Electric-field multiplexing/demultiplexing of volume holograms in photorefractive media

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We propose a new method of volume hologram multiplexing/demultiplexing in noncentrosymmetric media. Volume holograms may be multiplexed by tuning the material parameters of the recording medium (such as refractive index or lattice parameters) while keeping the external parameters (wavelength and angles) fixed. For example, an external dc electric field alters the index of refraction through the electro-optic effect, effectively changing the recording and reconstruction wavelengths in the storage medium. Then the storage of holograms at different fields, hence different indices of refraction, is closely related to wavelength multiplexing. We demonstrate this concept in a preliminary experiment by electrically multiplexing two volume holograms in a strontium barium niobate crystal.

Holographic data-storage systems typically use angular,[1,2] wavelength,[3] or phase-coded[4,5] multiplexing. Of these, the first two techniques exploit the dependence of the Bragg condition on the angle and wavelength of the writing beams:

$$\mathbf{K}_g = \mathbf{k}_1 - \mathbf{k}_2 , \quad (1)$$

where $K_g = 2\pi/\Lambda_g$ is the magnitude of the grating vector, $k_1 = k_2 = 2\pi n/\lambda$ are the magnitudes of the reference and signal-beam wave vectors, respectively, Λ_g is the grating period, n is the index of refraction, and λ is the vacuum wavelength. However, the index of refraction is an additional degree of freedom in the Bragg condition that can be controlled by an external electric field.[6] In this Letter we establish a relation between electric-field and wavelength multiplexing and present the results of a preliminary experiment that demonstrates the concept of field multiplexing.

We first derive a simple relation that illustrates the formal equivalence between wavelength and electric-field multiplexing under special conditions. This treatment is restricted to the case of counterpropagating signal and reference beams, both normally incident upon the crystal. In this case, the Bragg condition [Eq. (1)] becomes $\Lambda_g = \lambda/2n$, and the Bragg selectivity is maximal. Let us apply a field E to the crystal. Then, differentiating the Bragg condition at constant temperature T and mechanical stress σ, we obtain a relation for the change $\Delta\lambda$ required to maintain Bragg matching under field-induced changes $\Delta n(E)$ and $\Delta\Lambda_g(E)$:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n(E, \lambda)}{n} + \frac{\Delta\Lambda_g(E)}{\Lambda_g} . \quad (2)$$

Because the index of refraction in the crystal depends on the electric field and the wavelength,

$$\Delta n(E, \lambda) = \Delta n(E) + \frac{\mathrm{d}n(\lambda)}{\mathrm{d}\lambda}\Delta\lambda . \quad (3)$$

Substituting Eq. (3) into Eq. (2), we obtain a general relationship for the change in wavelength equivalent to a field-induced change of the index of refraction and grating period:

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{(1 - \lambda/n\ \mathrm{d}n/\mathrm{d}\lambda)}\left[\frac{\Delta n(E)}{n} + \frac{\Delta\Lambda_g(E)}{\Lambda_g}\right] . \quad (4)$$

In a noncentrosymmetric crystal, the field induces an index change that is due to a combination of the electro-optic, elasto-optic, and piezoelectric effects[7] and may rotate the principal axes by a field-dependent angle. We consider a simple yet common case, in which the optical and dc fields are parallel to the field-induced principal axes, and these axes do not rotate. Then the change in index along a principal axis is

$$\Delta n(E_k) = -\frac{{n_o}^3}{2}(r_{lk}E_k + p_{lm}d_{km}E_k) , \quad (5)$$

where r_{lk}, p_{lm}, and d_{km} are the electro-optic, elasto-optic, and piezoelectric tensors, respectively, and $l = (ij)$ and $m = (np)$ in contracted notation. The field also induces a strain in the crystal, given by the second term on the right-hand side in Eq. (2):

$$\frac{\Delta\Lambda_g}{\Lambda_g} = d_{km}E_k . \quad (6)$$

Therefore this multiplexing technique is based on varying the material parameters such as the index of refraction and the lattice parameters. These parameters are also dependent on the temperature T

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and mechanical stress σ, and a relation analogous to Eq. (4) is obtained on replacing E with T or σ for the cases of temperature or stress multiplexing. For the case of constant E and σ,

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{(1 - \lambda/n\ \mathrm{d}n/\mathrm{d}\lambda)}\left[\frac{\Delta n(T)}{n} + \frac{\Delta\Lambda_g(T)}{\Lambda_g}\right], \quad (7)$$

whereas for constant T and E,

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{(1 - \lambda/n\ \mathrm{d}n/\mathrm{d}\lambda)}\left[\frac{\Delta n(\sigma)}{n} + \frac{\Delta\Lambda_g(\sigma)}{\Lambda_g}\right]. \quad (8)$$

To simplify the analysis of electric-field multiplexing described by Eq. (4), we neglect the index dispersion $\mathrm{d}n/\mathrm{d}\lambda$ relative to n/λ [for strontium barium niobate (SBN:75), $\lambda/n\ \mathrm{d}n/\mathrm{d}\lambda \approx 0.2$, an error of 20%].[8] The second term on the right-hand side of Eq. (4), the strain term, is in general of the order of $\Delta n/n$. Define a scale factor ξ_E according to

$$\frac{\Delta n(E)}{n} + \frac{\Delta\Lambda_g(E)}{\Lambda_g} \equiv \xi_E\frac{\Delta n(E)}{n}, \quad (9)$$

where ξ_E is assumed to be a slowly varying function of field E and typically $0 \le |\xi_E| \le 10$,[9] depending on the sign and magnitudes of the linear electro-optic and piezoelectric coefficients. We define analogous scale factors for the temperature dependence

$$\frac{\Delta n(T)}{n} + \frac{\Delta\Lambda_g(T)}{\Lambda_g} \equiv \xi_T\frac{\Delta n(T)}{n}, \quad (10)$$

where $\Delta\Lambda_g = \alpha\Delta T$ (α is the thermal expansion coefficient), and for the stress dependence,

$$\frac{\Delta n(\sigma)}{n} + \frac{\Delta\Lambda_g(\sigma)}{\Lambda_g} \equiv \xi_\sigma\frac{\Delta n(\sigma)}{n}, \quad (11)$$

where the first term on the left-hand side is a piezo-optical contribution and the second term is the strain. Then the index selectivity or index half-power bandwidth, defined as $|\Delta n|_{\mathrm{FWHM}}$, for constant T and σ, is related to the spectral half-power bandwidth of a Bragg peak[10] by Eqs. (4) and (9),

$$\frac{|\Delta n|_{\mathrm{FWHM}}}{n} \approx \frac{1}{\xi_E}\frac{|\Delta\lambda|_{\mathrm{FWHM}}}{\lambda} \approx \frac{1}{\xi_E}\frac{\Lambda_g}{L}, \quad (12)$$

where L is the thickness of the crystal. This expression relates the Bragg selectivity for field multiplexing to the familiar result for wavelength multiplexing. Because the grating period for two plane waves in this configuration is $\Lambda_g = \lambda/2n$, the minimum index change $\Delta n_{\min} = 2|\Delta n|_{\mathrm{FWHM}}$ between adjacent holograms written at the same wavelength is

$$\Delta n_{\min} \approx \frac{\lambda}{\xi_E L}, \quad (13)$$

where the temperature and stress are assumed to be stabilized to within

$$\Delta T << \frac{\xi_E}{\xi_T}\Delta n_{\min}\left(\frac{\mathrm{d}n}{\mathrm{d}T}\right)^{-1}, \quad (14)$$

$$\Delta\sigma << \frac{\xi_E}{\xi_\sigma}\Delta n_{\min}\left(\frac{\mathrm{d}n}{\mathrm{d}\sigma}\right)^{-1}. \quad (15)$$

Therefore the number of holograms N_{holo} that can be multiplexed electrically is

$$N_{\mathrm{holo}} = \frac{\Delta n_{\max}}{\Delta n_{\min}} \approx \frac{\xi_E L}{\lambda}\frac{\mathrm{d}n}{\mathrm{d}E}\Delta E_{\max}. \quad (16)$$

To maximize N_{holo}, the crystal must satisfy two primary requirements. The material must have at least one large electro-optic coefficient that induces a significant index change for an electric field along (1) $\mathbf{K}_g$ for beam coupling and (2) $\hat{e}_1, \hat{e}_2$ (the polarization vectors of the reference and signal) for electrically biasing the index of refraction. In addition, there are three conditions of secondary importance; it is desirable that the field does not rotate (3) the polarization or (4) the principal axes, and (5) the material should have a large piezoelectric tensor component d_{km} of the proper sign such that ξ_E is maximized. Failure to satisfy conditions (3) and (4) will reduce the beam coupling, because the polarization of the two beams will no longer remain parallel and in the desired direction of condition (2) as they propagate through the crystal.

The optimum geometry for electric-field multiplexing is achieved with counterpropagating signal and reference beams normally incident upon the crystal. This configuration has two primary advantages. First, the counterpropagating configuration exhibits inherently low cross talk and high wavelength selectivity.[3] Second, it eliminates the detrimental Snell's law dependence of the angles in the crystal on the index of the crystal. In fact, for the transmission geometry with equal angles of incidence, the index dependence of the Bragg condition disappears:

$$2\Lambda_g n_{\mathrm{crystal}} \sin\theta_{\mathrm{crystal}} = 2\Lambda_g \sin\theta_{\mathrm{air}} = \lambda. \quad (17)$$

Note, however, that the Bragg condition retains its field dependence $\Lambda_g(E)$ even in this case. In the optimal counterpropagating normally incident geometry discussed above, electric-field multiplexing is closely related to wavelength multiplexing (except that the photorefractive beam coupling and phase are now field dependent,[11] and the field induces a strain).

In the optimal reflection-grating geometry, we can estimate N_{holo} from relation (16). For typical parameters ($\lambda_0 = 0.5\ \mu$m, $L = 1$ cm, extraordinarily polarized signal and reference beams) and estimating $\xi_E \approx \xi_T \approx 1.25$, we calculate from relation (13) that $\Delta n_{\min} = 4 \times 10^{-5}$. This implies from relation (14) that, for a material such as SBN:75 with $\mathrm{d}n/\mathrm{d}T = 2.5 \times 10^{-4}$,[9] the temperature must be stable to within $T \ll 0.16$ K at 300 K. Because r_{33} is the only significant electro-optic coefficient in SBN:75, the optimal geometry is a compromise to satisfy simultaneously both conditions (1) and (2) (Fig. 1). This configuration also satisfies conditions (3) and (4). The total index tuning range in the optimized configuration is $\sim\Delta n_{\max} = 0.0025$, half of $\Delta n_{\max} = 0.005$ (Ref. 12) for a material such as SBN:75. Then the number of holograms that may be electrically multiplexed about λ_0 in SBN:75 is calculated from relation (16) to be $\sim$60.

In order to demonstrate experimentally the concept of electric-field multiplexing, we have used

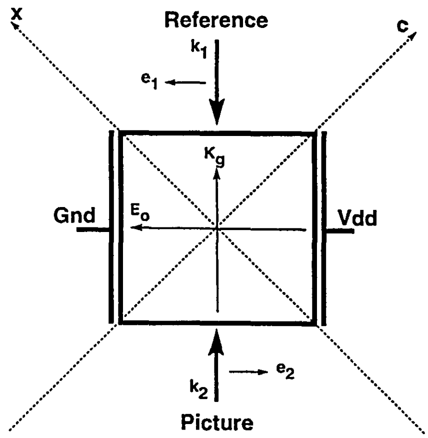


Fig. 1. Optimum configuration for electric-field multiplexing in SBN:75, with $r_{33} = 1340$ pm/V.

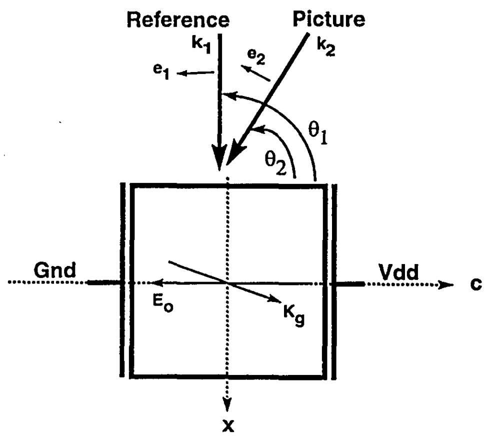
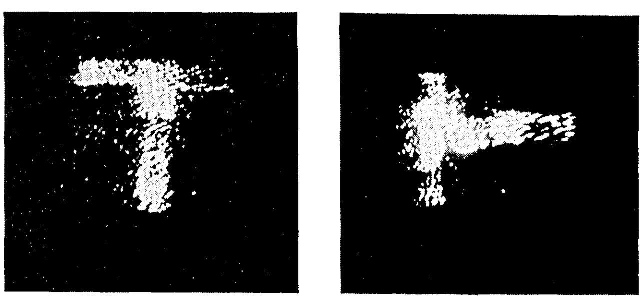


Fig. 2. Transmission configuration with external field applied opposite to the c axis.



(a) (b)

Fig. 3. Electric-field demultiplexing of two fixed holograms: (a) 0 V/cm, (b) 2000 V/cm.

$Sr_{0.75}Ba_{0.25}Nb_2O_6$ (SBN:75), with principal axes normal to the crystal faces. The orientation of the axes relative to the crystal faces (Fig. 2) prevents us from satisfying condition (1) in the counterpropagating configuration, because r_{33} is the only large electro-optic coefficient in SBN:75. Therefore, we performed a preliminary experiment in a transmission-grating configuration ($\theta_{1\,\mathrm{air}} = 90°, \theta_{2\,\mathrm{air}} = 60°$), which demonstrates the concept of electric-field multiplexing. A single fixed hologram at 0 V/cm may be switched to the off-Bragg condition with a field increment as low as 500 V/cm and recovered when the field returns to 0 V/cm. In addition, we have individually fixed two holograms (angular bandwidth of images ≈ 4 mrad), one written with no external field [Fig. 3(a)] and another written with a field of 2000 V/cm [Fig. 3(b)]. (To the authors' knowledge, this is the first demonstration of selective fixing of individual holograms and will be reported elsewhere.[13]) The holograms are selectively addressed by reapplying the field at which they were written. As seen in the figures, the two holograms exhibit little cross talk (diffraction efficiency $\approx 1\%$). The holograms have also been demultiplexed by varying the angle of the reconstruction beam.

In conclusion, the addressing of individual holograms, which is usually performed by tuning the angle or wavelength of the reconstruction, is demonstrated by applying an electric field. This method can be used either independently or in combination with other addressing methods to fine tune the Bragg condition. For instance, electric-field multiplexing can be used in conjunction with wavelength multiplexing to tune continuously around discrete laser lines. Alternatively, field-multiplexed holograms can be angle or wavelength demultiplexed or vice versa.

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