Angular selectivity of lithium niobate volume holograms

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(Received 29 May 1973)

The angular selectivities for the reconstruction of volume-phase holograms in doped and nominally pure $LiNbO_3$ crystals have been measured. The half-power angular widths for reading were found for the cases studied to be in agreement with theoretically predicted values.

It has been demonstrated that $LiNbO_3$ can be used as a recording material for volume-phase holograms.[1] These holograms are produced directly (without processing) by the interference of laser beams of the appropriate wavelength intersecting in the crystal. The volume nature of this holographic storage is especially interesting since it indicates the possibility of very-high-capacity information storage. Volume (thick) holograms exhibit a number of properties in addition to those possessed by two-dimensional (thin) holograms. Among these properties is angular selectivity—the need for the reference beam to illuminate the hologram at a precise angle in order to achieve reconstruction. Illumination outside of a narrow angular corridor produces a rapidly decreasing intensity of the reconstructed data.

A standard two-beam holographic configuration was used and plane-wave holograms were written. These holograms were reproductions of the original interference pattern, which has the geometry of a series of vertical planes, with an intensity variation perpendicular to the planes of $I(z)=2I_0 \sin^2(\pi z/L)$, where I_0 is the intensity of each writing beam and L is the resultant grating spacing ($L=\lambda/2\sin\phi_{\text{Bragg}}$).

Two poled single-domain $LiNbO_3$ crystals were used, one doped with 0.05 mole% iron and one nominally pure sample. The crystals were oriented as shown in Fig. 1 with their b-face surfaces perpendicular to the bisector of the writing beams and with the c axis in the plane of the writing beams. A frequency-doubled Nd:YAG laser (5300 Å) and an argon-ion laser operating at 5145 Å were used in these experiments to write the holograms.

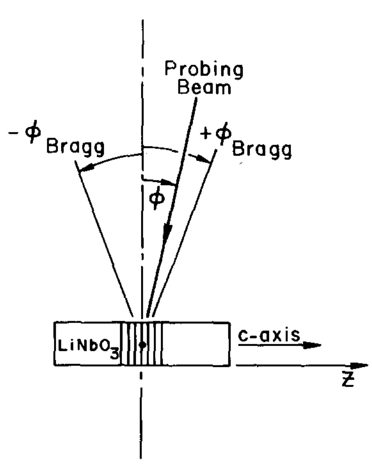

FIG. 1. Geometry of the writing and measuring configuration.

A HeNe laser (6328 Å) aligned to its corresponding Bragg angle was used to monitor the diffraction efficiency and to measure the angular selectivity. The polarization of the two writing beams was in the plane of these beams, while the polarization of the HeNe monitoring beam was perpendicular to the plane of incidence.

To measure the angular selectivity for reconstruction, the single HeNe probing beam was allowed to illuminate the hologram and the diffracted power was monitored. Then, by rotating the incident beam with respect to the crystal (varying the angle ϕ shown in Fig. 1), the variations in diffraction efficiency were measured. For the iron-doped $LiNbO_3$ crystal the measured angular selectivity is shown in Fig. 2.

Assuming that the sinusoidal interference pattern, $I(z)$, produced by the intersection of the two writing beams produces a sinusoidal variation in the index of refraction, then the diffraction efficiency of the volume grating hologram is given by[2] $\eta_0=\sin^2(\pi\Delta n t/\lambda\cos\phi_{\text{Bragg}})$, where η_0 is the on-Bragg-angle diffraction efficiency, Δn is the peak value of the sinusoidal grating of index of refraction, and t is the length of the interaction region (thickness of the crystal for these cases). During the writing process Δn increases and a peak in the diffraction efficiency (predicted to be 100%) occurs when Δn reaches a value of $(\lambda\cos\phi_{\text{Bragg}})/2t$. A further increase in Δn causes the diffraction efficiency to decrease until a Δn of $(\lambda\cos\phi_{\text{Bragg}})/t$ is reached at which

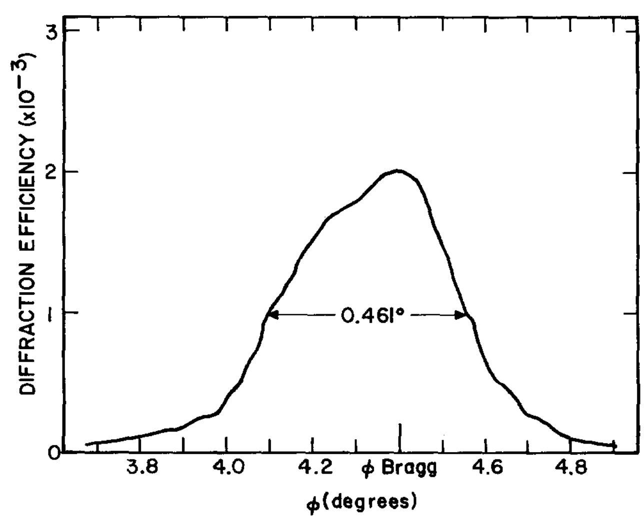

FIG. 2. Angular selectivity for reading of a hologram recorded in a 1-mm-thick iron-doped $LiNbO_3$ crystal using a writing wavelength of 5300 Å and a probing wavelength of 6328 Å.

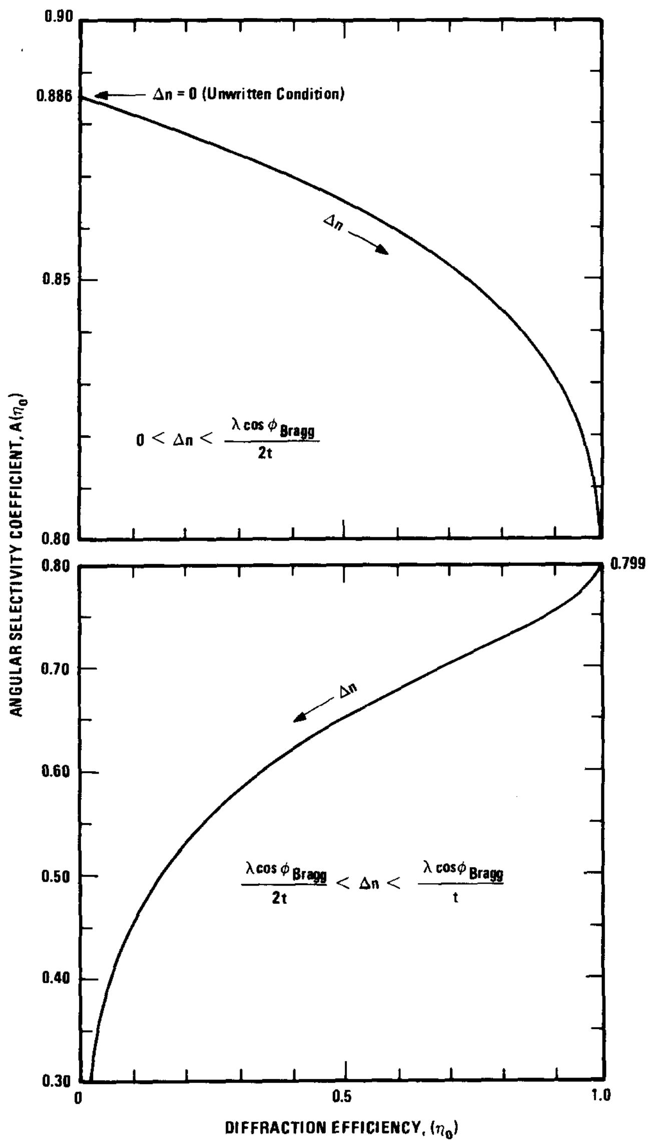

FIG. 3. The angular selectivity coefficient, $A(\eta_0)$, as a function of on-Bragg-angle diffraction efficiency, η_0.

time η_0 again begins to increase. This oscillatory behavior of the diffraction efficiency with exposure time has been experimentally observed.[3,4]

The theoretical angular selectivity for reading a volume hologram can be determined using the coupled-wave theory of Kogelnik.[2] For the full range of on-Bragg-angle diffraction efficiencies ($0 < \eta_0 < 1.00$), the half-power full angular width inside the crystal, $(\Delta\phi)_i$, can be determined by numerically solving Eqs. (42)–(45) in Ref. 2. The result is that $(\Delta\phi)_i = A(\eta_0)L/t$, where $A(\eta_0)$ is the angular selectivity coefficient. The half-power full angular width as measured from outside the crystal is thus

$$\Delta\phi \simeq A(\eta_0) n(\lambda, P) L/t \quad \text{rad}, \tag{1}$$

where $n(\lambda, P)$ is the appropriate index of refraction for the probing beam wavelength and polarization. The angular selectivity coefficient, $A(\eta_0)$, as determined by the coupled-wave theory is evaluated in Fig. 3.[5] As the change in index of refraction varies from zero (unwritten condition) to $(\lambda \cos\phi_{\text{Bragg}})/2t$ this factor changes from 0.886 to 0.799. This initial range of Δn values includes the relatively low diffraction efficiencies which correspond to practical holographic storage of information. For Δn beyond $(\lambda \cos\phi_{\text{Bragg}})/2t$, the angular selectivity coefficient decreases rapidly as shown in Fig. 3. Thus the angular corridor for reading narrows considerably with further exposure. Simultaneously, the diffraction efficiency increases at larger angular deviations from the Bragg angle as shown in Fig. 4. As the change in index of refraction, Δn, increases, these side lobe positions increase in diffraction efficiency and decrease their angular separation, $\Delta\phi$, from the exact Bragg angle. These side lobes coalesce at the Bragg angle ($\Delta\phi = 0$) when Δn increases to $1.5(\lambda \cos\phi_{\text{Bragg}})/t$ at which time the next set of side lobes are increasing in diffraction efficiency and moving toward the Bragg angle. Obviously for Δn greater than about $0.75(\lambda \cos\phi_{\text{Bragg}})/t$ the conventional notion of angular selectivity becomes ambiguous due to the presence of these side lobes.

Equation (1) assumes small angles of incidence. For the geometry of the experiments reported here, only a 0.24% error is introduced into this equation by the small-angle approximation. The more nearly exact expression for the half-power full angular width for reading for any angle of incidence is

$$\Delta\phi \simeq \sin^{-1}\{n(\lambda, P) \sin[(\phi_{\text{Bragg}})_i + \tfrac{1}{2}(\Delta\phi)_i]\} - \sin^{-1}\{n(\lambda, P) \sin[(\phi_{\text{Bragg}})_i - \tfrac{1}{2}(\Delta\phi)_i]\}, \tag{2}$$

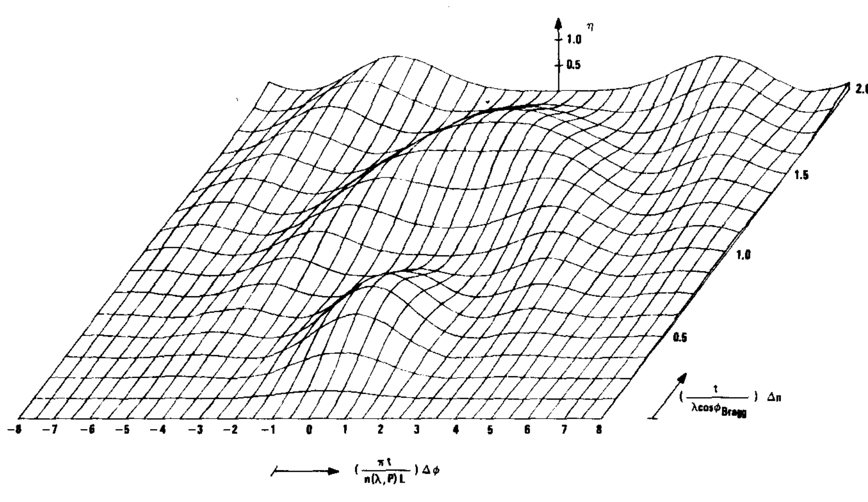

FIG. 4. Predicted variation of diffraction efficiency (η) with change in index of refraction (Δn) and angular deviation ($\Delta\phi$) from the exact Bragg angle.

where the angle of refraction $(\phi_{Bragg})_i = \sin^{-1}\{[1/n(\lambda, P)] \times \sin\phi_{Bragg}\}$. The HeNe probing beam ($\lambda = 6328$ Å) was polarized perpendicular to the c axis of the crystal (ordinary ray) and thus $n(\lambda, P) = 2.288$ for $LiNbO_3$. For the 1-mm-thick iron-doped $LiNbO_3$ sample, the measured half-power full angular width from Fig. 2 is seen to be $0.461° \pm 0.004°$. For the conditions of this experiment ($\phi_{Bragg} = 4.4°$, $\lambda = 5300$ Å, and $\eta_0 = 2.0\times10^{-3}$) the calculated value from (2) is 0.402°. For the 5-mm-thick nominally pure $LiNbO_3$ crystal, the half-power angular width was measured to be $0.080° \pm 0.004°$ as compared to the calculated value from (2) for that experiment ($\phi_{Bragg} = 4.35°$, $\lambda = 5145$ Å, and $\eta_0 = 1.1\times10^{-4}$) of 0.0789°. The deviations between the theoretical and experimental values were 14 and 1.6%, respectively. The agreement between theoretical and experimental values may be taken as an indication that the presence of divergence in the writing beams (writing beam divergence = 0.143° for the 5300-Å beams and 0.035° for the 5145-Å beams) does not have an appreciable effect on the resultant angular selectivity for reading. The presence of optical absorption has previously been shown to have very little effect on the angular selectivity of dielectric transmission holograms.[2]

In summary, the angular selectivity for the reconstruction of $LiNbO_3$ volume holograms has been measured and found to be in agreement with theoretical predictions. This information is of particular interest for high-capacity information storage applications since it indicates (1) a practical limit on the angular packing density of multiple holograms stored at a single location and (2) the required beam positioning accuracy to perform the process of reading.

*Work supported by the National Science Foundation.

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