USING A STIMULATED BRILLOUIN SCATTERING PC MIRROR TO CORRECT THERMAL BEAM DISTORTIONS IN A MOVING MEDIUM

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We carry out a theoretical and experimental study of the possibilities for using a PC mirror to compensate for distortions of pulsed-per iodic laser radiation in moving media due to thermal blooming. We show that the accuracy with which such distortions can be corrected decreases as the characteristic amount of thermal blooming decreases, while the pulse-to-pulse scatter in the values of the parameter for the correction accuracy at a given average radiation power increases as the pulse repetition rate increases.

The technique generally suggested for reducing - the distortion of laser beams in the Earth's atmosphere involve phase correction with controllable flexible or segmented mirrors.[1–3] It was later suggested that mirrors using the phenomenon of phase conjugation in nonlinear media (PC mirrors) be used for this purpose.[4–S] The advantages of such mirrors over segmented or flexible mirrors lies in their speed and in the fact that they simultaneously correct the phase and the amplitude. The use of PC mirrors has only been discussed in terms of correcting relatively low-power light beams with no thermal blooming. In the present paper, we use numerical simulations and laboratory models to study the possibility of using a PC mirror to compensate for thermal distortions of radiation from a pulsed-periodic laser in a moving medium. We discuss the case where the duration of each individual pulse is small and we can assume that it is not subject to blooming effects — any distortions in the pulse are due to heating of the medium by passage of the preceding pulses. The phenomenon of phase conjugation in stimulated Brillouin scattering of beams focused on an active medium are used to carry out the correction.

1. MATHEMATICAL FORMULATION OF THE PROBLEM

We model the propagation of an interacting light beam affected by thermal blooming through an absorbing medium along the z axis (Fig. 1). The absorbing medium occupies the interval $0 \le z < L_1$. The z axis is directed opposite the direction of propagation for the interacting beam. The origin of the z axis lies in the plane where the beam emerges from the absorbing medium. The beam leaves the medium at $z = L_1$. A low-intensity tag beam not affected by the thermal blooming in the medium was propagated opposite the interacting beam. At the entrance to the absorbing medium ($z = 0$), the tag beam had a planar wavefront and a Caussian intensity distribution. The wavefront of the tagging beam became distorted in the medium due to inhomogeneities in the index of refraction which were induced by the interacting wave. The revesred wavefront wave was produced by passing the tagging beam through absorbing medium (1) and amplifier (2), and then focussing it on active medium (4) (located at $L_2 \le z \le L_3$) with lens (3). Stimulated Brillouin scattering was excited in this region. The main beam propagated in a direction opposite the tagging beam, which suffered the effects thermal blooming in the absorbing medium after passing through the amplifier. The interacting beam was assumed to be a Stokes component after passage through linear amplifier (2). Further, the radiation in the region $L_1 \le z \le L_2$ was assumed to be affected by only the amplifier and the lens, and this section was assumed to be much smaller than L_1 and $L_3 - L_2$.

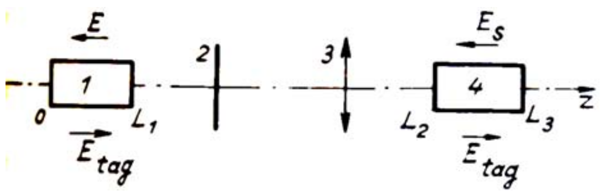

FIG. 1. Diagram illustrating the directions of propagation for the various waves.

The complex amplitude E of the interacting wave for $0 \le z \le L_1$ is given by the following equations:

$$\left[2ik_1 \frac{\partial}{\partial z} + \Delta_\perp + \frac{k_1^2 \Delta\varepsilon_1}{\varepsilon_1} + ik_1\alpha\right] E = 0, \quad (1)$$

$$\Delta\varepsilon_1 = \frac{d\varepsilon_1}{dT} T, \quad (2)$$

where $\Delta_\perp$ is the Laplacian in the plane $z = \text{const}$; $k_1 = k_0\sqrt{\varepsilon_1}$ is the wave number in the absorbing me-

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dium; $k_0 = 2\pi/\lambda$ is the wave number in vacuum; λ is the wavelength in vacuum; ε_1 is the dielectric permittivity of the unperturbed medium; α is the absorption coefficient of the medium; $\Delta\varepsilon_1$ and ΔT are the change in the dielectric permittivity of the medium and the change in the temperature of the medium, respectively, due to blooming. In the case where we have a series of short pulses and the duration of the individual pulses $t_{\rm pulse}$ is much shorter than the time interval between pulses Δt, the change in the temperature of the medium T after passage of N pulses will be given by the following expression[6]:

$$T(x, y, z, N\Delta t) = \frac{\alpha t_{\rm pulse}}{\rho C_p} \sum_{j=0}^{N-1} |E[x - V(N - j)\Delta t, y, z]|^2, \quad (3)$$

where V is the velocity (directed along the x axis) at which the medium moves; ρ and C_p are the density and heat capacity of the medium, respectively.

The propagation of the tag wave, which has complex amplitude $E_{\rm tag}$ in the absorbing medium (for $0 < z < L_1$) is described by the following equation:

$$\left[2ik_1 \frac{\partial}{\partial z} - \Delta_\perp - \frac{k_1^2 \Delta\varepsilon_1}{\varepsilon_1} + ik_1\alpha\right] E_{\rm tag} = 0. \quad (4)$$

When the feedback effect of the Stokes component of the oncoming wave on the tag wave is neglected, the propagation of these waves for $L_2 \le z \le L_3$ in the stationary case is described by the following equations[4]

$$\left[2ik_2 \frac{\partial}{\partial z} - \Delta_\perp\right] E_{\rm tag} = 0, \quad (5)$$

$$\left[2ik_2 \frac{\partial}{\partial z} + \Delta_\perp - ik_2 G |E_{\rm tag}|^2\right] E_s = 0, \quad (6)$$

where E_s is the complex amplitude of the Stokes component wave; $k_2 = k_0\sqrt{\varepsilon_2}$ is the wave number in the active medium for the PC mirror, ε_2 is the dielectric permittivity of this medium, and G is the amplification coefficient due to stimulated Brillouin scattering.

The complex amplitude of the interacting beam as the pulse passes the point $z = L_1$ takes the following form on the time interval $0 < t < t_{on}$, where t_{on} is the time at which the mirror is turned on:

$$E(x, y, L_1) = \sqrt{I_0} \exp\left[-\frac{x^2 + y^2}{2a_0^2}\right], \quad (7)$$

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

The complex amplitude of the interacting wave for each pulse (taking the lens and amplifier into account) in the "on" mode ($t > t_{on}$) is assumed to be given by

$$E(x, y, L_1) = KE_S(x, y, L_2) \exp\left[\frac{ik_0(x^2 + y^2)}{2z_f}\right], \quad (8)$$

where $E_S(x, y, L_2)$ is the solution to Eq. (6) at $z = L_2$, K is the amplification coefficient of the linear amplifier, and z_f is the local length of the lens. The value of K for each pulse is selected so that the pulse energy would be identical to the energy of the pulse before the PC mirror was turned on:

$$t_{\rm pulse} \iint_{-\infty}^{+\infty} K^2 |E_S(x, y, L_1)|^2 dxdy = t_{\rm pulse} \pi I_0 a_0^2 . \quad (9)$$

Equations (7) and (8) are the initial conditions for Eq. (1). For Eq. (4), the initial complex amplitude distribution of the tag beam (at $z = 0$) for each pulse is specified in the following form:

$$E_{\rm tag}(x, y, 0) = \sqrt{I_N} \exp\left[-\frac{x^2 + y^2}{2b_0^2}\right], \quad (10)$$

where I_N and b_0 are the initial axial intensity and the effective radius, respectively. It will hereinafter be assumed that $b_0 = a_0$. The initial condition for Eq. (5) at $z = L_2$ taking the lens and amplifier into account takes the following form:

$$E_{\rm tag}(x, y, L_2) = KE_{\rm tag}(x, y, L_1) \exp\left[\frac{ik_0(x^2 + y^2)}{2z_f}\right], \quad (11)$$

where $E_{tag}(x, y, L_1)$ is the solution to Eq. (4) for $z = L_1$. Equation (6) for the Stokes-component wave was solved under the condition

$$E_s(x, y, L_3) = \tilde{E}(x, y), \quad (12)$$

where $\tilde{E}$ is a random field. The standard deviation or (the seed signal for the Stokes component) is equal to $10^{-n}\sqrt{I_0}$, where n is approximately 4–6.[4]

System of equations (1)–(6) with the boundary conditions given above was solved numerically. The complex amplitude distributions of the interacting beam $E(x, y, z)$, the tag beam $E_{tag}(x, y, z)$, and the Stokes component $E_S(x, y, z)$ were calculated for each pulse, along with the angular spectrum

$$F(k_x, k_y, z) = \frac{1}{(2\pi)^2} \iint_{-\infty}^{+\infty} E(x, y, z) \times \exp[-i(k_x x + k_y y)] dxdy. \quad (13)$$

The parameter describing the correction accuracy

$$H = \frac{W_2}{W_1} = \frac{\iint\limits_{k_x^2 + k_y^2 \le k_d^2} \left|F(k_x,\ k_y,\ 0)\right|^2 dk_x dk_y}{\iint\limits_{-\infty}^{+\infty} \left|F(k_x,\ k_y,\ 0)\right|^2 dk_x dk_y}, \tag{14}$$

[where W_1 is the total energy in the pulse of interacting radiation upon exiting the absorbing medium, W_2 is radiation energy contained within a certain diffraction angle, and k_d corresponds to the diffraction angle for the initial interacting beam (7)] was then calculated.

We also calculated the squared moduli of the angular spectra [normalized to their peak values $B(z)$]:

$$A(k_x,\ k_y,\ z) = \frac{|F(k_x, k_y, z)|^2}{B(z)}. \tag{15}$$

2. LABORATORY MODELING

When the pulse repetition rate for identical short pulses passing through an absorbing medium heated by these pulses is sufficiently high, we can assume that each pulse in such a regime propagates in the index-of-refraction field that would be induced by a beam of continuous radiation with a power equal to the mean power of the sequence of pulses.[7] In the case of a moving medium, this statement is valid as long as the number of pulses generated in the time required for the wind flow to pass through the beam cross section ($t_V = a_0/V$), N_V, is much greater than 5 and the pulse train has duration much greater than t_V. Under these conditions, the problem of the propagation of radiation from a pulse-periodic laser under thermal blooming conditions reduces to that of the propagation of a single pulse through the index-of-refraction field induced by continuous radiation with the same mean power as the sequence of pulses. Once the PC mirror is turned on, the characteristics of the interacting radiation (its phase and amplitude distribution) and the characteristics of the absorbing medium may vary quite strongly from pulse to pulse. Thus, replacing the pulsed-per iodic radiation with continuous radiation is valid before the PC mirror is turned on, and this simplification only yields the correct result for the first pulse after the mirror is turned on.

Our laboratory modeling of the compensation of thermal distortions in pulsed-periodic laser emission using a PC mirror were carried out under the conditions described above. The experimental setup is shown in Fig. 2. After passage through beamsplitter 2 (with coefficient of reflection 20%), the continuous (interacting) radiation from an argon laser (1) (wavelength 0.48 μm, beam diameter 5 mm, power 0–0.8 W) was then directed into a cell (3) which simulated a moving absorbing atmosphere. This cell was mounted on a reversible dolly and could be moved perpendicular to the beam. The cell was filled with fuchsine-dyed ethyl alcohol. The cell had a length L_1 = 30 cm in the direction of propagation; the velocity of motion V = 0.33 cm/s, and the absorption coefficient of the medium α = 0.04 cm^{-1}. The radiation power from the argon laser was monitored using mean-power meter 4. A similar power meter was used to measure the radiation power after passage through the absorbing medium.

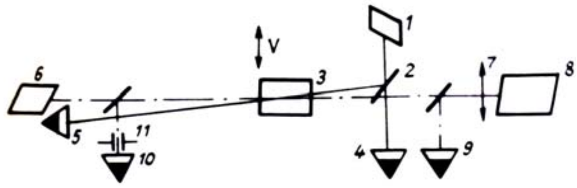

FIG. 2. Diagram showing the experimental configuration.

Absorption of the radiation from the argon laser in cell 3 and the resultant heating of the medium induced an inhomogeneous index-of- refraction field in the beam channel. A single-mode tag beam at the second harmonic of a pulsed neodymium laser (6) (wavelength 0.53 μm. maximum energy 0.3 J, pulse duration at half maximum 40 ns, beam diameter at entrance to medium 5 mm, and divergence $\Theta_d \approx$ 0.26 mrad) was introduced into the cell (3). The tag laser was located approximately 20 m from the cell (3). The radiation from this laser passes through the cell and becomes distorted in the index-of-refraction field induced by the radiation from the argon laser. A lens was then used to focus the radiation on a second cell (8) containing carbon tetrachloride. where stimulated Brillouin scattering was excited. The lens had a focal length of 12 cm. and the cell occupied the region from 7 cm to 20 cm.

The Stokes-component beam reflected by the PC mirror propagated in the opposite direction from the tag beam. The total energy of this beam before passing through the absorbing medium W_0, was measured using a calorimeter (9). A calorimeter (10) and diaphragm (11) were used in combination to measure the energy W_2 within an angle approximately equal to the diffraction angle (Θ = 0.28 mrad) of this beam after passing through the absorbing medium. The quantity $H = W_2/CW_0$ (where C is the transmission coefficient of the beamsplitter plate (2) and the cell containing the absorbing medium (3)) was used as an indicator of the accuracy to which the distortions in the radiation had been corrected. Each of the beams was photographed during the individual pulses. The image of the beams was recorded in the focal plane of a lens placed in a portion of the beam removed from various portions of the path using a beamsplitter plate.

3. RESULTS

The experiment and theoretical calculation were carried out using the following parameter values:

$L_1 = 30$ cm, $L_2 = 50$ cm, $a_0 = B_0 = 2.5$ mm, $z_f = 12$ cm, $\rho = 0.8$ g/cm^3, $C_P = 2.4$ J/g · deg; $\varepsilon_1 = 1.85$; $\varepsilon_2 = 2.1$; and $\left|\frac{d\varepsilon}{dT}\right| = 1.1 \cdot 10^{-3}\,\text{deg}^{-1}$. In the calculations, we assumed $\lambda = 0.5$ μm, and the mean power of the interacting beam at the entrance to the absorbing medium P, was varied from 0 to 0.6 W. The experiment was carried out with $0 \le P \le 0.16$ W.

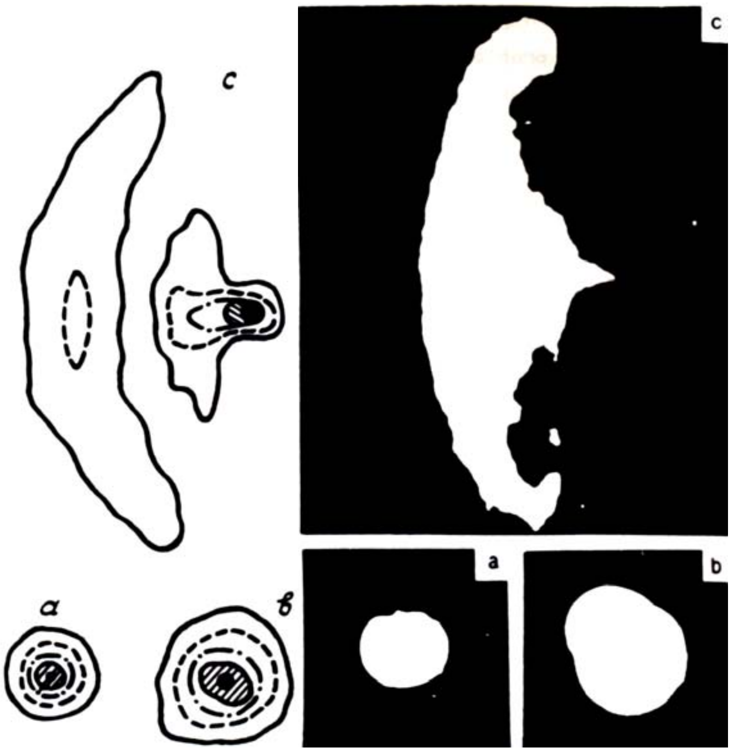

FIG. 3. Theoretical (left) and experimental (right) angular distributions of the radiation: (a) at the entrance to the medium; exit mirror; (c) with exit mirror.

In the experiments, the radiation energy reflected from the PC mirror was never any more than 25% of the energy of the incident pulse. No optical breakdown was observed in cell 8.

The right-hand panel of Fig. 3 shows pictures of the beams obtained in the focal plane of the lens; these photographs show the angular distribution of the probe beam at the entrance to the absorbing medium (a), the beam after being distorted by the medium (b), and the beam reflected by the PC mirror (Stoke component) after passage through the distorting medium (c). The corresponding theoretical distributions are Indicated by the isophotes in the left-hand panel. The calculations were carried out for the case where the number of pulse repetitions during the time required for the wind flow to pass through the beam cross section t_V, is large ($N_V = 10$).

The PC mirror was turned on at time $t = 3t_V$, i.e., after a steady-state regime had been established for propagation of the radiation. Figure 3 shows the observed situation for the first pulse after the mirror was turned on. The conditions for the calculation were identical to those for the experiment. The mean power of the interacting radiation at the entrance to the medium was assumed to be equal to $P = 0.16$ W. Figure 3 indicates that the distribution of the radiation reflected from the PC mirror was restored to nearly diffraction quality after passing through the distorting medium. The experimental and theoretical results are in agreement.

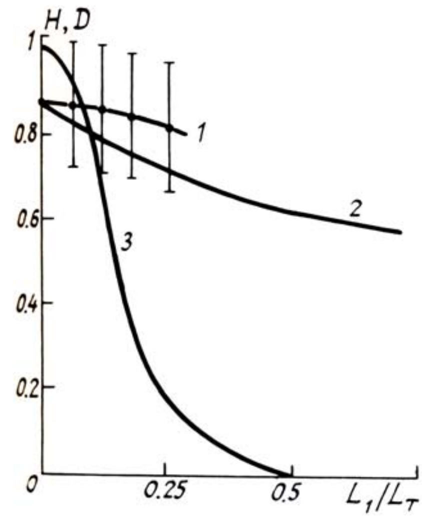

FIG. 4. Parameter H (which describes the accuracy of correction) and D as a function of L_1/L_T: 1) experiment; 2, 3) theory.

Figure 4 shows the experimentally (curve 1) and theoretically obtained (curve 2) curves for the correction-accuracy parameter H as a function of the ratio of the length of the distorting medium to L_1 the characteristic thermal blooming length[8]

$$L_T = \left[-\frac{1}{2\pi\varepsilon_1} \left|\frac{d\varepsilon_1}{dT}\right| \frac{\alpha P}{\rho c_p V a_0^3} \right]^{-1/2} . \quad (16)$$

The conditions for the experiments and calculations are the same as in Fig. 3, except that the mean power of the interacting beam P, was varied. Figure 4 shows the ratio D of the energy W_2 within the diffraction angle to the total radiation energy W_1 passing through the distorting medium in the case where the PC mirror was not used (curve 3). Figure 4 clearly indicates that the parameter describing the accuracy of correction H, is greater than the parameter D for $L_1/L_T \geq 0.1$.

The theoretical and experimental results agree with one another to within the accuracy of measurement. These results indicate that the accuracy of correction decreases as the thermal distortions (the degree of thermal distortion is determined by the characteristic thermal blooming length L_T, which becomes smaller as the thermal distortions increase) in the beam become more severe.

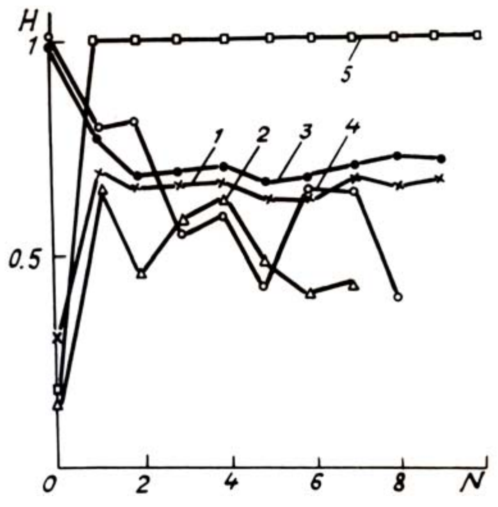

FIG. 5. Parameter H (which describes the accuracy of correction) as a function of pulse number N.

Figure 5 shows the curves obtained in the calculations for the accuracy of correction as a function of the number of pulses N. Curves 1–4 are for the case where the phase conjugation is carried out using stimulated Brillouin scattering of the focused beams; these curves were obtained by solving Eqs. (1)–(6) numerically for $0 \leq z \leq L_3$. Curve 5 was obtained by solving Eqs. (1)–(4) numerically for $0 < z \leq L_1$ in the case of ideal phase conjugation at the entrance to the absorbing medium, when $E(x, y, L_1) = kE^*_{tag}(x, y, L_1)$. Curves *1* and *3* are for the case where the number of pulse repetitions in the time required for the wind to travel across the beam is small ($N_V = 1$), while curves 2, 4, and 5 were obtained for a large number of pulse repetitions $N_V = 10$. The PC mirror was turned on either once the thermal blooming entered a steady-state regime $t_{on} = 3t_V$ (curves I, 2, and 5) or at the initial time t_0 (curves 3 and 4). In all of the cases, $P = 0.16$ W and $L_1/L_T = 0.25$. The remaining parameters in the calculation are the same as in Fig. 3.

Figure 5 indicates that in the case where the PC mirror is not ideal, the parameter describing the accuracy to which the thermal distortions are corrected may vary from pulse to pulse (curves 1–4). At fixed mean power, the scatter in the values for this parameter is larger for higher pulse repetition rates (curves 2 and 4). This result is independent of when the mirror was turned on, and is due to the fact that a portion of the perturbed medium is carried out of the beam between pulses when the velocity of the perturbed medium is finite and the pulse repetition rate is low. In this case, the thermal distortions of the medium are not as severe, and the pulse-to-pulse reproducibility of the parameter describing the accuracy of correction is higher than in the case of large pulse repetition rate.

So, the present paper contains the results of the first experimental and theoretical research on whether it is possible to use a PC mirror to compensate for thermal distortion of pulse-periodic laser radiation in a moving medium. We show that the accuracy with which such distortions can be corrected decreases as the characteristic thermal-blooming length decreases; at fixed mean radiation power, the pulse-to-pulse scatter in the values of the parameter describing the accuracy of correction increases as the pulse repetition rate increases.

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