COLOR HOLOGRAPHIC FILTERS FOR LIQUID CRYSTAL DISPLAYS

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Abstract – We describe the fabrication of high-efficiency (>95%) transmission and reflection color holographic filters for use with liquid crystal displays (LCDs). Tri-color (RGB) filters are made in a photopolymer film by selecting the appropriate angle between two interfering plane-wave laser beams from an argon-ion laser. The gratings are then fixed by uniform illumination from a UV light source. This approach is simple and highly versatile and it allows for the custom tailoring of the optical properties of the holographic filters such as the center wavelength, spectral bandwidth, peak efficiency, and viewing angle in order to suit a specific LCD product's performance requirements for color filters.

I. INTRODUCTION

One of the primary methods for the fabrication of color filters currently used in LCDs, consists of the selective deposition of tri-colored dyed materials onto individually pixellated areas of the display. These types of colored filters are difficult to manufacture requiring three separate processing steps for each primary color, i.e., layering of dyed films, photolithographic patterning to define the individual pixel regions, and subsequent etching of the films to obtain the desired colored region. Such a fabrication process usually results in an uneven surface finish with blurred boundaries between the colored pixels – characteristics which can degrade the optical performance of the filters. However, the biggest drawback of dyed color filters are their relatively low efficiencies of ~25%. This accounts for a significant fraction of the total optical loss in LCDs which typically suffer from low overall throughput efficiencies on the order of only a few percent [1]. In the case of portable display products such as back-lit laptop computers, this low transmissivity directly impacts the power consumption and useable battery life. Since color filters account for the largest percentage of direct material cost in the fabrication of LCD displays[1], there are significant incentives to improve their efficiency, reduce the total number of processing steps, and decrease their manufacturing cost.

Alternative methods for fabrication of color filters have included the use of dielectric thin films, color separation or diffractive gratings [2], and holographic color filters using dichromated gelatins [3].

Dielectric filters, which require the vacuum deposition of multiple layers of thin films, can have excellent high transmissivities but their spectral output is sensitive to the incident angle making them unsuitable for off-axis viewing. Color separation gratings (or Dammann optical elements) which are based on diffractive as opposed to refractive phenomena are difficult to fabricate requiring multiple patterning (for high-efficiency filters) and etching processes. These types of gratings, like the dielectric thin film filters, are expensive to manufacture. Holographic filters made with dichromated gelatins (DCG) have recently been demonstrated with high efficiencies but suffer from shrinkage problems during the post-exposure wet processing required to fix the gratings [3].

In this paper we describe the fabrication of high-efficiency (>95%) transmission and reflection color holographic filters using DuPont photopolymer films. These filters are simple to fabricate by interfering two plane-wave beams from an argon-ion laser and requiring only an aperture or shadow mask to define the RGB pixel areas. Post-exposure curing and "fixing" of the interference patterns is achieved by uniform illumination with a UV light source. The photopolymer materials are comparable in performance to dichromated gelatins since both are capable of high diffraction efficiencies (theoretically 100%). However, we believe the photopolymer material is superior since it does not require any wet processing to fix the pattern which causes shrinkage of the DCG films and results in a shift of the center wavelength (i.e., color) for which the grating was originally designed.

II. EXPERIMENTAL PROCEDURE

Transmission and reflection holographic filters were made using DuPont's experimental photopolymer materials HRF-150 and HRF-750 respectively. The latter material can also be obtained in liquid form with the advantage that it can be spun to any desired thickness. The HRF-150 photopolymer has a peak absorption in the green between 450-550 nm and is best suited for transmission-type filters whereas the HRF-750 is specifically made for both reflection and transmission RGB filters with peak absorptions at 456 nm, 575 nm,

Figure 1. Optical set-up for the fabrication and characterization of transmission color holographic filters. For reflection filters, the write beams would be incident from opposite sides of the photopolymer film.

and 647 nm making it suitable for recording in a broad range of the visible spectrum (Fig. 2).

Figure 2. Transmittance of HRF-150 and HRF-750 DuPont holographic photopolymer films showing the absorption minima at the wavelengths where the films are photosensitive.

The photopolymer material used in the fabrication of the transmission filters (HRF-150) had a nominal thickness of 38 μm . The index of refraction of the film was $n = 1.52$ with a maximum index modulation $\Delta n \sim 0.008$. The films are composed of acrylic monomers, a polymeric film binder, initiator, and photosensitized dye. A complete description of the properties and behavior of the DuPont photopolymer material including grating formation models can be found in Ref. 4. The color holographic filters were made by laminating the film onto glass slides and exposed (incident on the air-glass

interface) by interfering two spatially filtered and uniformly expanded collimated beams from an argon-ion laser (514 nm). Both recording beams had an equal intensity of 50 mW/cm^2 ($K = 1$). The center wavelengths of the RGB filters were determined using the Bragg condition for diffraction:

$$d \sin \theta = m \lambda \quad [1]$$

where d = grating spacing, λ = wavelength of the recording beams, and θ = angle between the two write beams. By varying the angle (θ) between the two incident write beams, different color transmission or reflection filters (for beams incident from opposite sides of the photopolymer film and using the HRF-750 material) which diffract light at the chosen wavelength were fabricated. Alternatively, if using HRF-750 material, the angle can be kept constant and the wavelength varied instead. The exposure time to saturate the color filters was typically between 1-2 seconds. After exposure, the films were cured by illuminating them for 10-15 minutes with a uniform beam of UV light which fixes the grating and increases the hologram throughput efficiency by bleaching the absorptive dye. The diffraction efficiency of the exposed and bleached films as a function of wavelength and angle of incidence were measured using a broadband white light source which was passed through a tunable monochromator and made incident on the holographic color filter placed on a highly accurate rotatable stage (Fig. 1).

III. EXPERIMENTAL RESULTS

The measured diffraction efficiency (η) versus wavelength for a red transmission filter is shown in

Fig. 3. The diffraction efficiency is defined as the ratio of the intensities of the diffracted beam divided by the sum of the intensities of the diffracted and undiffracted or zero-order beams (see Fig. 1).

$$\eta = I_d / (I_d + I_0) \quad [2]$$

Figure 3. Diffraction efficiency as a function of angle for a red-transmission filter (centered at 650 nm) fabricated in HR-150 photopolymer film. The peak efficiency is greater than 98% and the FWHM is 1.5°.

In order to increase the angular bandwidth of the color filters, for applications which require a larger viewing angle, two gratings with the same period (i.e., same relative angle between the recording beams and therefore same center wavelength and color), but which were angularly separated, were simultaneously recorded so that the Bragg peaks of the two diffraction peaks overlapped by approximately one-half of the FWHM value (Fig. 4). This technique was effective in broadening the width of the diffraction angle and may be used to tailor the viewing angle properties of the color filters.

Fig. 4. Diffraction efficiency as a function of angle for two spatially separated multiplexed gratings. The FWHM has been increased to ~3°.

Tri-color transmission and reflection filters were made in HR-150 and HRF-750 films respectively by varying the relative angle between the two write beams (co-propagating beams for transmission and counter-propagating for reflection). The performance of three different colored RGB transmission filters fabricated in a single film of HRF-150 for which exposure times were individually optimized, is shown in Fig. 5.

Fig. 5. Diffraction efficiency as a function of wavelength for RGB color transmission holographic filters centered at 450 nm, 520 nm, and 650 nm respectively. The FWHM of the filters is between 10-15 nm.

Since the filters were made holographically, they exhibited spectrally pure colors as characterized by their C.I.E. chromaticity values [5] shown in Fig. 6.

Fig. 6. C.I.E., chromaticity diagram for RGB transmission holographic filters. The measured data is indicated by the solid squares. The NTSC standard has been included for reference.

IV. SUMMARY

Holographic RGB color filters using photopolymer materials have the following advantages over conventional dyed filters: i) they are extremely efficient, capable of greater than 95% efficiency for either reflection or transmission-type filters; ii) the values of the peak

efficiencies can be chosen between 0-100% by varying the exposure times and/or film thicknesses in order to compensate for the eye's responsivity to RGB colors; iii) the center wavelengths of the primary colors can be selected by setting the relative angle between the two write beams; iv) the fabrication process involves a simple series of exposures using an aperture mask (to define each of the tri-color regions) followed by a dry UV-curing process with a minimal amount of film shrinkage; v) they can have sharp boundaries between the pixels and a smooth surface finish, and; vi) they can be low cost in large volumes. One possible disadvantage of the holographic color filters may be their relatively narrow viewing angle but this limitation can be overcome by the technique of multiplexing two or more spatially separated gratings which can effectively broaden the Bragg width.

V. CONCLUSIONS

We have demonstrated the fabrication of color holographic filters made using photopolymer films which we believe are superior in performance to conventional dyed materials in terms of their high-efficiency, versatility, and fabrication simplicity.

VI. REFERENCES

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