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Efficient, Polarization-Independent, Reflective Liquid Crystal Phase Grating

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A reflective liquid crystal diffraction grating is proposed which makes use of the maximum available surface area. The structure consists of alternating stripes, each a twisted-nematic domain with surface orientation perpendicular to that of its neighbors. All domains have the same twist sense. This device yields, in principle, 100% diffraction efficiency independent of incident polarization. © *1997 American Institute of Physics.* [S0003-6951(97)03342-1]

One advantage of using liquid crystals to construct a diffraction grating is that a pure phase grating can be designed. In addition, the phase profile is easily controlled using the well-known electro-optical behavior of liquid crystals.

Electro-optically controlled phase gratings are suitable for use in large screen projection display systems, where each pixel in a two-dimensional array is an independent grating. In its fully diffractive state each pixel steers light around a set of louvers.[1] With the diffractive condition removed, light is blocked by those same louvers.

Transmissive liquid crystal diffraction gratings have been proposed for these Schlieren projection display systems.[1,2] To control the electric field at required pixels, the active matrix technique that has been developed for direct view liquid crystal displays can be utilized. However, opaque features of the active matrix limit the maximum transmission of this type of device.

Hence the need for a reflective liquid crystal phase grating, which allows the active matrix circuitry to be hidden behind the reflective area. This paper describes such a device.

Three operational characteristics are needed. First, in order to be an efficient grating, the diffractive performance must be independent of incident polarization. Second, diffraction efficiency must vary smoothly between 0% and 100% for applications requiring efficient, high contrast operation with grayscale capability. Third, that range must be achieved at practical voltage levels.

We investigated a number of candidates. Two of them are discussed here. The first of these, labeled the ''Orthogonal-Twist'' grating (Fig. 1), is new. It consists of alternating twisted domains with the same twist sense and perpendicular surface orientations.

The second configuration is identical to that used in one of the previously reported transmissive devices.[2] For the sake of simplicity, this structure is labeled the ''Reverse-Twist'' grating. Similar to the Orthogonal-Twist configuration, it consists of alternating twisted-nematic domains of opposite twist sense and similar surface orientation.

We modeled both of these devices, computing liquid crystal director orientation as a function of applied potential. Calculations utilized material characteristics of the E7 liquid crystal blend.

Diffraction efficiency (fraction of incident light diffracted out of the zero order) was computed as a function of $\Delta nd/\lambda$ in order to obtain the optimal thickness for a given material. For the Reverse-Twist grating the maximum 0-V diffractive efficiency was found to be 71% at a $\Delta nd/\lambda$ value of 0.332. However, as shown in Fig. 2, the Orthogonal-Twist grating produces diffraction efficiencies of greater than 90%, depending on choice of $\Delta nd/\lambda$.

Employed in a transmissive device, the Reverse-Twist grating owes its diffractive nature to rotation of polarization.[2–4] When optimized as a perfect optical rotator, such a grating can produce, in theory, 100% diffraction efficiency because the output fields of adjacent domains are one-half wavelength out of phase. However, this grating will not perform as well in a reflective device. Under conditions producing pure optical rotation, all incident polarizations are rotated back to their incident state, outputs from adjacent domains are identical, and no diffraction occurs. In order for any diffraction to take place, $\Delta nd/\lambda$ must not equal the condition for perfect optical rotation. Light emerging from adjacent domains will be elliptically polarized, producing less than perfect constructive interference.

The Orthogonal-Twist configuration makes use of both optical rotation, because of the twisted nematic domains, and retardation, because the surface orientations of adjacent domains are perpendicular to each other. As can be seen from Fig. 2, there are still values of $\Delta nd/\lambda$ (given by the Gooch and Tarry minima conditions[3]) for which the polarization state of incident light is preserved on reflection, resulting in no diffraction. However, at $\Delta nd/\lambda$ values approximately one-fourth above those minima, retardation effects work with the twist-induced ellipticicity to produce perfect diffrac-

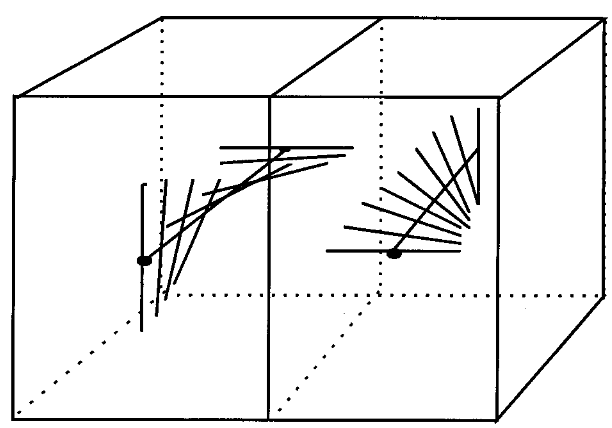

FIG. 1. Orthogonal-Twist configuration of liquid crystals in adjacent domains.

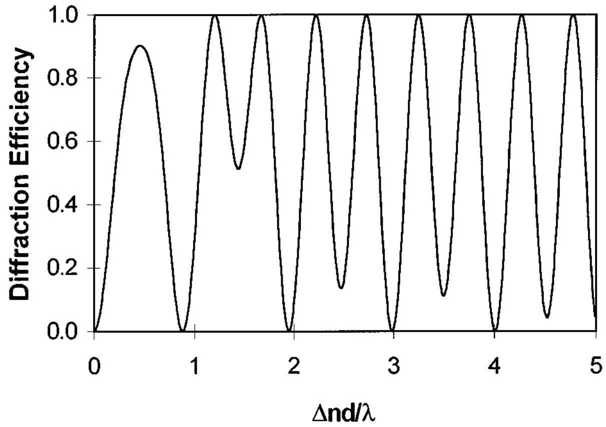

FIG. 2. Computed diffraction efficiency vs $\Delta nd/\lambda$ for Orthogonal-Twist grating at 0 V, calculated at 633 nm.

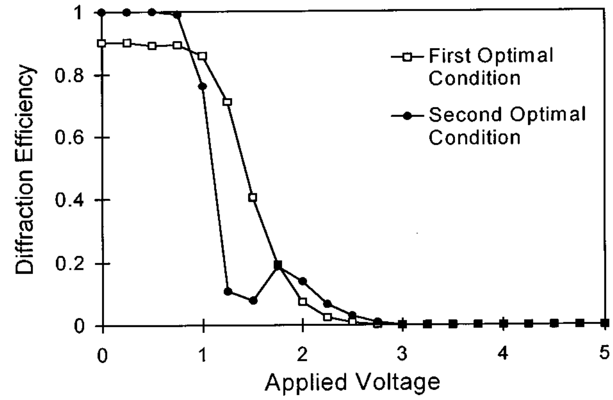

FIG. 4. Computed diffraction efficiency of E7-filled Orthogonal-Twist grating, for first and second optimal $\Delta nd/\lambda$ values.

tion conditions. Light reflected from any domain is elliptically polarized, but now both components are one-half wave out of phase with respect to corresponding components reflected from adjacent domains.

Diffraction is removed from both gratings when sufficient potential difference is applied across the substrates. Liquid crystal molecules having positive dielectric anisotropy will be tilted toward the substrate normal. This occurs first midway between the substrates. All twist moves to this region. As a result, the domains appear optically identical (Fig. 3).

Since the Orthogonal-Twist grating produced the most efficient diffraction, we proceeded to compute its ideal electro-optical response. We used the values of $\Delta nd/\lambda$ from Fig. 2 which produced the first and second diffraction maxima to calculate the predicted electro-optical response seen in Fig. 4.

We then fabricated an Orthogonal-Twist grating to check our predictions. The 75 μm wide domains were produced using the double-rubbing technique[1,5] applied to substrates coated with Nissan 7311 polyimide. The transparent substrate was ITO coated glass. The reflective substrate was aluminum-coated glass.

We assembled the test device in a wedge configuration in order to provide both the first and second optimal conditions in a single device. The wedge incline was parallel to the domain (stripe) axis. The cell was filled with ZLI-4792 liquid crystal blend ($\Delta n = 0.09$). After filling the cell, the substrates were aligned manually while viewing the device in a polarizing microscope.

The electro-optical performance of the Orthogonal-Twist wedge cell was determined experimentally. The grating was illuminated with an He–Ne laser. The reflected diffraction pattern was passed through a set of louvers, placed so that only the first five odd orders were collected onto a detector. This selection of odd orders is similar to the operation of a Schlieren optical projection system.

The laser was first directed at a location which produced the first optimal state. Measurements were taken with the laser polarized parallel and then perpendicular to the domain stripes (Fig. 5). The measured response was normalized to the signal detected with the louver removed and 20 Vrms applied to the cell. A second set of data was taken with the laser directed at a location which produced the second optimal state (Fig. 6).

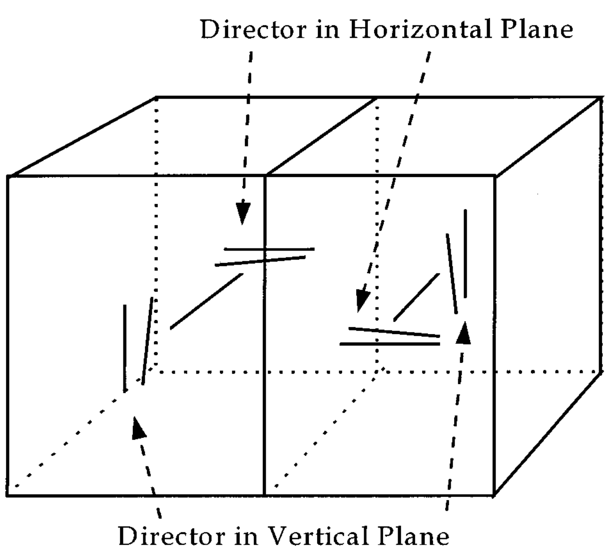

FIG. 3. Orthogonal-Twist configuration in nondiffractive state.

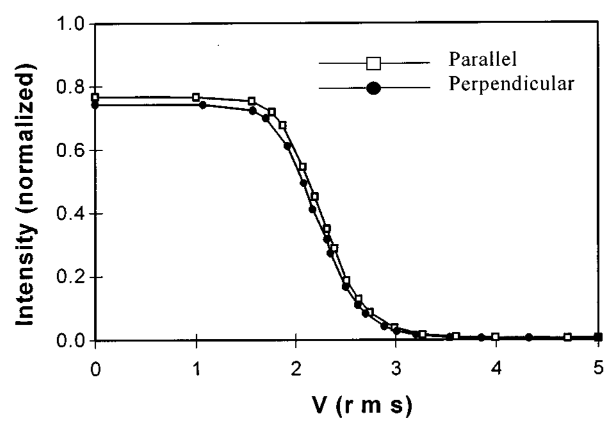

FIG. 5. Measured first five odd orders from ZLI-4792 filled Orthogonal-Twist grating, for first optimal $\Delta nd/\lambda$ value. Electro-optical response measured for incident polarizations parallel and perpendicular to the grating stripes.

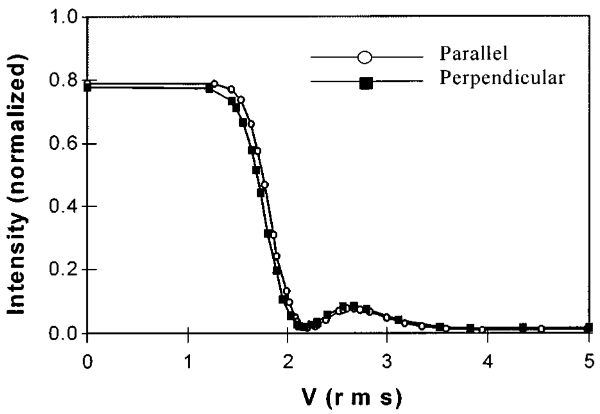

FIG. 6. Measured first five odd orders of ZLI-4792 filled Orthogonal-Twist grating, for second optimal $\Delta nd/\lambda$ value.

Both sets of data indicate polarization independent performance. The switching voltages are slightly higher than predicted because ZLI-4792 was substituted for E7 in the experimental device, and because domain boundary walls were not included in the calculation.

The measured intensities are lower than predicted for several reasons. First, we collected only the first five odd orders, whereas the predicted electro-optic data is a collection of all nonzero orders. Second, disclinations at the domain boundaries reduce the diffraction efficiency. Third, the domain boundaries were not perfectly straight, parallel and of equal width due to use of a low quality photolithography mask. Fourth, inspection of the grating under a polarizing microscope indicated some surface flaws.

The latter two imperfections are easily addressed by improved fabrication parts and processes. Higher quality masks, more precise photolithography, and automated spincoating, rubbing, and alignment should enhance diffractive performance.

The proposed electro-optically controlled reflective liquid crystal phase grating consists of alternating twisted-nematic stripes of the same twist sense and perpendicular surface orientations. This device can produce diffraction efficiency approaching 100%, with complete removal of diffraction at low applied voltage. The test device confirms the operation principles.

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