commercially available fiber operating at a wavelength of $0.82\,\mu m$, bending radii of 0.32 cm are possible corresponding to a 100-ps delay time or a fundamental frequency of 10 GHz.

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Real-time phase conjugate window for one-way optical field imaging through a distortion

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We demonstrate one-way optical field imaging through a distorting medium using a four-wave mixing implementation of real-time holography. Information can be transmitted at an arbitrarily fast rate as long as the mixing medium can respond to changes in the distortion.

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A number of methods for imaging through distorted media based on holography have appeared in the literature,[1–6] and more recently[7–9] imaging experiments based on phase conjugation by four-wave mixing have been performed. Imaging by phase conjugation requires that the picture field pass twice through the distortion which is a major disadvantage in the large number of practical situations where the pictorial information is to be transmitted in a single direction only. In a recent paper[10] a formal analysis was presented of a proposed four-wave mixing method for real-time one-way imaging through a distortion.

In this letter we describe and demonstrate experimentally this proposed one-way optical field imaging through distortions. The experimental arrangement is shown in Fig. 1. A transparency T contains our pictorial information to be transmitted through the distortion D. The nonlinear medium is a poled $7\times4.5\times4$ mm single crystal of $BaTiO_3$. This material is capable of supporting phase holograms of high diffraction efficiency,[11] especially when extraordinary polarization is used for the interacting beams, and the crystal is oriented in such a way as to take advantage of the very large value of the electrooptic coefficient r_{42}. Plane wave A_2 passes through T on its way to the crystal. In the crystal it encounters plane wave A_1 coming in the opposite direction as well as wave A_4 which passes first through the distortion D. The field at D is imaged into the crystal by lens L_1. For this particular experiment, the beams are from the 514.5-nm line of an argon ion laser.[12] The nonlinear mixing of A_1, A_2, and A_4 in the crystal gives rise to a new wave, A_3.

In the absence of spatial modulation on A_2, i.e., with T removed, A_3 would be the complex conjugate of A_4 ($A_3 \propto A_4^*$). In our case, however, the return wave A_3 contains pictorial information in addition to distortion information, and, on the whole, the phase conjugate property of the reflected beam has been destroyed. Nevertheless, if the returned wave is imaged onto the plane S, an image of the transparency T is recovered. The pictorial information is thus transmitted *in a single pass* from T to S.

The analysis is rather formal, so that a simple explanation of why the scheme works may be in order. By imaging the distortion D onto the crystal, say at the midplane C, we reproduce there the complex field $A_4(Q')$. The complex field at any point, say Q on C, is proportional to the field at the image point Q' to the right of the distortion D.

$$A_4(Q) \propto A_4(Q') = A_4 \exp[i\Phi(Q')], \tag{1}$$

where $\Phi(Q')$ is the phase retardation at Q' due to the distortion and A_4 is the field of the wave impinging on the distortion from the left. The nonlinear mixing in the crystal gives rise to the polarization[13,14]

$$P(Q) \propto A_1 A_2(Q)[A_4(Q)]^* = A_1 A_2(Q) A_4^* e^{-i\Phi(Q')}. \tag{2}$$

We note the sign reversal of $\Phi(Q')$ due to phase conjugation.

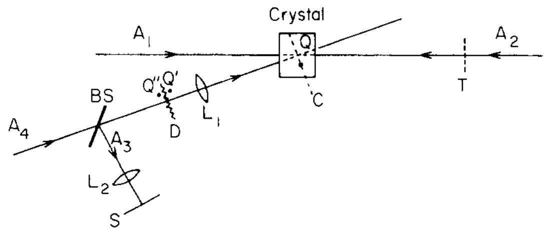

FIG. 1. Phase conjugate mirror altered to perform function of phase conjugate window. Beams 1 and 2 are the conventional pumping beams. Beam 2 carries the picture information T. The probe beam 4 passes through the distortion D which must be imaged onto the crystal by lens L_1. The reflected beam 3 carried the information through the distortion, split off at beam splitter BS, and is imaged on screen S by lens L_2.

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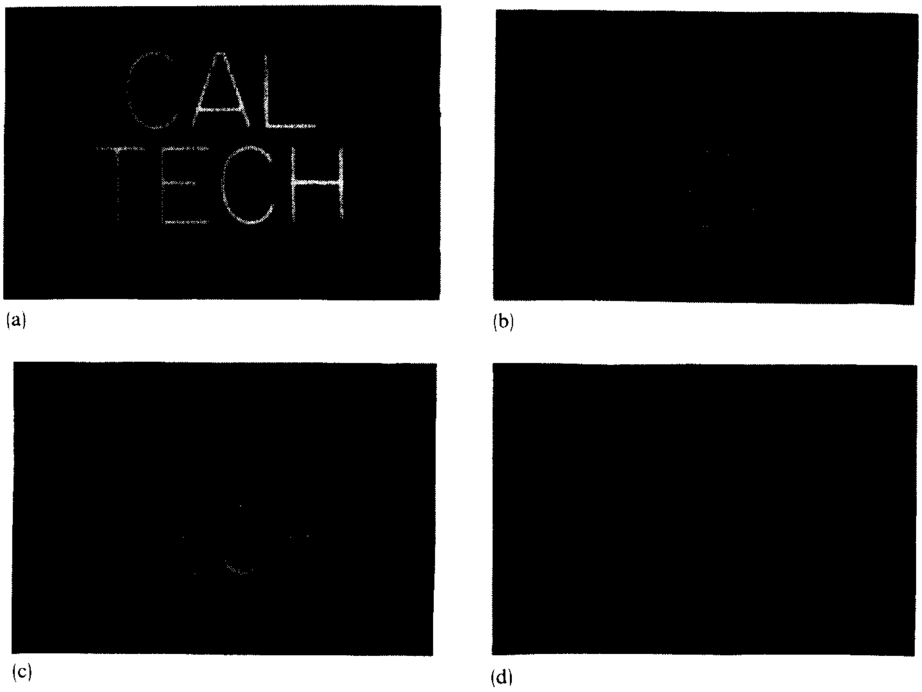

FIG. 2. Transparency T (a) before optical processing, (b) seen through distortion alone, (c) seen through distortion/phase conjugate window combination, and (d) seen through phase conjugate window alone.

The imaging condition causes the field due to $P(Q)$ to be reproduced (to within a proportionality constant) at Q' so that finally

$$A_3(Q'') = A_3(Q')e^{i\Phi(Q')} \propto A_1A_2(Q)A_4^* e^{-i[\Phi(Q') - \Phi(Q')]} = A_1A_4^*A_2(Q). \quad (3)$$

Since $A_1A_4^*$ is a constant, the field A_3 at Q'' just to the left of the distortion is a replica of the coherent and complex object field $A_2(Q)$ in the crystal *with no distortion*. It is easy to see that our device is really acting as a real-time "*phase conjugate window*." To compensate for a thin distortion with aberrations $e^{i\Phi(Q')}$, we might place in direct contact with it a window with the conjugate aberration $e^{-i\Phi(Q')}$, so that the net phase aberration of the combination is zero. It is just such a phase conjugate window which we have produced, except that for practical convenience, we image it by lens L_1 onto the distortion.

A similar idea can be implemented for a phase conjugate mirror (PCM) with planar pump waves, where amplitude information, in the form of a transparency, is added to the distorted reference wave A_4 before impinging on the PCM. The phase conjugate mirror cannot compensate for amplitude distortions, and A_3 returning through the distortion is not any more the phase conjugate of A_4. However, if the distortion has been imaged onto the same plane as the transparency, then A_3 will be corrected upon passing through the distortion and will transmit the amplitude information of the transparency.

Figure 2 shows the result of the experiment. Figure 2(a) is the transparency which is illuminated by beam A_2. Figure 2(b) is a photograph of the transparency taken through a sheet of etched glass. The image has been blurred beyond recognition. Figures 2(c) and 2(d) show the results of the compensation scheme on the image in plane S of Fig. 1, respectively, with and without the distortion D.

Finally, we note that in our experiment the important hologram is that of the distortion with reference beam A_1 (so that two beams A_1 and A_4 must be coherent). The images transmitted on beam A_2 (which need not be coherent with the other beams) may be changed at an arbitrarily high speed provided the nonlinear medium can respond to the changing distortion.

We can also overcome the necessity of supplying beam A_1 from an external source coherent with beam A_4, by using the passive (self-pumped) phase conjugate mirror to be discussed in a future publication.

In summary, we have demonstrated a real-time four-wave mixing optical processing device, the phase conjugate window, which allows one-way imaging through thin phase distortions.

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