Contrast-reversible photorefractive incoherent-to-coherent optical converter by using an anisotropic strong volume hologram

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An anisotropic strong volume hologram with a large coupling parameter is demonstrated in a normal-cut $BaTiO_3$ crystal. We use this hologram to fabricate an incoherent-to-coherent optical converter that has a contrast-reversible output.

In the past several years photorefractive materials have been proposed for use as photorefractive incoherent-to-coherent optical converters (PICOC's) because of their dynamic real-time grating recording properties.[1-5] In a general PICOC, the image-bearing incoherent light is used to erase the grating, which is constructed by two coherent writing beams. The output image is carried by the diffracted beam from the grating, which can be produced by several methods including four-wave mixing,[1,2] anisotropic self-diffraction,[3] self-pumped phase conjugation,[4] and grating projection.[5] Because the incoherent erasure light is used to decrease the strength of the grating and then decrease the output intensity of the diffracted light, the output image is always a negative replica of the incoherent input image.[1-4]

In this Letter we demonstrate a new PICOC by using a strong volume hologram in which the erasure of the grating may let the output diffraction efficiency either increase or decrease. The contrast of the output image can be adjusted simply by controlling the writing conditions of the grating. In other words, this PICOC is contrast reversible.

The diffraction properties of a volume hologram can be described accurately by the coupled-mode theory established by Kogelnik.[6] The Bragg-matching diffraction efficiency for a volume transmission index grating is given by

$$\eta = \sin^2\left(\frac{\pi \Delta n d}{\lambda \cos\theta}\right)\exp\left(\frac{-\alpha d}{\cos\theta}\right), \qquad (1)$$

where Δn is the amplitude of the index change, d is the thickness of the hologram, θ is the incident angle of the readout light inside the crystal, λ is the readout light wavelength, and α is the absorption coefficient. The factor in the parentheses of the sine function in Eq. (1) is called the coupling parameter. Equation (1) shows that the diffraction efficiency is a periodic function of the coupling parameter, and its maximum occurs when the coupling parameter is $\pi/2, 3\pi/2, \ldots$. For a given grating recording medium and a fixed incident angle, the diffraction efficiency depends on the amplitude of the index change of the medium. In the general case, the coupling parameter is less than $\pi/2$, so the diffraction efficiency increases whenever the grating amplitude is increased. The diffraction efficiency is decreased whenever the grating amplitude is reduced. However, in the case of a strong volume hologram, the maximum coupling parameter can be greater than $\pi/2$ and even reaches π or more. If we adjust the grating condition so that the coupling parameter lies in the region between $\pi/2$ and π, the erasure of the grating will result in an increase in the diffraction efficiency. A coherent positive replica of the incoherent image can be produced. Figure 1 shows the idea of such a PICOC. In practice, a normal-cut $BaTiO_3$ crystal is easier to manufacture, and its cost is lower, than is a 30°-cut crystal. The

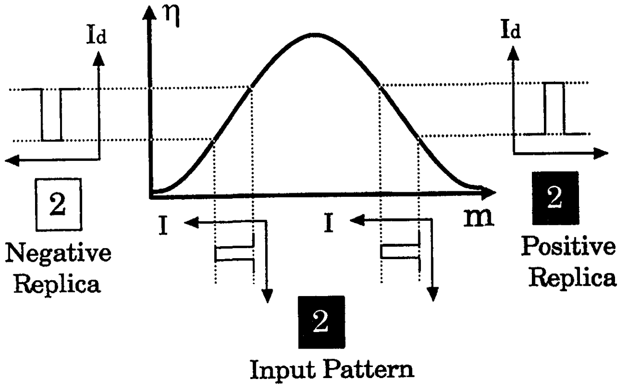

Fig. 1. Contrast-reversible PICOC by using a strong volume hologram. I is the intensity of the erasure light, I_d is the intensity of the diffracted light, η is the diffraction efficiency, and m is the modulation depth.

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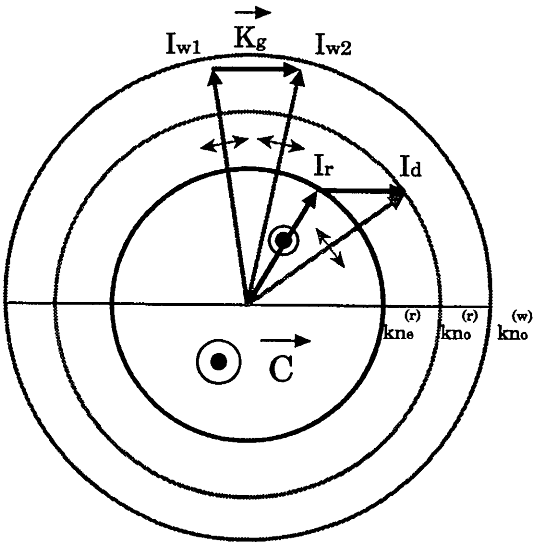


Fig. 2. Wave-vector diagrams for anisotropic Bragg diffraction in $BaTiO_3$. $\mathbf{K}_g$ is the grating vector. $kn_o^{(w)}$, $kn_o^{(r)}$, and $kn_e^{(r)}$ are the wave numbers of ordinary polarization at $\lambda = 514.5$ nm and of ordinary and extraordinary polizations at $\lambda = 632.8$ nm, respectively. I_{w1} and I_{w2} are the writing beams, I_r is the reading beam, and I_d is the diffracted beam.

coupling parameter under the general incident conditions for a 5 mm × 5 mm × 5 mm normal-cut crystal is less than $\pi/2$, thus it is not easy to obtain a PICOC for a positive replica. However, a photorefractive strong volume hologram in which the coupling parameter is several times that needed for obtaining the maximum diffraction efficiency has been observed in a 30°-cut $BaTiO_3$ crystal.[7] In our study, we find that a strong volume hologram exists in a normal-cut $BaTiO_3$ crystal in the case of anisotropic diffraction, as shown in Fig. 2. For the Bragg-matching grating vector $\mathbf{K}_g$, the index change is given[8] by

$$\Delta n = -\frac{1}{2} m n_o{}^2 n_e \gamma_{42} E_{\mathrm{sc}}, \qquad (2)$$

$$m = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2 + I_e}, \qquad (3)$$

where E_{sc} is the amplitude of the space-charge field, γ_{42} is the largest electro-optic element in $BaTiO_3$, n_o and n_e are the refraction indices of the ordinary and extraordinary waves, respectively, I_1 and I_2 are the incident intensities of the writing lights, and I_e is the intensity of the erasure light. From Eqs. (1)–(3), the coupling parameter can be adjusted by controlling the modulation depth of the grating. This is easy to achieve in the experiment by adjusting the beam ratio of the two writing beams.

In our experiment, a 6.6 mm × 6.6 mm × 7 mm ($a \times b \times c$) $BaTiO_3$ crystal was used. A schematic diagram of the experimental setup is shown in Fig. 3. The strong volume hologram was written by two ordinary-polarization beams from an argon-ion laser ($\lambda = 514.5$ nm), and the readout beam was derived from a He–Ne laser ($\lambda = 632.8$ nm) in extraordinary polarization. Both the writing and reading beams were expanded and collimated to a diameter of 1 cm outside the crystal. The image-bearing erasure light was derived from a He–Cd laser at $\lambda = 442$ nm and was imaged at the center of the crystal with an intensity of 10 mW/cm^2. The focal length of the imaging lens is 240 mm. The direction of the erasure light is aligned with that of the diffraction light to obtain the best resolution of the replica. The total intensities of the writing beams were 20.4 mW/cm^2, while the intensity of the reading beam was 0.3 mW/cm^2. In order to match the Bragg condition, a micropositioner was used to adjust the direction of the reading beam. As a result, a collimated beam with ordinary polarization was diffracted. In order to obtain a coherent positive replica of the incoherent image, we have to adjust the coupling parameter in the region between $\pi/2$ and π. The erasure light of the image beam was first turned off, and the directions of the writing and reading lights were adjusted until the Bragg-matching condition was satisfied for anisotropic diffraction. Under this condition, the extraordinary-polarized reading beam was diffracted by the holographic grating recorded by the two ordinary-polarizing writing beams. We adjusted the coupling parameter of the grating by adjusting the modulation ratio of the two writing beams. When the ratio was adjusted properly for a coupling parameter of π, the temporal behavior of the diffracted beam first increased from zero to a maximum and then decreased to a minimum value. To ensure that this phenomenon was due to the fact that the coupling parameter had reached π, we turned off the writing beams and observed the grating decay behavior by erasure of the reading beam. The diffraction intensity first grew to the maximum and then decayed to zero. After the coupling parameter was adjusted to π, the erasure light of the incoherent image was turned on, and a steady-state coherent image was obtained on the diffracted light. Figure 4 shows the experimental results. Figure 4(a) is the original incoherent image; Fig. 4(b) is the coherent image diffracted from the grating. It is seen that Fig. 4(b) is a good replica of Fig. 4(a). For the case of Fig. 4(c), the beam ratio of the writing beams' intensities is adjusted so that the coupling parameter reached $\pi/2$, where the nonerasing diffraction efficiency was maximum. When the incoherent image

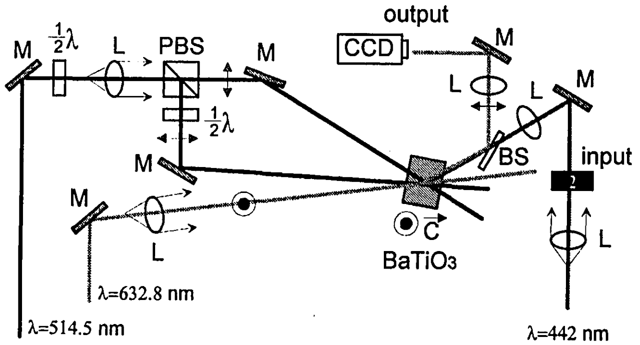
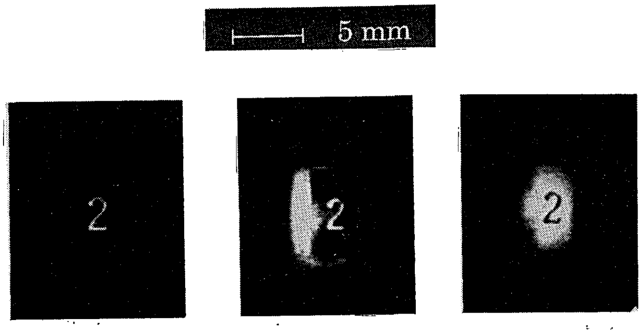


Fig. 3. Diagram of the experimental setup. L's, lenses; M's, mirrors; PBS, polarized beam-splitter cube; BS, beam splitter.



(a) (b) (c)

Fig. 4. Photographs of the input and output images. (a) The input image, (b) the output of the positive-image replica, (c) the output of the negative-image replica.

was turned on, the negative coherent replica image was obtained. On the other hand, when the positive replica is reached, if the writing beams are blocked, the replica in the positive domain to the negative domain can be observed continuously with the decay of the grating.

In the experiment, when the coupling parameter reached π, we found that the diffraction efficiency was only at the lowest value instead of being at zero. This is different from that predicted for the ideal case. A 10:1 ratio of maximum diffraction efficiency to the minimum diffraction efficiency was observed in our experiment. The nonzero diffraction could be caused by scattering in the crystal or by bending of the gratings. As a result, the contrast of the positive-image replica is limited. Otherwise, there is a limiting intensity for the incoherent erasure image in the case of a positive-image replica. A too-large erasure light intensity may overerase the grating so that the coupling parameter becomes less than $\pi/2$. This will destroy the operation of the positive-image replica. We found that the positive replica is destroyed when the total intensities of the writing beams are less than 10 mW/cm^2 in the experiment without changes in the beam ratio of the writing beams and the intensity of the erasure light. Such limitations do not exist in the case of a negative-image replica if the coupling parameter is maintained within $\pi/2$. The response time for both negative and positive operation is approximately 1 s at 1-W/cm^2 erasure intensity.

In conclusion, a contrast-reversible incoherent-to-coherent converter by using a strong volume hologram in a normal-cut $BaTiO_3$ crystal is proposed and demonstrated. The strong volume hologram is obtained by anisotropic diffraction in a normal-cut $BaTiO_3$ crystal. By properly adjusting the writing-beam intensity ratios, the coherent positive- and negative-image replicas of the incoherent input image are obtained.

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