Passive one-way aberration correction using four-wave mixing

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We have demonstrated a passive method for recovering an optical image that has been degraded by being passed through a thin phase-aberrating medium. This method relies on a point source situated near the object of interest to sample the aberration impressed upon the wave front. Degenerate four-wave mixing in fluorescein-doped boric acid glass was used to reconstruct the wave front.

Phase conjugation is a useful method for correcting an optical image that has been distorted as the result of having passed through a phase-aberrating medium. In the usual demonstration of this capability the phase-conjugate replica of the aberrated wave front is allowed to retrace its path through the distorting medium; through this procedure the effects of the phase aberration cancel out and the image of the original object is recovered.[1–3] This geometry, in which the original object and the corrected image end up on the same side of the phase aberrator, has several potential applications, e.g., to phase-conjugate resonators[4–6] and photolithography.[7,8]

Other possible applications of phase conjugation to aberration correction require that the original object and the corrected image be on opposite sides of the distorting medium.[9–17] A method for transmitting an image through a thin phase-aberrating medium to a receiver by using four-wave mixing was proposed by Yariv and Koch[15] and demonstrated by Fischer *et al.*[13] In this scheme the ultimate receiver sends a laser beam to the transmitter to sample the intervening distorter. The distorter is imaged into the nonlinear medium, where it interacts with a mutually coherent reference beam (which could be derived from the incident beam by spatial filtering, for example) and a third beam containing the image to be transmitted. The nonlinear polarization generates a wave that contains both the image information and the complex conjugate of the phase distortion; the distortion is canceled out when the generated beam passes back through the distorter to the receiver. The principal drawback to this scheme is that it is not passive: it requires the active participation of both the sender and the receiver of the image. Moreover, Feinberg has pointed out[16] that if one is interested in sending only intensity information it is possible to transmit an image through a thin distorting medium with neither coherent illumination nor nonlinear processing simply by imaging the object into the phase aberrator.

In the Letter we demonstrate an entirely passive imaging system that corrects aberrations in applications in which the receiver does not have access to the half space beyond the aberrator. Our device is an inplementation, using real-time degenerate four-wave mixing, of an idea put forward by Goodman *et al.* and demonstrated with static holographic techniques in 1966.[9] Goodman's concept was based on the observation that phase aberrations affect the resolution of a holographic imaging system differently from that of a conventional imaging system. In a conventional imaging system each point in the image contains contributions from rays that have passed through every point in the entrance pupil. As a result a phase aberrator placed at the entrance pupil degrades the resolution of the system by reducing the effective diameter of the aperture to the distance over which the aberration imparted to the incident wave front is negligible. On the other hand, a phase aberrator degrades the resolution of a holographic imaging system only to the extent that the two wave fronts that interfere in the recording medium to form the hologram do not experience the same aberration. Therefore the effect of the distortion is minimized when the aberrator is at the entrance pupil of the holographic imaging system so that the aberrator is imaged into the recording medium.[9,16]

The setup of our experiment is shown schematically in Fig. 1. Light from the object of interest and a nearby reference point source passes through a thin distorter situated near the entrance pupil of the optical system (in this case, the aperture defined by the lens with focal length f_1). In passing through the phase aberrator, each of the two incident optical fields acquires the same nonuniform phase shift, $\exp[i\phi(x, y)]$. The two well-matched field lenses with focal lengths f_2 placed in the object and reference beams form an image of the aberrator in the nonlinear medium. As a result, the image-bearing and reference waves at the nonlinear medium contain information about the aberrator only in identical exponential phase factors, which cancel in the third-order nonlinear polarization induced in the medium:

$$P_{\mathrm{NL}} \propto \{E_1 \exp[i\phi(x', y')]\}E_2\{E_3 \exp[i\phi(x', y')]\}^* = E_1E_2E_3^*.$$

The wave generated by this nonlinear polarization is free of the effects of the aberration and is split off to recover the unaberrated image.

The experimental details are as follows: The probe and pump beams were derived from the spatially fil-

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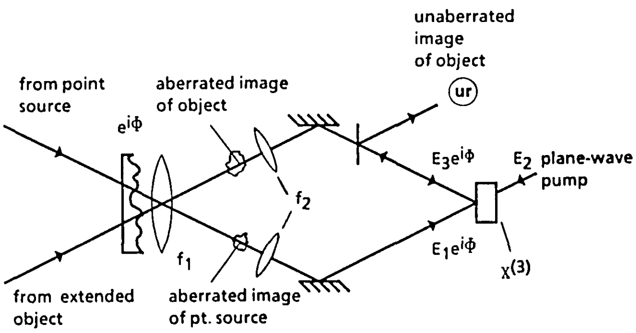

Fig. 1. Schematic experimental arrangement for passive, one-way phase-aberration correction using four-wave mixing. Light from an extended object and a point source passes through an aberrator and is collected by an imaging system—in this case a lens of focal length f_1. Field lenses of focal length f_2 image the aberrator into the nonlinear material. The aberrated pump and probe waves interact with a plane-wave pump in the nonlinear material through the third-order susceptibility. The phase-conjugate signal so generated is free of the deleterious effects of the aberrating medium. A beam splitter projects the unaberrated image of the extended object into a camera.

tered and collimated output from an argon-ion laser operating at a wavelength $\lambda = 476.5$ nm. A transparency illuminated by the probe beam served as the object. The aberrator was a glass microscope slide etched with hydrofluoric acid. The imaging lens had a focal length $f_1 = 36.0$ cm, and the field lenses had focal lengths $f_2 = 17.2$ cm. The distances between the object and the aberrator, the aberrator and the field lenses, and the field lenses and the nonlinear medium were 96.0 m, 51.6 cm, and 25.8 cm, respectively. The total optical intensity incident upon the nonlinear medium was $\simeq 25$ mW/cm^2. We used fluorescein-doped boric acid glass as the nonlinear medium because of its large value of $\chi^{(3)}$ and because thin samples of high optical quality are easily fabricated.[18] The particular sample of fluorescein-doped boric acid glass used in this experiment had a nonlinear susceptibility $|\chi^{(3)}| = 0.1$ esu, a response time of $\simeq 100$ msec, a small-signal absorption coefficient $\alpha_0 = 77.5$ cm^{-1} at 476.5 nm, a fluorescein dye concentration of 10^{-3} M, and a thickness of 40 μm.

The ability of this imaging system to compensate for phase aberrations is demonstrated in Fig. 2. Figure 2(a) shows an undistorted image of the extended object. The presence of an aberrator in the probe beam near the entrance pupil of the optical system rendered this image unrecognizable [Fig. 2(b)]. The images in Figs. 2(c) and 2(d) were obtained by four-wave mixing involving aberrated and unaberrated wave fronts, respectively. A comparison of Figs. 2(a) and 2(c) shows that the original image was recovered in spite of the severity of the aberration. By repeating the experiment with a resolution chart, we determined that the one-way imaging system was able to resolve 9.0 line pairs per millimeter regardless of whether the aberrating medium was present, indicating that the optical quality of the nonlinear material itself is now limiting the resolution of the scheme presented here.

This aberration-correction scheme can successfully remove aberrations imparted to the image-bearing wave under the following two conditions. The first condition is that the aberrator must be thin both with respect to the propagation of the image through it, so that the effect of the aberrator on the reference and image waves can be represented by a multiplicative factor $\exp[i\phi(x, y)]$, and with respect to the focal depth of the system (in our experiment, the field lenses), so that the entire aberrator can be focused into the nonlinear medium. The second condition is that the nonlinear medium itself must be thinner than the focal depth of the imaging lens and, in addition, be thin enough for the two aberration-bearing waves to over-

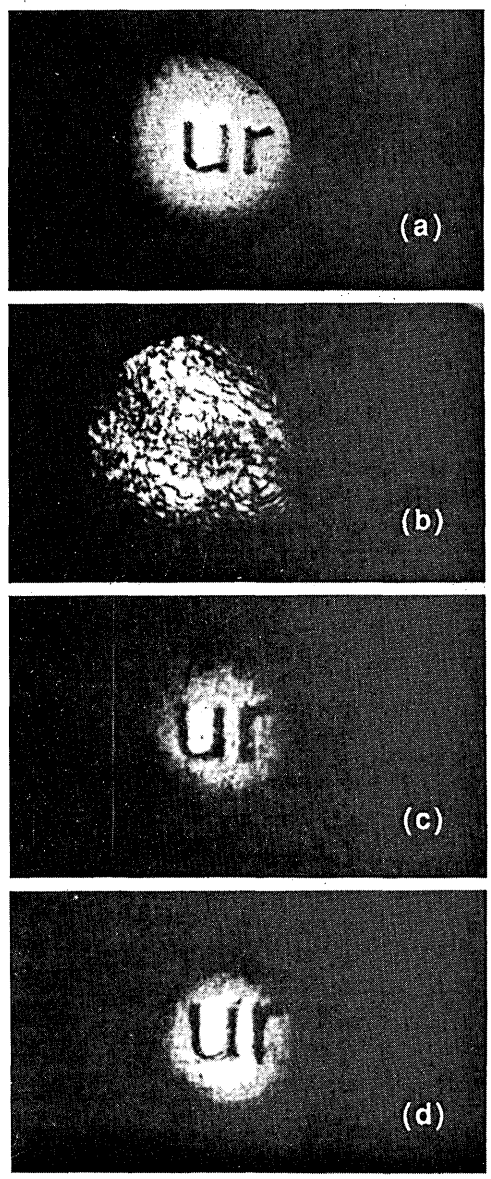

Fig. 2. Photographs demonstrating aberration correction using four-wave mixing. The input image (a) is severely aberrated (b) by a distorter placed at the entrance pupil of the optical imaging system. The restored image (c) is recovered on the far side of the aberrator from the original object. The quality of the recovered image is the same as that obtained by four-wave mixing with unaberrated input waves (d).

lap precisely over the whole length of the medium. Previously demonstrated one-way aberration-correction schemes are subject to the same limitations (see, e.g., Refs. 15 and 16).

A potential application of the aberration-correction scheme that we have described is to the observation of complex astronomical objects through atmospheric turbulence using as a reference a star located within the same isoplanatic patch. For example, a major contribution to the aberrations encountered in astronomical observation that could in principle be removed by our technique is turbulence at the interface between the telescope structure and the outside air.[19] Implementation of this technique, however, would require the development of nonlinear media both sensitive and fast enough to respond to the interference between two spectrally filtered astronomical signals.

In summary, we have demonstrated a passive, one-way imaging system using four-wave mixing that corrects distortions incurred by an optical wave front in passing through a thin phase-aberrating medium.

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