Electrically conductive thin-film color filters made of single-material indium-tin-oxide

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Periodic multilayer thin-film color filters (CFs) entirely made of nano-porous indium-tin-oxide (ITO) with tunable refractive index are explored. The interference CFs are electrically conductive and transmit light in the pass-band spectral region without absorbing light outside of the pass-band region. The transfer matrix method, implemented in conjunction with a genetic algorithm optimization method, is used to design the optimal thickness and refractive index of layers for red, green, and blue (RGB) filters. RGB filters with 2 pairs (4 layers) are experimentally demonstrated by using a porosity-controlling deposition technique for a single material—ITO. A maximum transmittance of 95.2% and a minimum transmittance of 26.2% are demonstrated for the four pairs of a red filter structure. A light recycling structure using these RGB filters is proposed to reduce the optical loss occurring in conventional liquid-crystal display systems. © *2011 American Institute of Physics*. [doi:10.1063/1.3592222]

I. INTRODUCTION

Liquid crystal display (LCD) is the dominant technology for flat panel display (FPD) applications ranging from low-power handheld mobile phones to large scale high-definition (HD) televisions. The core components of an LCD are a backlight unit (BLU), a diffuser plate, optical films such as Brightness Enhancement Film (BEF) and Dual Brightness Enhancement Film (DBEF), a liquid crystal (LC) with thin-film transistors (TFTs), polarizers, and color filters (CFs). Light emitted by the BLU should go through all components of the LCD until it hits the screen. Although it is desirable that the efficiency of the LCD system is as high as possible, optical loss mechanisms exist in each step; usually less than 5% of total light output from a light source is available at the screen of the LCD system.[1] In particular, the optical absorption loss of a pigment CF is the largest among the LCD components (such as polarizers, TFT array, and a diffuser plate) because it transmits only a specific color range and absorbs light outside the range. This results in an approximately 66% optical loss due to the pigment CF. One challenge is to reduce this optical loss for enhanced optical efficiency of the entire system while not deteriorating the properties of each component. An interference CF has been of interest when considering the advantages of a sharp transmittance band edge, high transmittance in the pass-band spectral region, and especially high reflectance in the outside the pass-band region.[2,3] Typically, the structure of interference CFs consists of periodic multilayer structures which are made by multiple depositions of low- and high-refractive-index (n) materials on top of each other, i.e., material pairs of SiO_2/TiO_2 or GaN/AlN.[4,5]

In this article, we propose and demonstrate conductive interference CFs for the red, green, and blue (RGB) spectral ranges. The transfer matrix method[6] implemented in conjunction with a genetic algorithm (GA) optimization method[7] is used to calculate the optimal thickness and refractive index of three RGB conductive-periodic multilayer CFs consisting of a single material—indium-tin-oxide (ITO). Fabrication methods and transmittance measurements of the ITO CFs are also presented.

II. CONCEPTUAL IDEA FOR AN LCD SYSTEM WITH INTERFERENCE CFS

An LCD system having novel interference CFs is presented in which higher optical efficiency and a wider color gamut (compared with conventional LCDs) are enabled. The proposed LCD system, illustrated in Fig. 1, has interference CFs as a photon recycling structure to redirect backward the undesired wavelengths which are not within the desired transmittance spectral range. In this structure, interference CFs have high transmittance only at a specifically designed wavelength range while reflecting outside that wavelength range [see Fig. 1(b)]. For this reason, the interference CF can save the optical energy which is absorbed (and thus lost) in conventional pigment CFs; as a consequence, by using interference CFs, light from the BLU is utilized more efficiently.

In order to realize the efficient interference CFs, a large refractive index contrast between the high- and low-refractive-index materials is desired. Because the refractive index of a material is a material constant, the choice of material pairs constituting the CF is normally limited. However, technologies

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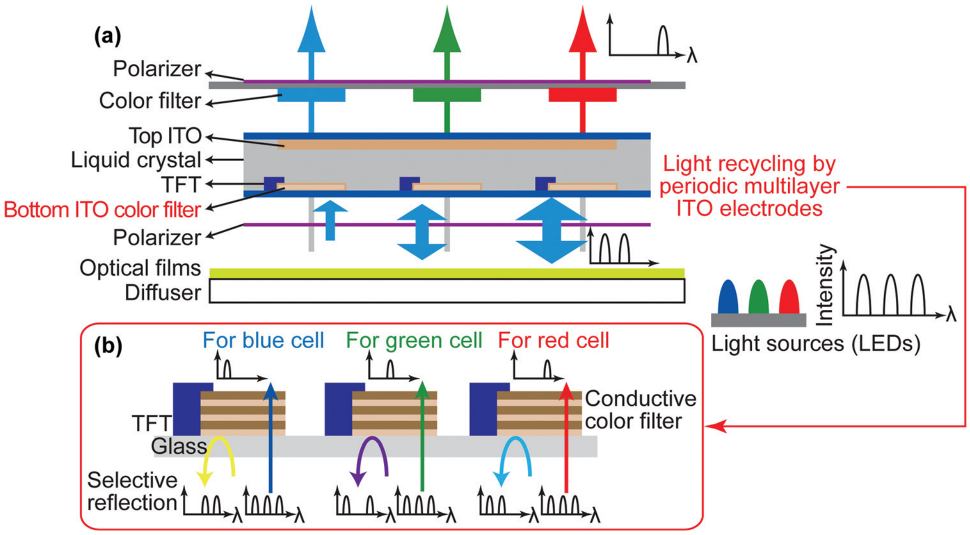

FIG. 1. (Color online) (a) Schematic illustration of the light recycling mechanism by conductive ITO electrodes, which also function as an interference color filter, in an LCD system; and (b) enlarged cross-sectional view of the bottom ITO CFs with their expected function.

to tune the refractive index of one material have been developed recently; one such technology is oblique angle deposition.[8] In the oblique angle deposition technique, the porosity of a material can be precisely controlled to attain a targeted refractive-index value. The deposition technique has been successfully demonstrated for anti-reflection coating,[7,9] distributed Bragg reflector (DBR),[10] and ITO electrode[11] applications and, as we present here, it opens a way to fabricate efficient CFs with only a *single* material—e.g., ITO.

Most materials that are transparent in the visible spectrum are dielectrics with low electric conductivity. For the proposed LCD system, as another special feature of our interference CFs, we propose that adding the function of optical filtering to the bottom ITO electrode can be a useful and viable approach. ITO electrodes, which sandwich the LC, are used to induce an electrical bias to the LC. Accordingly, the interference CFs made of the ITO electrode should have properties of high electric conductivity as well as high optical transmittance in order to allow certain wavelengths from the light source to be selectively transmitted or reflected.

III. DESIGN AND SIMULATION OF RED, GREEN, AND BLUE FILTERS

In DBR and interference CF design, the well-known quarter wavelength ($\lambda/4$) approximation[12] has been used for choosing the layer thicknesses. In DBRs, λ is the wavelength in the center of the stop-band (high reflectance) spectral region but is not the center wavelength of the pass-band (high transmittance) spectral region. For the design of periodic multilayer structures with a targeted pass-band parameter, currently there are not many theories available to well predict the layer thicknesses. Nevertheless, by changing the thickness ratio of the high/low refractive index layers in a multilayer structure, the pass bands and stop bands of the transmittance spectrum can be tuned. This property enables the design and optimization of periodic multilayer structures using numerical methods. The starting structure for an optimization using a GA is an alternation of low-refractive-index ITO with layer thickness t_{low} and high-refractive-index ITO with layer thickness t_{high} deposited on glass substrate. Based on an experimental database,[13] an ITO film with a porosity of 70% and a refractive index of $n_{ITO} \approx 1.33$ shows very reasonable mechanical stability. As a result, in our simulation, we choose a refractive index of $n_{ITO} \approx 1.33$ with a porosity of 70% for the porous ITO layer (the low-refractive-index material) in the multilayer structure. The typical refractive index of $n_{ITO} \approx 2.1$ is used for the dense ITO layer (the high-refractive-index material). Note that for both porous ITO and dense ITO layers, the extinction coefficient k is neglected to simplify the simulation. In order to find a thickness combination suitable for the three different RGB CFs by the GA, every member of the population should have a Figure of Merit (FOM) indicating the fitness value of this individual as used in the GA. We first set the spectral range where a CF is supposed to transmit light. The blue/green and green/red boundary wavelengths are chosen as $\lambda_{blue/green} = 490$ nm and $\lambda_{green/red} = 580$ nm, respectively, consistent with conventional pigment CF transmittance spectra.[14] Next, the standard to evaluate the fitness of the CFs is established by using $T(\lambda)$, the actual transmittance spectrum of CF as a function of wavelength. Ideally, a CF should show 100% transmittance and 100% reflectance in pass-band and stop-band region of the spectrum, respectively. The FOMs for blue, green, and red filters can be expressed by the following three equations.

$$FOM_{red} = \sum_{\lambda=400\,\text{nm}}^{\lambda_{green/red}} [1 - T(\lambda)] + \sum_{\lambda=\lambda_{green/red}}^{700\,\text{nm}} T(\lambda), \qquad (1)$$

$$FOM_{green} = \sum_{\lambda=400\,\text{nm}}^{\lambda_{blue/greeen}} [1 - T(\lambda)] + \sum_{\lambda=\lambda_{blue/greeen}}^{\lambda_{green/red}} T(\lambda) + \sum_{\lambda=\lambda_{green/red}}^{700\,\text{nm}} [1 - T(\lambda)], \qquad (2)$$

$$FOM_{blue} = \sum_{\lambda=400\,\text{nm}}^{\lambda_{blue/greeen}} T(\lambda) + \sum_{\lambda=\lambda_{blue/greeen}}^{700\,\text{nm}} [1 - T(\lambda)]. \qquad (3)$$

Table I shows the GA optimization results having the highest FOMs for three types of CFs. For the red filter structure, the

TABLE I. Summary of designed structure of red, green, and blue filters.

Layer	Material	Porosity	Refractive index at 500 nm	Thickness of three color filters		
				Red	Green	Blue
Ambient	Air	—	1.00	—	—	—
High index layer	Dense ITO	0%	2.10	56 nm	257 nm	73 nm
Low index layer	Porous ITO	70%	1.33	86 nm	97 nm	111 nm
Substrate	Glass	0%	1.46	—	—	—

optimized layer thicknesses are 56 nm for the dense ITO layer and 86 nm for the porous ITO layer. Similarly, for the blue filter structure, the layer thicknesses are 73 nm for the dense ITO layer and 111 nm for the porous ITO layer. These structures of red and blue filters correspond to a DBR structure reflecting at wavelengths of around 605 and 460 nm, respectively, which is consistent with the quarter-wavelength approximation. That is, red and blue filter structures have essentially the same function as DBR mirrors reflecting in the blue and red regions, respectively. However, for the green filter structure, the optimized layer thicknesses are 257 nm for the dense ITO layer and 97 nm for the porous ITO layer. Because two stop-band regions are needed for the green filter (one in the red, the other one in the blue) the typical quarter-wavelength approximation cannot be used for the optimization of the green filter. Note that the numerical optimization enabled by the GA expands our design capability to all types of periodic multilayer structures.

Figure 2 shows the calculated transmittance of structures specified in Table I. For all three types of CFs, two-pair, three-pair, and four-pair structures show a minimum optical transmittance of 40%, 10%, and 5%, respectively. When increasing the layers from two pairs to four pairs, the maximum-to-minimum transmittance ratio increases significantly. Further increasing the number of pairs for all three types of CFs will push maximum reflectance and maximum transmittance toward 100%. However, the absolute amount of the increase in reflectance and transmittance is not very significant (only about 5%). From Fig. 2(c), the full width at half maximum (FWHM) of blue, green, and red filters are 104 nm, 112 nm, and 120 nm, respectively. The typical pass-band-center wavelengths for blue, green, and red filters in display applications are 452 nm, 534 nm, and 620 nm, respectively,[14] which correspond approximately to the three primary colors.

IV. FABRICATION METHOD OF ITO FILMS

Unlike other dielectric materials such as SiO_2 and TiO_2, ITO is somewhat absorptive at visible wavelengths as a result of its electrical conductivity. In order to maintain high transparency in a real device application, the thickness of an ITO multilayer structure should be generally restricted. For this reason, only CFs with one to four pairs of alternating layers are fabricated for characterization in the following experiments. Regarding the experimental setup, we use 90% indium oxide/10% tin oxide (wt. %) for our ITO source material. Inside our e-beam evaporation system, we use a sample mount that has a computer-controlled motor that can turn the sample to any deposition angle between 0° and 90°. During the deposition, we keep the deposition rate steady at 0.3 nm/s, as measured by a quartz crystal monitor inside the chamber. After the deposition, all samples are annealed, using a rapid thermal annealing (RTA) system, in oxygen ambient at 550 °C for 1 min to enhance its transparency. Given the porosity of the ITO in our simulation, the deposition angle (beam flux incidence angle) parameter is chosen according to literature references.[13,15] We use variable-angle spectroscopic ellipsometry to determine the refractive index and thickness of each ITO coating.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows the SEM images of a two-pair green filter and a three-pair red filter on glass substrates. We give the total CF thickness values in each figure. Compared with the

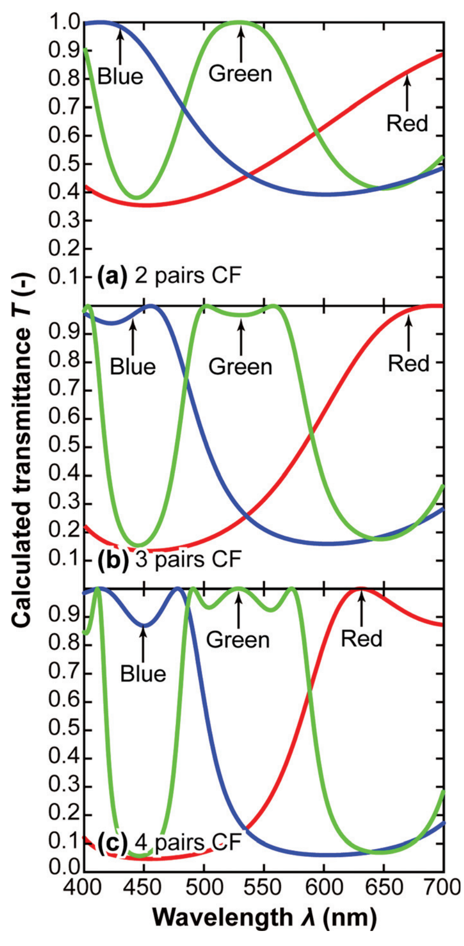

FIG. 2. (Color online) Transmittance simulation of red, green, and blue filters with (a): 2 pairs, (b): 3 pairs, (c): 4 pairs of high/low refractive index layers.

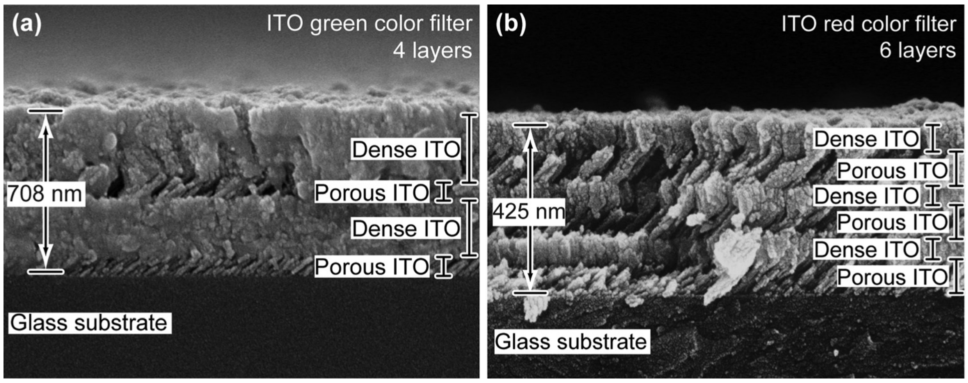

FIG. 3. SEM images of (a): 2 pairs green filter (total thickness: 425 nm) and (b): 3 pairs red filter (total thickness: 708 nm) implemented by variable angle deposition of ITO on a glass substrate.

designed structure given in Table I, which specifies the total thickness to be 708 nm for a two-pair green filter and 426 nm for a three-pair red filter, our experimental structures meet the designed structure very well with respect to the total CF thickness.

Figure 4 shows the measured and calculated transmittances of two-pair blue, green, and red filters. The inset of each figure shows a schematic diagram for each film structure. Generally, the measured minimum transmittances for the three types of CFs are in the 50%–60% range. All three CFs show well-matched maximum and minimum transmittance locations compared to the calculated results.

We further verify the effect of an increasing number of layer pairs on transmittance with the red filter. Figure 5 compares the measured transmittance among two-, three-, and four-pair red filters. The maximum transmittance measured on two-, three-, and four-pair red filters are 85.6%, 92.2%, and 95.2%, respectively. The measured values of the minimum transmittance on two to four-pair red filters are 54.9%, 38.1%, and 26.2%, respectively. So the maximum-to-minimum transmittance ratios for two-, three-, and four-pair red filters are 1.56, 2.42, and 3.63. The maximum and minimum transmittances increase and decrease respectively when the number of pairs increases. This characteristic closely follows the calculation result. Note that all CFs in our experiments are made of the single material-ITO—that is, without using a combination of different dielectric materials.

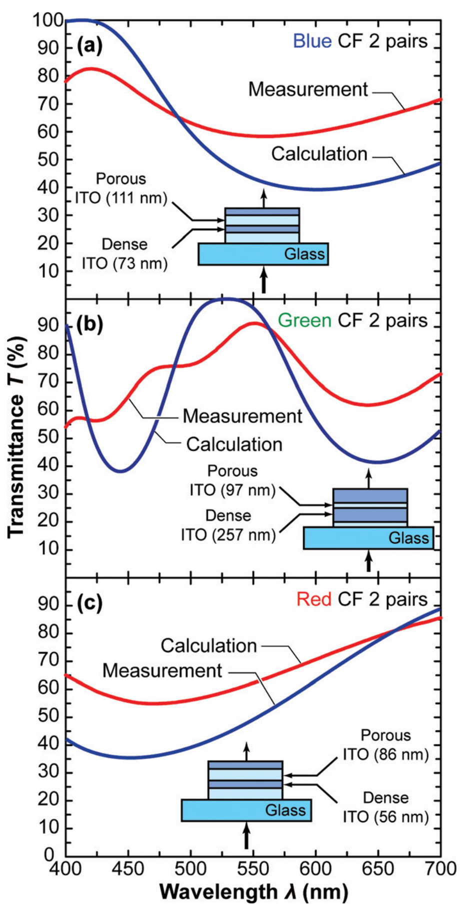

FIG. 4. (Color online) Calculated and measured optical transmittances of two-pair (a) blue, (b) green, and (c) red filters as a function of wavelength. The designed thicknesses for the three color filters are shown in the insets.

As we previously mentioned in this article, because of the conductivity of ITO and high reflectance in the stop-band spectral region for our CF, it has a potential for light recycling in the LCD application. Because optical absorption loss through the LCD panel is an important loss mechanism, various techniques have been developed to reduce this loss. DBEF[16] is a representative technology that significantly enhances brightness of an LCD. Unlike DBEF, which reduces polarizer absorption, our periodic-multilayer interference CFs will reduce absorption by conventional pigment CFs, which causes the largest optical loss in an LCD system. Instead of passing white light through an absorbing pigment CF, ITO electrodes acting as interference CFs can replace each pixel of pigment CF in an LCD color cell. Every pixel is designed to transmit light in one spectral region and reflect in other spectral regions. Light reflected by our novel CF electrodes will be reflected forward by the backside mirror, and then the

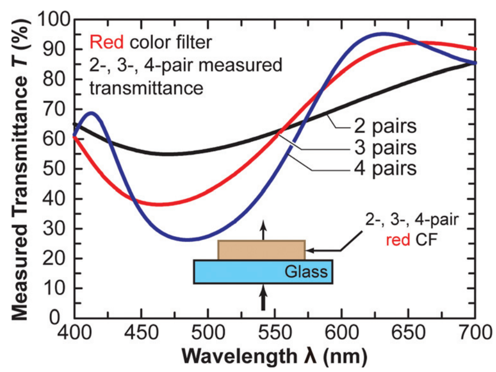

FIG. 5. (Color online) Transmittance measurement of red filters with 4 layers (two pairs), 6 layers (three pairs), and 8 layers (four pairs) on a glass substrate as a function of wavelength.

light has a good chance to be transmitted through other pixels of the display. The proposed light recycling mechanism is illustrated in Fig. 1. Generally, after passing through the interference CF, the purity of the light spectrum is enhanced (i.e., the spectral broadening is reduced) because the CF have a high transmittance at specific wavelengths. This effect contributes to widen the color gamut, that is, the portion of the color space represented by the LCD.

VI. CONCLUSIONS

In summary, oblique angle deposition, as a promising technique for refractive-index manipulation, is successfully implemented in a periodic-multilayer interference CF for the LCD application. By alternating high- and low-refractive-index ITO layers on glass substrate, red, green, and blue filters are fabricated. Transmittance measurements verify the effect of color filtering by three different two-pair ITO films (RGB films). Increasing the number of pairs with the same pair thickness generally enhances the performance of all three types of CFs. As an experimental verification, multiple pairs (2, 3, and 4 pairs) of red filters are successfully fabricated and the filters closely match the expected transmittance. These CFs presented here can be implemented in the conventional ITO electrode, in which a light-recycling structure is proposed to reduce the optical loss occurring in LCDs using absorptive pigment CFs.

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