Inversion of the wave front by a surface

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A method of wave-front inversion produced by a profiled destruction of an aluminum film sputtered on a glass surface is used. The coefficient of reflection to an inverted wave as a result of a 30% inversion reached 39% in total energy and 130% in instantaneous intensity. A theoretical model, which satisfactorily accounts for the power and for the dynamics of the process, is proposed.

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The effect of wave-front inversion (WFI) of light[1-5] has attracted the attention of researchers because of its wealth of application. Recently, a new method of WFI, based on construction of dynamic holograms on a reflecting surface, was proposed.[6] Suppose two waves impinge on a reflecting surface with an intensity or energy-dependent reflection coefficient—a plane reference wave E_0 rigorously normal to the surface and a signal wave E_s incident at a certain angle to the normal, which must be inverted. In this case the reference wave E_0 is scattered by the produced plane reflection hologram to an inverted wave during the time the pulse is recorded. In this paper this method of WFI is realized by a profiled destruction of a thin ~1 μm aluminum film sputtered on the surface of glass.[7]

The experimental setup is shown in Fig. 1. An enhanced radiation of a single-mode, neodymium-glass master oscillator ($\lambda = 1.06$ μm) with a modulated Q-factor was transmitted through a circular diaphragm D_1. The reference beam E_0 was directed to the working mirror $M3$ through a beam splitting mirror Z_1 and a prism Pr. The signal beam E_s, after being reflected by the mirror Z_1, was transmitted through the diaphragm D_2, through the glass plates P_1 and P_2, and through the canonical phase

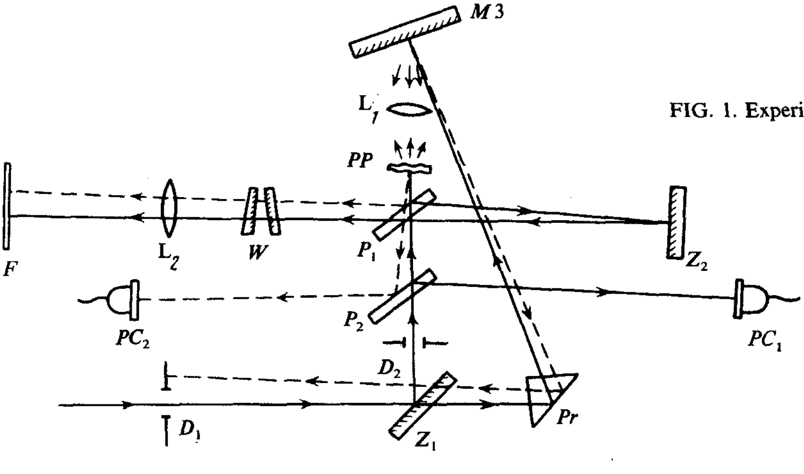

FIG. 1. Experimental setup.

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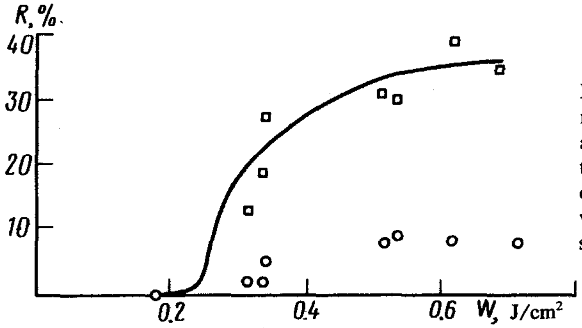

FIG. 2. Dependences of the coefficient of reflection of the energy of a signal wave to an inverted wave on the energy density of the reference beam: □, for total intercepted energy; ○, for the energy of an exactly inverted component; the solid curve represents the theoretical dependence.

plate[2] *PP* whose image was shaped by the lens L_1 ($f = 6$ cm) with a single amplification near the working mirror *M* 3. The divergence of the signal beam behind the phase plate increased to 0.5×10^{-2} rad. The inverted beam, compensated for its inhomogeneities during its reverse transmission through L_1 and *PP*, was directed to the recording device.

The angular distributions of the signal beam and of the inverted beam were compared in the standard scheme[2,5] with use of the beam diverging wedge W^2 with a coefficient of successive attenuation of 50%, and a photographic plate *F* in the focal plane of the lens L_2. The undistorted signal beam produced on the photographic plate *F* a number of successively attenuated spots with a size corresponding to the divergence of the diffraction quality. A bright center corresponding to the divergence of the diffraction quality was present in the angular spectrum of the inverted wave that was corrected by the phase plate *PP*. The experimental points for the coefficient of reflection of the signal wave to an *exactly inverted configuration* at different energy densities of the reflected beam in the mirror *M* 3 are represented by circles in Fig. 2.

However, the WFI in our experiment was nonideal. First, rather irregular wings with an angular divergence exceeding the diffraction limit by a factor of 1.3 to 1.5 were observed against the background of the bright center in the angular spectrum of the inverted wave. In the experiment these wings had approximately the same amount of energy as the exactly inverted component. Second, the inverted radiation had a background that was not recorded on the photographic plate, whose fine structure is uncorrelated with the invertable radiation. To quantitatively determine the coefficient of reflection of the signal to an inverted wave and the fraction of the inversion,[2,5] we compared, with the help of the photoelectric cells PC_1 and PC_2, the total energy of the inverted wave propagating in the limits of the solid angle of ~ 0.15 sr with the total energy of the signal wave. The experimental points for the coefficient of reflection with the WFI with respect to the total energy for different energy densities of the reference beam are represented by the black squares in Fig. 2.

It can be concluded from the experimental dependences in Fig.2 that the WFI process has a threshold nature and in our case is observed at a power density of the reference wave greater than 0.2 J/cm^2. The inversion is accomplished with a power efficiency up to 39%; moreover, the fraction of inversion—the ratio of the energy in the exactly inverted configuration to the total energy of the inverted beam—reaches

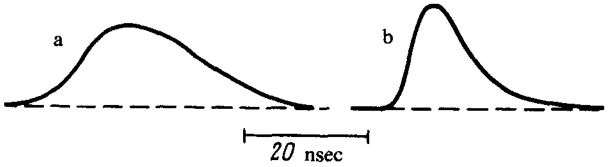

FIG. 3. Oscillograms of the signal (a) and of the inverted (b) pulses.

25–30%. The reasons for the low quality of inversion are not clear, but they can be related to the high contrast of recording of the dynamic hologram due to destruction of the mirror surface.

In the experiment we also compared the time dependence of the signal pulse and of the inverted pulse. Their oscillograms for the case of a large reflection coefficient with respect to energy are shown in Figs. 3a and 3b, respectively. It was found that the power of the inverted pulse may even exceed that of the incident pulse. In this case its duration decreases and its time contrast increases: the pulse duration at half-height decreases from 21 to 10 nsec, and that of the leading edge (for the levels 0.1 and 0.9) decreases from 11 to 4 nsec.

The calculation was performed in the framework of the following simple model. Let us assume that as soon as the density of the incident light energy exceeds the threshold value W_{thresh} in a certain location of the film, the coefficient of specular reflection of the surface changes irreversibly from unity to zero in this location. We introduce an instantaneous average energy density

$$W(t)=(I_0+I_s)\int_0^t f(t')dt'$$

and the coefficient

$$\beta=(I_0+I_s)/2\sqrt{I_0I_s}\ ,$$

which characterizes the correlation between the intensities of the signal beam I_s and the reference beam I_0 [here $f(t)$ is the time curve for both pulses]. The grating of the reflection coefficient is formed on the mirror at the time t_1 when the energy density in the maxima of the interference pattern reaches the threshold value $W(t_1) = \beta W_{\text{thresh}}/(\beta+1)$ and vanishes at the time t_2 when the mirror-reflected bands vanish in the minima of the interference pattern $W(t_2)=\beta W_{\text{thresh}}/(\beta-1)$. The scattering efficiency of the field E_0 in the first diffraction maximum of the grating is nonvanishing only in the range $t_1<t<t_2$ and depends on time via the width of the grating $\Delta x(t)$.

For the coefficient of reflection $\eta(t)$ from the signal wave to the inverted wave we can easily obtain

$$\eta(t)=\frac{1}{\pi^2}\frac{I_0}{I_s}\sin^2\left[\frac{1}{2}q\,\Delta x(t)\right]=\frac{1}{\pi^2}\frac{I_0}{I_s}\left[1-\beta^2\left(\frac{W_{\text{thresh}}}{W(t)}-1\right)^2\right],$$

where q is the length of the wave vector of the holographic grating. The time variation of the pulse of the inverted wave is given by the dependence $I_{\text{inv}}(t)=I_s\times f(t)\eta(t)$ and its duration is always shorter than that of the pulse of the signal wave.

The solid line in Fig. 2 represents the dependence of the coefficient of reflection of the total energy to the inverted wave, which was calculated according to the formula

$$\eta = W_0^{-1} \int_0^{W_0} \eta(W) dW,$$

where W_0 is the average energy density of radiation incident on the surface at $\beta = 1.48$, which corresponds to the experimental case $I_0 = 6.7\ I_s$.

The calculations in this model are in satisfactory agreement with the energy measurements (Fig. 2) and reduce the pulse duration of the inverted wave by a factor of 2 at $W_0 = W_{\text{thresh}}$; however, they give a maximum instantaneous inversion coefficient that is too low $(I_{\text{inv}}/I_s)_{\max} = 0.68$, which indicates that in a real case the contrast of the holographic grating is smaller.

In conclusion, we summarize the potentialities of this method of WFI. It is distinguished by its simplicity and absence of toxic, nonlinear substances. Of equal importance is the fact that the inversion can be accomplished with a large, simultaneous gain of intensity by a factor of $0.2 \times I_0/I_s$. The pulse duration of the inverted signal in this case decreases with a simultaneous increase of contrast of the leading edge. Despite this fact, the reflection coefficient with respect to the total energy, $\approx 0.3 \sqrt{I_0/I_s} \times W_{\text{thresh}}/W_0$, can be greater than unity. In addition, this method can be used for any wavelength of the optical radiation, and for long-duration pulses it requires a low-power density.

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