Concentration of light by inverting its wavefront

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The principle of automatic focusing of light on a target is realized. A flat target of small diameter was illuminated with a ruby laser. The light from the target was amplified and then subjected to stimulated scattering with inversion of the wavefront. The scattered radiation, going through the amplifier in the backward direction, was practically entirely incident on the illuminated region, regardless of its position in space and regardless of the presence of aberrations in the optical elements.

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The concentration of laser radiation on a small area, which is essential for the performance of various physical investigations, is frequently a rather difficult problem. It is important to solve this problem, for example, for laser-induced thermonuclear fusion[1,2] and for laser acceleration of macroscopic particles.[3] The difficulties are connected here both with the smallness of the target and with the fact that the targets can be situated at different points in different experiments.

It is known that in stimulated scattering of light through an angle 180° its wavefront can become inverted.[4,5] This transformation of the wavefront corresponds to the return of all the rays to their source. The possibility of using this effect for target irradiation has been noted in the literature,[6,7] but no experiments of this kind have been reported to date. We have succeeded in concentrating laser radiation by inversion of the wavefront.

The principal elements of the experimental setup are shown schematically in Fig. 1. The mirror M_1 projects on a silvered mylar film an image of the screen S_1, reduced by a factor of 5.3. As a result, when one of the apertures made in the screen is illuminated, a circle of 190 μm diameter is illuminated on the film. When a second aperture is exposed to light, the illuminated region appears in another place on the film. Such a scheme is equivalent to placing isolated targets of the same diameter at different points of space and illuminating them in sequence with a broad beam.

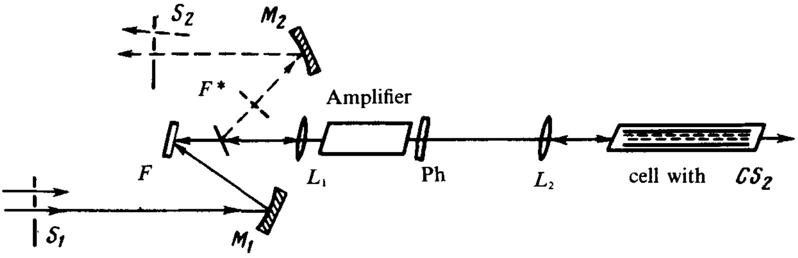

FIG. 1. Experimental setup: S_1 and S_2—indentical screens with four openings of 1 mm diameter; M_1—spherical mirror with curvature radius 41 cm and reflection coefficient 98%; F—mylar film 15 μm thick with silver coating 2 mm thick deposited on the far side relative to the mirror; L_1—lens of focal length 30 cm, distance from film to lens 25 cm; amplifier—ruby crystal 23 cm long and 12 mm in diameter, with end faces inclined at an angle 4°; Ph—inhomogeneous phase plate 1.3 mm thick with transverse dimension of inhomogeneities $\sim 150\,\mu$m; L_2—lens with focal length 50 cm; the cell filled with carbon disulfide is 103 cm long and its windows are inclined 20°; the length of the quartz light pipe in the cell is 100 cm and its inside diameter is 3 mm; F^* is the plane conjugate to the surface of the mylar film; M_2 is a spherical mirror with curvature radius 30 cm; the beam incidence angles on the mirrors M_1 and M_2 do not exceed 3°.

The light from the target is amplified and subjected to scattering with inversion of the wavefront. Therefore the backscattered radiation, after going through the amplifier in the backward direction, should return completely and exactly to the target, regardless of the target position and regardless of the aberrations in the propagation path.

In our experiments the apertures in the screen were illuminated in succession by radiation from a laser beam, which was "decoupled" from the rest of the apparatus with the aid of a Faraday cell. The initiating light beam striking the target had a maximum intensity $\lesssim 200$ MW/cm^2, a pulse duration at half height 17 nsec, and a spectrum width $< 5 \times 10^{-3}$ cm^{-1}. This beam causes no visible damage of the film.

With the aid of lens L_1, the light from the target is directed to the amplifier, where it is amplified 21 times. The lens L_2 constructs the image of the end face of the amplifier on the entrance to the light pipe, which is filled with carbon disulfide. Therefore, regardless of the target position, all the light passing through the amplifier enters the light pipe, where the stimulated scattering develops. The light pipe is a quartz tube placed in a cell with liquid carbon disulfide. The light is totally reflected internally from the walls of the tube, since the refractive index of quartz is less than that of carbon disulfide. To prevent lasing, the cell is blackened on the inside and its windows are inclined. The employed optical system is subject to large aberrations, since the target is displaced from the focal plane of the lens L_1 by one tenth of the focal length and, in addition, the lenses L_1 and L_2 are inclined.

It is known that wave-front inversion takes place when radiation is scattered from a spatially inhomogeneous intensity distribution. An inhomogeneous phase plate was therefore placed near the end face of the amplifier to ensure such a distribution regardless of the optical quality of the amplifier. The plate is analogous in its characteristics to that used in[4].

The light intensity at the entrance to the light pipe reaches ~ 10 MW/cm^2, which exceeds greatly the threshold of stimulated Mandel'shtam-Brillouin scattering. As a result an appreciable fraction of the light ($>50\%$ in energy) is scattered. The scattered radiation propagating towards the target is amplified anew, and as a result its energy when striking the film is 90–170 times larger than the energy of the initiating beam. Under the influence of this radiation, an opening is cut through the film.

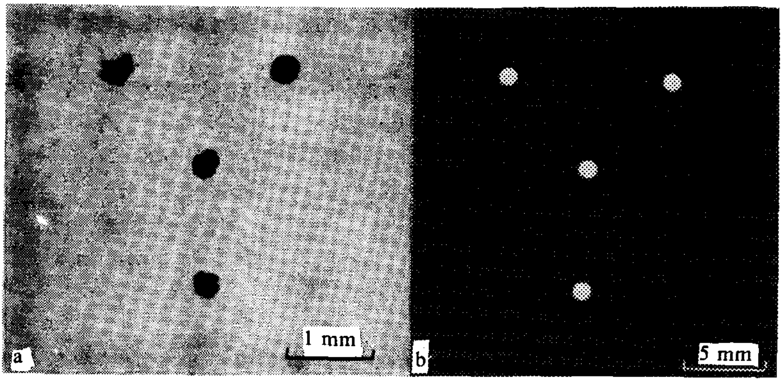

FIG. 2. Photographs: a—film damaged by the main beam; b—screen.

Figure 2(a) shows a photograph of the film damaged by four pulses after successive illumination of the screen openings. Figure 2(b) shows a photograph of the screen. It is clear from a comparison of these figures that the intensity of the main radiation flux is maximal precisely at those points of the film which are illuminated by the initiating beam.

But is all the radiation concentrated at these points? To answer this question, a fraction of the main beam was diverted, and the image of the plane F^* conjugate to the mylar film was constructed with a magnification 5.3 on a screen S_2 identical with the screen S_1 (see Fig. 1). The radiation energy passing through the opening in S_2 is therefore proportional to that fraction of the main beam which is incident on the film in a circle of 190 μm diameter, i.e., exactly into the target. Comparison of this energy with the total main-beam energy registered with a large-aperture calorimeter has shown that *≈80% of all the radiation enters the target.*

It has thus been established that by using the phenomenon of inversion of the wavefront it is possible to concentrate the radiation effectively on small targets located at various points.

We note in conclusion that the parameters of our installation were far from optimal. There is no doubt that the radiation energy and power can be increased,[1)] the target dimensions decrease, the range of the permissible target displacements increase, etc. The nonselectivity of the stimulated scattering permits the use of the principle described here in laser installations operating at various wavelengths. In the realization of the principle it must be recognized that inversion of the wavefront can compensate only for distortions that are of the phase type. It follows therefore, for example, that the minimal target diameter at which effective operation of the system is determined by diffraction limitations. It is necessary that the distortions be the same for a beam propagating from the target to the scattering medium and for a beam traveling in the opposite direction. Since these beams pass through the same optical elements at different times and have different intensities, the operation of the system may be influenced, generally speaking, by rapid changes in the elements and by nonlinear effects (for example, self-focusing). A detailed discussion of these factors is outside the scope of the present communication; we note merely that they can all be controlled.

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[1)] For example, as shown by oscillography, the front of the main pulse has under our conditions a duration ≈4.5 nsec at half-height, which is only double the hypersound damping time (τ_s) in CS_2. This gives grounds for hoping to obtain pulses of duration $\lesssim 1$ nsec by using scattering media with smaller τ_s.

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