Demonstration of color filters for OLED display based on extraordinary optical transmission through periodic hole array on metallic film

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1. Introduction

Organic light emitting diodes (OLEDs) constitute one of the most applicable technologies for next generation display. The full-color display of OLEDs is generally realized by two approaches: multi-emission layers structures [1] and color filters (CF) [2]. The former is using independent RGB luminous source and realizes true color by adjusting blending ratios. The demerits include high cost, low efficiency, and limited durability [1]. The more feasible way is to gain the RGB light by locating color filters after a white OLEDs source.

Conventionally, color filters are fabricated from dyes or pigments with RGB colors [1]. Lately, a brand new method for OLEDs structure based on extraordinary optical transmission (EOT) through metallic periodic holes has been introduced [3,4]. The cutting edge is the metallic hole array plays dual roles of metal cathode and light extracting emission facility [4]. In previous study, a novel multicolor filter structure and theoretical transmission spectra have been realized [4]. In this work, the influences of crucial parameters as film thickness, diameter as well as period are taken into account and color filters featuring brightness and monochromaticity are achieved experimentally. The color filter displayed improved angle invariance, polarization independence, and oblique incidence transmission strength than previous theoretical work [4]. Simulation and analysis of the structure are based on an extensively used Photonic Simulation Software OptiFDTD (Optiwave Corporation) [5]. In this way, a practical color filter for OLEDs display is experimentally realized and analyzed. Such filters not only can contribute to the color fibers for OLED, but also can play the role of the electrode layer for OLED, and even enhance the luminescent efficiency [3].

2. Theory and proposed structure

With periodic structure perforated on Ag metal as Fig. 1, the incident light will be easily coupled into Surface Plasmon Polaritons (SPPs) because of phase matching condition [6,7]. An appropriate period should be chosen to ensure resonant wavelength centering on tricolor region.

Circular hole array is selected for its polarized incidence isotropy compared with rectangular, square holes or slits [6,8,9]. Caused by its isotropic symmetry, the Local Surface Plasmon (LSP) modes excited are all the same and are all parallel to incident polarized direction [6,8,9]. So circular hole array's coupling effect with SPPs is much less dependent on incident polarization states. SEM pictures of studied samples are shown in Fig. 1, parameters such as period, hole shape, metal film thickness, and the measurement of hole are optimized to enhance light extraction quality and monochromaticity. Expected result is improved OLEDs' performance norms in brightness, purity, and definition by ensuring single resonant peak, narrow transmission bandwidth and strong transmission strength.
Energy into other directions. Fig. 2a shows the transmission intensity for zero order transmission, while higher order will distribute energy. Because (1, 0) peak enables larger energy concentration over thick film is also disqualified because of great peak strength and SPPs peak. And thus causes the distinction of LSPs and SPPs peaks both in 150 nm and 160 nm case. For thickness over 180 nm, uncoupling eliminates the influence of LSPs and gives a narrower and lower peak [10,11]. Note that in tricolor filters, wide peak will allow in undesired light and strongly harm the purity. Over thick film is also disqualified because of great peak strength reduction. The most feasible thickness lies between 200 nm and 500 nm as shown in Fig. 2b. Such a region uncouples two surfaces SPPs and enables an ideal band width within 100 nm.

Another factor to discuss is the hole diameter. The aim is to lower color filters’ self-permeated peaks interference by ensuring that (1, 0) peak is much larger than (2, 0). Here in Fig. 3a period is chosen as 500 nm but diameters are different. The peak intensity shows consistent increase with the hole diameter because larger holes make SPPs evanescent waves coupling easier [11]. Such intensity enhancement shows no prejudice on both (1, 0) and (2, 0) order. The demand of ensuring single resonant peak requires (d/p)^2 in Fig. 3b. Findings are that the desirable situation appears when (d/p)^2 is around 0.3–0.5, because in this case the (1, 0) peak can be 5–10 times stronger than the unwanted (2, 0) peak.

3. Experimental results and discussion

As discussed, the optimized case is that (1, 0) peak targets on tricolor central wavelength, etched thickness is thicker than
160 nm, and feasible duty factor \((d/p)^2\) is around 0.3–0.5. So in etched samples, thickness of metal layer is chosen as 200 nm.

Fig. 4a shows the calculated transmission spectra of structure parameters as: \(p = 560\) nm, \(d = 360\) nm, \(t = 200\) nm for red light; \(p = 460\) nm, \(d = 280\) nm, \(t = 200\) nm for green light; and \(p = 300\) nm, \(d = 160\) nm, \(t = 200\) nm for blue light. Their central wavelengths precisely target on that of RGB according to CIE standard [12]. The real transitivity is shown in the same diagram, it is shown all transmission strength are qualified.

We use white light source (halogen lamp) as our incidence light source, which has broad, strong and flat transmission from 500 nm to 700 nm. It is because EOT is both near field and far field transmission and their transmission spectrum are the same. We measure the output EOT far field spectrum and this is also the near field spectrum for compact display case. Experimental results have confirmed theoretical spectra and analysis made above. Five samples are chosen with parameters as follows: \(p = 560\) nm, \(d = 300\) nm and \(t = 100\) nm respectively. (c) Measured angle dependence and angle transmission rate of same parameters in (b) with inclination angle ranging from positive 30° to negative 30°. The inclination angle is schematically shown on the right of this figure, it is the oblique incidence case. The left axis aligning to central wavelength position (Red and Green) and the right axis aligning to transmission strength (Red eff and Green eff).

Results in Fig. 4b show the influence of hole thickness and diameter. Thickness as 100 nm gives a much broader transmission band than that of 200 nm. This is because in thinner film tunneling resonance is much stronger as analyzed above. It is obvious that 100 nm wide hole shows blue shift than others. This is because threshold of circular hole diameter is about 200 nm [8]. If the
diameter is blow this value, the LSP resonance of hole shows smaller cut-off wavelength. Thus causes the blue shift of resonant wavelength in spectra [8].

Fig. 4c shows experimental transmission spectra of Red and Green light. Filters’ central wavelengths are 700 nm for red light and 560 nm for green light. Their full width at half maximum (FWHM) are both within 100 nm respectively. Although the thickness is only 200 nm, monochromaticity and narrow band are guaranteed. The increase of film thickness will greatly improve bandwidth as manifested in Fig. 2b. The CCD picture and averaging color of output light are shown in the same figure, pure color is well reserved as demonstrated by near field output color. The oblique incidence wavelength dependence is a crucial performance in display application in real situation [1–3]. Fig. 4d shows us the angle dependence and transmission strength in oblique incidence situation. Largest peak shift is only 30 nm when incidence angle changes from positive 30° to negative 30°. Under this scale, the permeated light still locates in monochromatic region. So structure shows keeping of ensuring monochromaticity in oblique incidence. The transmission strength is also crucial. In oblique incidence case, more than 60% of orthogonal transmission energy is conserved in oblique incidence case. This performance ensures clarity and definition in real OLED display. Further improve of angle invariance can be achieved by inducing periodic drape or fractal slit [6,9].

Simulation and experimental results show good conformity with CIE standard: the central wavelengths of the three structures shown in Fig. 4c are 700 nm (R), 560 nm (G) and 430 nm (B) (only theoretical curve), which are concisely aligning CIE standard central wavelength, respectively [12]. However, we show only theoretical spectrum of blue light because our white light source has too little light strength in blue light region to measure. But the theoretical spectrum also shows conformity. Most importantly, polarized incidence wavelength independence is well achieved (the polarized case is schematically shown in Fig. 1). Peak shift is ensured within 5° when the largest polarized angle is 60° as shown in Fig. 5. Experimental results confirm the effectiveness of optimization work. It is manifested a good control of resonant strength as well as narrow band and large normalized transmission strength (Blue light is excluded, but this defect can be overcome by increasing transmission strength through increasing independent bias on its independent light source. It is because each RGB filter has its own independent white light source shown in our previous work [4]). In this way, monochromaticity, narrow half peak width and large normalized transmission strength are realized simultaneously.

As discussed in previous work, resolution is the last factor to consider [4]. The pixel numbers standard for display are: VGA 640 x 480, SVGA 800 x 600, and XGA 1024 x 768, SXGA 1280 x 1024, and UXGA 1600 x 200 [1,4]. Since samples’ fabrication area is 0.2 x 0.2 mm², it is suitable for display in a typical example as 14 in. XGA. Because its standard visual area size is 285.7 x 214.3 mm², each pixel pitch is 285.7/1024 or 214.3/768 = 0.29 mm. Under this scale, the number of periodicity in filters is 160 (R), 196 (G), and 300 (B), respectively. This filter is qualified for having more than 100 periods, but the dimension is just 56 μm (R), 46 μm (G), and 30 μm (B). Since each filter is less than 60 μm, total pixel pitch can be less than 180 μm. Compared with the highest definition UXGA 1600 x 1200, of which visual dimension is commonly 15 inch with diameters as 306.1 x 229.6 mm², its pixel’s dimension is 191 μm. Cell of color filter is small enough to realize such high resolution because current pixel pitch is smaller than the smallest threshold 191 μm. Because the EBL scale limit is 0.5 mm–1 mm, it is large enough for real manufacturing as one pixel and compose arrays of these pixels to achieve display matrix. The RGB elements of a traditional color filter’s pixels are fabricated with colorants such as dye and pigment [1–4]. Compared with those traditional color filters, this filter is suitable for mass production for its tiny size. Also, the interval of each color array is made of metal film, its strong absorption can effectively prevent light intervention, and light leakage, which will ensure display quality and clarity and promote large-scale integration.

4. Conclusion

In conclusion, experimentally improving performance of OLED display color filters based on EOT by taking metals’ absorption, actual transmission strength and crucial parameters such as period, hole shape, thickness and diameter into consideration is achieved. The best parameters for tricolor filters featuring strong peak, narrow width and high purity are also obtained through experiment. Improved features as tiny scale, angle invariance and oblique incidence transmission efficiency and polarization independence are useful for OLED design and manufacturing guidance in high compact display application.

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References


Fig. 5. Measured transmission spectra under polarized light incidence angle ranging from 0° to 60°, the polarized angle θ is schematically shown in Fig. 1.

