High-speed, low-power optical phase conjugation using a hybrid amorphous silicon/ferroelectric-liquid-crystal device

K. M. Johnson, C. C. Mao, and G. Moddel

Center for Optoelectronic Computing Systems, Department of Electrical and Computer Engineering, University of Colorado at Boulder, Boulder, Colorado 80309-0425

M. A. Handschy and K. Arnett

Displaytech, Inc., 2200 Central Avenue, Boulder, Colorado 80301

Received November 14, 1989; accepted June 25, 1990

Optical phase conjunngation using an amorphous silicon/ferroelectric-liquid-crystal light modulator shows an optical response of 100 μsec with a diffraction efficiency of 8.5% for an incident optical intensity of 1 mW/cm^2.

Optical phase conjugation has a variety of applications, including aberration correction, spatial image processing, temporal signal processing, and optical computing.[1-4] Some of the most sensitive materials for performing optical phase conjugation are photorefractive crystals (Fe:LiNbO$_3$, BaTiO$_3$, SBN, and Bi$_{12}$SO$_{20}$). The optical response of these materials is slow when cw lasers are used as the optical sources in producing phase-conjugate waves (typical response times are milliseconds to minutes for 10 mW/cm^2 of total incident intensity[5]). In this Letter we introduce a high-speed optical phase conjugator that is a hybrid device, employing a photosensor combined with a separate modulator.

Garibyan *et al.*[6] and Marom and Efron[7] demonstrated phase conjugation with simple hybrid devices, namely, optically addressed spatial light modulators (OASLM's) composed of photoconductors and nematic liquid crystals. The nematic liquid crystals used in these OASLM's limited the response times of their phase conjugators to approximately 10 msec. The microsecond response of ferroelectric liquid crystals[8] suggests that OASLM's could perform phase conjugation much faster, as reported here. We use a new OASLM[9] composed of a hydrogenated amorphous silicon (a-Si:H) photosensor and a surface stabilized ferroelectric-liquid-crystal (FLC) modulator to achieve optical phase conjugation with a 10–90% rise time of 100 μsec for incident optical intensities of $I = 1$ mW/cm^2.

The structure of our OASLM is shown in Fig. 1. The left glass substrate has an amorphous silicon p-i-n photodiode deposited on top of a uniform tin oxide transparent electrode. The right glass substrate carries another uniform transparent electrode made of indium tin oxide (ITO). A 1.75-μm-thick gap between the two substrates provides a space for the FLC modulating material. A British Drug House SCE-9 mixture was used in this device.[10] To operate the OASLM, a 30-V peak-to-peak square-wave clock voltage with a 5-V offset is applied across the two electrodes. Ideally, when the voltage is positive and the photodiode is forward biased, +20 V drops across the FLC layer. The FLC is switched to what we define as the off state. When the clock voltage is −10 V, the photodiode is reverse biased in the absence of illumination, and the FLC remains off. If an intensity pattern is incident upon the photosensor during this period, currents flow in the illuminated regions, reducing the voltage across the FLC (ideally to −10 V) and switching these areas to the on state. This forms a refractive-index pattern corresponding to the incident intensity pattern, since the FLC's optic axis directions are different between the on and off regions. Thus, a read beam incident upon the device from the FLC side is modulated by this refractive-index pattern. This modulation property of the device can be used to perform optical phase conjugation. Next, we describe a method for performing high-speed, low-power optical phase conjugation using this new OASLM.

The beam geometry of the phase-conjugation experimental arrangement, shown in Fig. 1, is similar to that of Garibyan *et al.*[6] and Marom and Efron.[7] A uniform reference beam $E_1 = A_1$ and a plane object

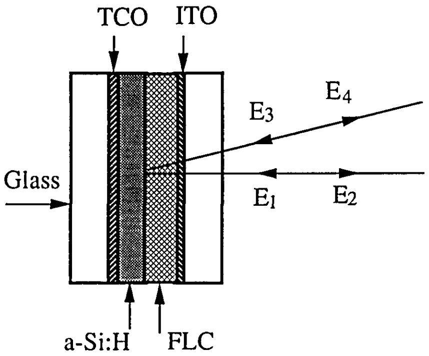

Fig. 1. Cross section of the a-Si:H/FLC optically addressed spatial light modulator showing the amorphous silicon p-i-n photodiode deposited onto the transparent conducting electrode (TCO) and the FLC modulator sandwiched between the photodiode and the ITO transparent electrode. Also shown are the incident reference (E_1) and signal (E_3) beams and the reflected reference (E_2) and phase-conjugate signal (E_4) beams.

0146/9592/90/201114-03$02.00/0

beam $E_3 = A_3 \exp[ik \sin(\theta)x]$ are incident upon the device from the FLC side with an angle θ between these two beams, and with $k = 2\pi/\lambda$. Based on the refractive indices of the FLC ($n \approx 1.57$)[11] and the a-Si:H ($n \approx 4.2$),[12] we estimate that approximately 80% of the incident light is transmitted through the FLC/a-Si:H interface and absorbed by the a-Si:H photosensor. The remainder of the light is reflected at the interface. Thus E_1 and E_3 interfere in the amorphous silicon photosensor, which yields an intensity pattern

$$\begin{aligned} I(x) &= 0.8|E_1 + E_3|^2 \\ &= 0.8\{|A_1|^2 + |A_3|^2 + 2A_1A_3 \cos[k \sin(\theta)x]\}. \quad (1) \end{aligned}$$

This produces a spatially varying voltage across the FLC proportional to $I(x)$, which creates a refractive-index grating in the FLC. Since the FLC typically assumes either an on or off state according to the sign of the applied voltage, the resulting refractive-index grating is binary. We may express the transmittance of this binary phase grating as[13]

$$t(x) = \exp(im) \sum_{n=-\infty}^{+\infty} \mathrm{rect}\left(\frac{x - nb}{a}\right), \quad (2)$$

where a is the width of the high-refractive-index region, b is the period of the grating given by $b = \lambda/\sin(\theta)$, and m is the peak-to-peak excursion of the phase delay. The $n = 1$ term of the Fourier series is given by[14]

$$t(x) = \frac{2}{\pi} \sin\left(\frac{\pi a}{b}\right) [\exp(im) - 1]\cos(2\pi x/b). \quad (3)$$

Incident beam E_1 and reflected beam E_2 diffract off the grating. The diffracted first orders produce a new beam E_4,

$$E_4 = A_4 \exp[-ik \sin(\theta)x], \quad (4)$$

where A_4 is the amplitude of E_4. This diffracted wave is the complex phase conjugate of the object plane wave E_3.

The analysis of the optical phase conjugation for arbitrary incident waves using a binary phase grating is more complicated. We give an example of such an analysis by assuming a diverging object wave and considering the one-dimensional case. As shown in Fig. 2, the diverging object wave E_3 may be written as $E_3 = A_3 \exp\{[i\pi \sin(\theta)/\lambda d]x^2\}$. The intensity pattern incident upon the a-Si:H is

$$I(x) = 0.8\left\{|A_1|^2 + |A_3|^2 + 2A_1A_3 \cos\left[\frac{\pi \sin(\theta)}{\lambda d} x^2\right]\right\}. \quad (5)$$

The maximum values of the modulation appear when

$$x_n = \pm\left[\frac{2n\lambda d}{\sin(\theta)}\right]^{1/2}, \quad (6)$$

where n is an integer and d is the distance between focal point O of the lens and the FLC layer. The binary grating formed in the FLC acts like a Fresnel lens.[15] The primary focal length of this Fresnel lens is given by $d/\sin(\theta)$. When a plane wave illuminates the FLC modulator, part of the diffracted light will be focused to point O. This focused, first-order beam may be written as

$$E_4 = A_4' \exp\left[\frac{-i\pi \sin(\theta)}{\lambda d} x^2\right], \quad (7)$$

which is the complex conjugate of E_3. The Fresnel lens shows some aberration owing to the presence of high diffraction orders, which reduces the fidelity of the phase conjugation.

The experimental apparatus for demonstrating optical phase conjugation is shown in Fig. 3. An argon-ion laser beam (λ = 514 nm) is expanded and collimated to a beam diameter of 1 cm. Beam splitter BS_1 transmits 50% of the incident light to form the reference beam. The intensity ratio of the reference and object beams are optimized using neutral-density filters F_1 and F_2 in order to obtain the highest diffraction efficiency. The reflected light is partially transmitted by beam splitter BS_2 to form the object beam E_3. A U.S. Air Force resolution chart is positioned just before BS_2. Lens L_1 images the chart onto the OASLM. The OASLM is arranged such that the FLC modulator faces the horizontally polarized incident beams. First, the reference beam E_1 was blocked and the OASLM was adjusted normal to the object beam E_3 such that the image of the resolution chart was displayed in the output plane. A photograph of this image is shown in Fig. 4(a). A piece of clear plastic, acting like a phase distorter (Strehl ratio 0.55), was inserted into the object path between BS_2 and L_1. A distorted image appeared at the output plane, as shown in Fig. 4(b). Finally, E_1 was unblocked and the OASLM was adjusted normal to E_1.[7] The phase-conjugate beam E_4 generated by the OASLM propagated back to BS_2, where it was reflected to the output plane

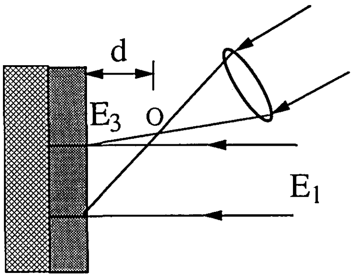

Fig. 2. Schematic of optical phase conjugation with a diverging object beam and a plane reference beam.

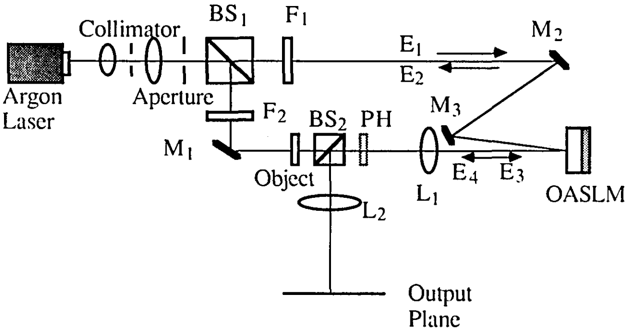

Fig. 3. Experimental apparatus for optical phase conjugation. PH, phase plate; M's, mirrors.

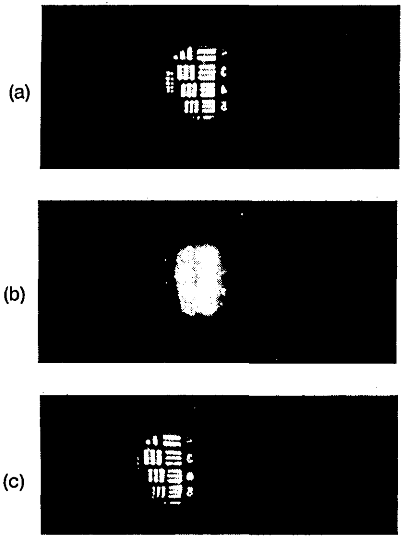

Fig. 4. Photographs of the images of the U.S. Air Force resolution chart. (a) Image reflected from the a-Si:H/FLC interface without the phase plate in the path; (b) image reflected from the a-Si:H/FLC with the phase plate in the path; (c) image after aberration correction owing to optical phase conjugation.

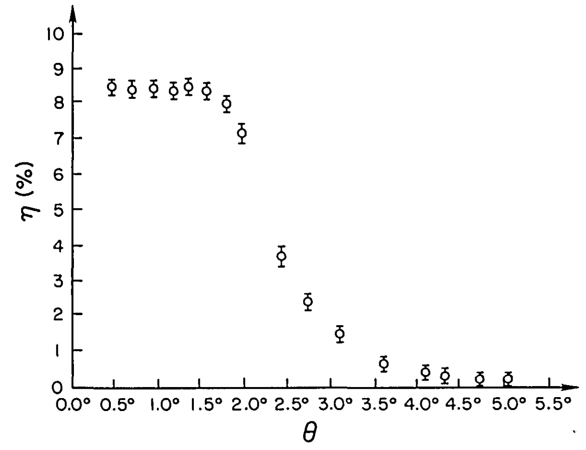

Fig. 5. Diffraction efficiency of the OASLM as a function of the incident angles E_1 and E_3.

and photographed, as shown in Fig. 4(c). After the phase-conjugate beam passes through the phase distorter, the phase aberration of the object wave caused by the phase distorter is canceled. The fidelity of the phase-conjugate beam is high, which demonstrates that the aberration of the phase-conjugate wave generated by a binary refractive-index grating is not serious.

The diffraction efficiency of the device as a function of angle θ between two incident beams was measured with an optical intensity of 0.5 mW/cm^2 (optical power 0.5 mW) for both reference and object beams. For small angles, the power of the phase-conjugate beam was approximately 8.5 μW. The diffraction efficiency $\eta = (E_4/E_1)^2$ is 8.5%, after accounting for the 80% loss of E_4 at the a-Si:H/FLC interface and neglecting Fresnel losses at the air–glass interfaces. The reflectivity $R = (E_4/E_3)^2$ is 1.7%. For $\theta < 1.6°$, the diffraction efficiency is nearly constant, as shown in Fig. 5.

The optical phase-conjugation response times of the OASLM are determined as follows. A Stanford Research System chopper with modulation frequency of 3.1 kHz was inserted into the optical path between BS_1 and mirror M_1, and the driving frequency of the power supply was adjusted to 1.3 kHz. The modulated object wave was monitored with a photodetector from the reflection at BS_2, and the phase-conjugate beam was detected at the output plane. The 10–90% response time is measured to be ~100 μsec.

We have demonstrated that the a-Si:H/FLC OASLM can be used to perform high-speed, low-power optical phase conjugation with good fidelity. The optical phase-conjugation response time of this device is 100 μsec. When the angle between the two incident beams is less than 1.6°, the diffraction efficiency is nearly constant ($\eta = 8.5\%$) and the reflectivity is 1.7%. The diffraction efficiency can be increased by changing the thickness of the FLC layer so that the phase delay m is exactly equal to π for the illumination wavelength of interest. This research is in progress.

This research was supported by National Science Foundation/Engineering Research Center for Optoelectronic Computing Systems grant CDR862228 (C. C. Mao and K. M. Johnson), the National Science Foundation Presidential Young Investigator Award (K. M. Johnson), and the U.S. Air Force Weapons Laboratory (M. A. Handschy and K. Arnett).

References

1. A. Yariv, IEEE J. Quantum Electron. **QE-14,** 650 (1978).
2. D. M. Pepper, Opt. Eng. **21,** 156 (1982).
3. R. A. Fisher, *Optical Phase Conjugation* (Academic, New York, 1983), p. 537.
4. M. Cronin-Golomb, B. Fischer, J. O. White, and A. Yariv, IEEE J. Quantum Electron. **QE-20,** 12 (1984).
5. G. C. Valley and M. B. Klein, Opt. Eng. **22,** 704 (1983).
6. O. V. Garibyan, I. N. Kompanets, A. V. Parfyonov, N. F. Pilipetsky, V. V. Shkunov, A. N. Sudarkin, A. V. Sukhov, N. V. Tabiryan, A. A. Vasiliev, and B. Ya. Zel'dovich, Opt. Commun. **38,** 67 (1981).
7. E. Maron and U. Efron, Opt. Lett. **12,** 504 (1987).
8. N. A. Clark and S. T. Lagerwall, Appl. Phys. Lett. **36,** 899 (1980).
9. G. Moddel, K. M. Johnson, W. Li, R. A. Rice, L. A. Pagano-Stauffer, and M. A. Handschy, Appl. Phys. Lett. **55,** 537 (1989).
10. BDH-British Drug House, Broom Road, Poole, BH12 4NN, UK.
11. From data sheet of BDH-British Drug House, Ref. 10.
12. J. I. Pankove, *Semiconductors and Semimetals* (Academic, Orlando, Fla., 1984), p. 20.
13. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1988), p. 69.
14. R. J. Collier, C. B. Burckhardt, and L. H. Lin, *Optical Holography*, student ed. (Academic, New York, 1971), p. 224.
15. E. Hecht, *Optics*, 2nd ed. (Addison-Wesley, Reading, Mass., 1987), p. 446.