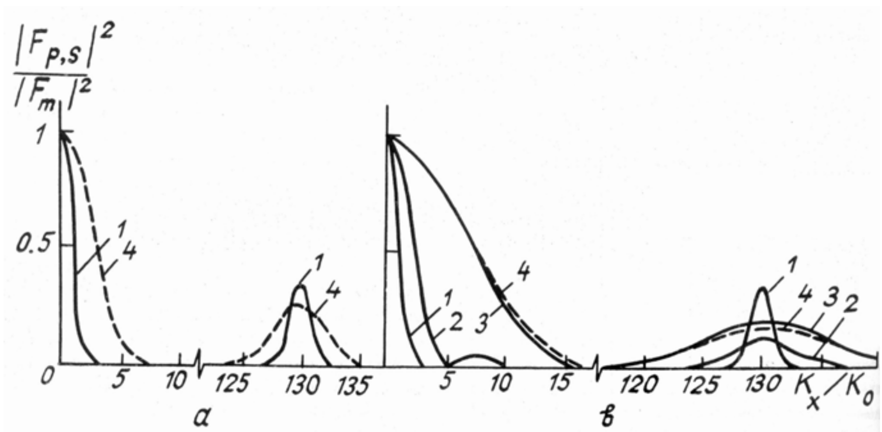

FIG. 1. Normalized squared moduli of the angular spectra: 1, 2) the pump radiation and 3, 4) the Stocks component. b = 20 cm (a) and 0.3 cm (b).

After passage of the phase screen, the beam falling within the PC mirror comprises two components: the unscattered and scattered (curves *1*). It can be clearly seen from Fig. 1*a* that even without aperture losses, the stimulated Brillouin scattering can not completely reconstruct the angular spectrum of radiation incident on it. Both intervals of the angular spectrum of reflected radiation corresponding to the scattered and unscattered fractions of the pump beam, are broadened. In the case in which only a certain fraction of the incident radiation is intercepted by the mirror (Fig. 1*b*), the spectra of the scattered and unscattered parts of the beam (curve *2*, Fig. 1*b*) are broadened because of the diffraction of pump wave by the mirror aperture. The corresponding parts of the angular spectrum of the Stokes component become even wider (curve *3*, Fig. 1*b*). When the reflected beam passes through the diaphragm, its angular spectrum remains practically unchanged (curve *4*, Fig. 1*b*), because this beam is narrower than the diaphragm opening. Finally, the decrease of the radius of the stimulated Brillouin scattering mirror results in a deterioration of the reconstructed angular spectrum of incident radiation, and the accuracy of correlation of phase distortions becomes lower.

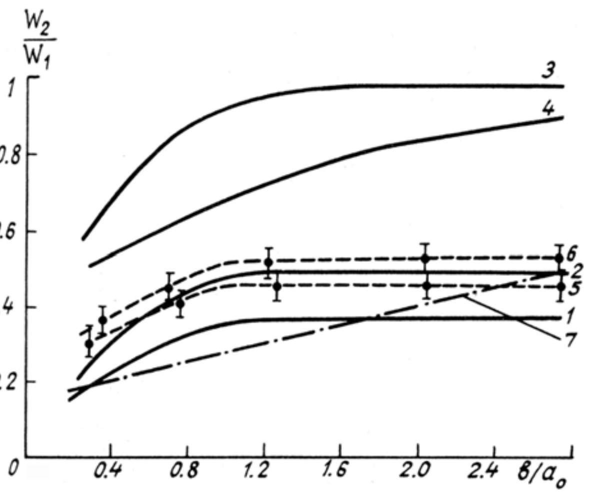

FIG. 2. Dependence of the correct ion–accuracy parameter on the normalize radius of the receiving aperture of the mirror for fixed φ_0 *and* ρ_0 *and different d. 1–4, 7) computations and 5, 6) experiment.*

Curves *1–4* of Fig. 2 show the computed dependences of the correction-accuracy parameter on the radius of the receiving aperture of the PC mirror normalized to the initial radius of the beam. The degree of phase modulation φ_0 and the distance between the phase screen and the mirror are the same as in Fig. 1. The period of the phase grating d was equal to 150 μm (curves *1* and *3*) and 60 μm (curves *2* and *4*). Curves *1* and *2* correspond to the phase conjugation in stimulated Brillouin scattering of the focused beams. They are obtained from the numerical solution of system (1)–(4) for $0 \le z \le z_3$. Curves *3* and *4* are obtained from the numerical solution of Eqs. (1)–(4) for $0 \le z \le z_2$ on the assumption of ideal phase conjugation within a limited area of the mirror: $A_s(x, z_2) = f(x)A_{\text{pump}}(x, z_2)$.

It can be seen from Fig. 2 that in stimulated Brillouin scattering of the focused beams and the ideal stimulated Brillouin scattering the correction–accuracy parameter decreases when the aperture radius decreases for a fix period of the phase grating. If the aperture radius of the mirror is fixed, stimulated Brillouin scattering of the focused beams may result in greater parameter for the correction accuracy for shorter period of the phase grating. However, this parameter decreases for ideal phase conjugation. The parameter W_2/W_1 is greater for phase conjugation achieved by the ideal mirror than by the mirror of the same radius in stimulated Brillouin scattering of the focused beam.

The results shown in Fig. 2 may be explained by the fact that for shorter period of the phase grating the number of inhomogeneities in the beam incident on the mirror increases, so that its "gray" divergence becomes larger. This effect results in decreasing of the compensation quality of phase distortions by a mirror of a limited radius during ideal phase conjugation,[6] while in the stimulated Brillouin scattering of the focused beams it would reduce the "snake–like" distortions of the inverse waves, so that the compensation quality would be increased.[9]

Two distorting factors affect the inverse wave formed by the stimulated Brillouin scattering mirror of a limited radius: the diffraction by a limited aperture of the mirror and the distortions due to the limited accuracy of phase conjugation in stimulated Brillouin scattering because of nonideal phase conjugation. If these two factors independently affect the inverse wave, the correction–accuracy parameter W_2/W_1 of the stimulated Brillouin scattering PC mirror of limited radius would be equal to the product K_1K_2, where $K1$ is the correction–accuracy parameter for an ideal PC mirror of the same radius, and K_2 denotes the correction–accuracy parameter for the stimulated Brillouin scattering in the case of complete interception of incident radiation. Curve *7* in Fig. 2 shows the dependence of the product K_1K_2 on b/a_0 for the case corresponding to curve *2* ($\rho_0 = 50$ cm, $\varphi_0 = 1$, and $d = 150$ μm). It can be seen that curves *2* and *7* do not coincide. Therefore, the two above–indicated distorting factors cannot be considered independently.

Figure 3*a* shows the computed dependences of the correction–accuracy parameter on the radius of the receiving aperture of the stimulated Brillouin scattering mirror normalized to the initial beam radius for various degree of phase modulation φ_0 (curves *1*, *2*). Curve *1* corresponds to $\varphi_0 = 1$ and curve *2* — to $\varphi_0 = 0.2$. The distance between the phase screen and the mirror and the period of the phase grating were fixed: $\rho_0 = 50$ cm and $d = 60$ μm. It can be seen from the figure that the correction–accuracy parameter increases with decrease of the degree of modulation for fixed values of ρ_0, d, and b.

Figure 3*b* shows the computed dependences of the correction-accuracy parameter on the radius of the receiving aperture of the stimulated Brillouin scattering mirror for different distances betweeif the phase screen and the mirror (curves *1* and *2*). Curve *1* corresponds to $\rho_0 = 50$ cm and curve *2* — to $\rho_0 = 0.2$ cm. The degree of phase modulation φ_0 and the period of the phase grating are fixed: $\varphi_0 = 1$ and $d = 60$ μm. It can be distinctly seen that the correction-accuracy parameter increases with decrease of the screen–to–mirror distance for fixed values of the parameters φ_0, d, and b. The computations showed that this increase is important for $z < z_k = \kappa_0 d^2$, where z_k is the longitudinal scale of inhomogeneities in the pump field after it has passed the phase screen.

The results presented above remain practically unchanged when the "seed" signal σ changes. Thus, while the parameter m in Eq. (11) changes from 4 to 6, the relative change in W_2/W_1 is not more that 5%.

EXPERIMENT

Variations in the parameter of the correction of distortions induced in the beam by different phase plates were measured with the stimulated Brillouin scattering PC mirror.

The experimental arrangement is shown in Fig. 4. A single–mode beam from a neodymium laser *1* (wavelength $\lambda = 1.06$ μm, pulse duration at half maximum 40 ns, energy up to 1 J, beam diameter 0.6 cm) passed through the phase plate *2* and then, after its propagation through the free space, fell on the PC mirror. The mirror aperture was varied with the help of the aperture diaphragm *3*, positioned in front of the lens *4*. This lens had a focal length 12 cm and was used to focus the beam on a cell *5* containing carbon tetrachloride, where the stimulated Brillouin scattering was excited. A length of the cell was 25 cm. The total beam energy W_1 was measured by the calorimeter *6* after reflection from the stimulated Brillouin scattering mirror. Another calorimeter *7* in combination with the diaphragm *8* measured the energy W_2 of radiation reflected from the stimulated Brillouin scattering mirror and passed through the phase plate within the nearly diffraction limited angle. The ratio of energies $W_2/W1$ is the parameter for the correction accuracy.

Figure 2 shows the experimentally obtained dependences of the correction-accuracy parameter on the aperture radius of the stimulated Brillouin scattering mirror normalized to the initial beam radius (curves *5* and *6*) for phase plates with different average transverse sizes of inhomogeneities. The average transverse sizes of such inhomogeneities for curves *5* and *6* were approximately equal to the periods of the phase gratings for curves *1* and *2*. The distance between the phase, plate and the stimulated Brillouin scattering mirror as well as the average degree of phase modulation were fixed: they were the same as for curves *1* and *2*. The experimental curves *5* and *6* lie close to curves *1* and *2* obtained by numerical solution of system of equations (1)–(4).

Curves *3* and *4* in Fig. 3*a* show the experimental dependences of the correction-accuracy parameter on the normalized receiving aperture radius of the stimulated Brillouin scattering mirror for different phase plates modulating the phase to different degree. Such average degree of modulation for curves *3* and *4* is approximately equal to that for curves *1* and *2*. The distance between the phase plate and the stimulated Brillouin scattering mirror as well as the average size of inhomogeneities are fixed: they are the same as those for curves *1* and *2*. Figure 3*a* makes evident a satisfactory agreement between the experimental and the numerically obtained results.

Figure 3*b* compares the experimental (curves *3* and 4) and the theoretical (curves *1* and *2*) results. It shows the dependences of the correction-accuracy parameter on the normalized effective radius of the stimulated Brillouin scattering mirror for different distances between the phase plate (the phase screen) and the mirror. For curves *3* and *4* the average transverse size of inhomogeneities and the average degree of modulation are fixed: they are the same as those for curves *1* and 2. It is seen from Fig. 3 that the experimental results agree with the theoretical.

Thus, both experimental and theoretical studies show that for fixed radius of the stimulated Brillouin scattering mirror the correction-accuracy parameter decreases when the degree of phase modulation of the incident radiation increases. The same effect takes place when the distance between the phase-distorting medium and the mirror increase. In contrast to the ideal phase conjugation[1,6,7] and the PC mirror fabricated using the scheme of nonthreshold reflection[5] the correction–accuracy parameter may increase for fixed radius of the mirror in which phase conjugation is achieved in stimulated Brillouin scattering of the focused beam with increase of the incident radiation divergence within a certain interval. The distorting factors affecting the Inverse wave (diffraction by a limited mirror aperture and limited accuracy of phase conjugation in stimulated Brillouin scattering) are interdependent.

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