Luminous-efficiency improvement of photovoltaic-device-integrated organic light-emitting diode by applying guiding mode resonance filter

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***Abstract*-Single layer RGB-guided mode resonance filters (GMRFs) of unified thickness were designed to reflect the OLED emission to viewers and pass the ambient light to PV. The luminous efficiencies are improved from 50% to 64.7%, 63.2%, and 61.6% for red, green, and blue colors, respectively. By broadening the GMRF bands, the luminous efficiency can be maintained higher than 60% and the color deviation are negligible under oblique incidence condition.**

keywords **:** light recycling, photovoltaic integrated organic light-emitting diodes (PV-OLEDs), guide mode resonance filter (GMRF).

I. INTRODUCTION

Organic electroluminescent (EL) devices have been attracting widely due to their application to flat panel display and solid-state lighting. Recently, organic light-emitting diodes (OLEDs) have been reported to be integrated with photovoltaic (PV) devices as a tandem structure [1]. Such structure improves the degradation of display contrast ratio of OLEDs due to the ambient reflection and recycles the trapped light due to total internal reflection. However, the luminous efficiency of this structure decreases due to the absorption by the integrated PV device. In our previous researches [2]-[3], we designed a distributed Bragg reflector (DBR) between OLED and PV devices to improve the luminous efficiency from 50% to 85% and maintain the contrast ratio. While the DBR requires quite a large stack of layers, the thicknesses of layers are different for red, green, and blue colors. These make the process of full color panel complicated. Resonant grating filter represents an alternative solution to make dichroic filters. The guided-mode resonance (GMR) in grating structure can be designed to attain 100% peak response at a desired wavelength [4] and be used in either transmission or reflection color filters [5]-[6]. However, the performance of guided-mode resonance filters (GMRFs) strongly depend on the incident angle, i.e., the narrower the spectral response is, the tighter the angular tolerance becomes. In this paper, we design a GMRF to replace the DBR inside the OLED integrated PV device and improve the angular tolerance to have better performance in luminous efficiency, contrast ratio and color reproducibility.

II. Method

In order to realize a full color reflective panel, three different kinds of GMRFs were designed to get high reflection for red, green and blue colors, respectively. A conventional OLED spectrum [6] was used in our simulation. In our previous study, we confirmed that more than 50% of luminous intensity was absorbed by the PV devices [2]-[3]. The output spectrum and the luminous efficiency of the PV device integrated OLED were calculated by Eqs. (1) and (2). We choose silicon as the material of grating for the sake of fabrication process. The CIGS (copper indium gallium selenide) thin film solar cell was used as the PV device in our integrated structure [3], which is one of potentially dominant solar cells. The GMRF is placed between the OLED and PV devices as shown in Fig. 1. Due to the strongly angular-dependence of GMRF, the 90° rotational symmetry grating is not suitable for both p- and s-waves as the incident angle increases. Therefore, the rectangular shape were designed and examined. We considered the luminous efficiency, the contrast ratio and their color reproducibility not only under normal incident but also under the oblique incident condition. For a conventional OLED display, the contrast ratio is about 100,000 or more. And we examined the color deviation by calculating the color coordinates (x, y) based on CIE 1931 color space chromaticity diagram. The simulations were mainly conducted by using Rsoft^{TM}, a commercialized diffractive optical simulation tool for sub-wavelength optical devices.

$$spectrum_{oled-GMRF-PV} \equiv \frac{1}{2} spectrum_{oled} \times \left[1+[r_{GMR}+t_{GMR}\times r_{PV}\times t_{GMR}\times(1/(1-r_{GMR}\times r_{PV}))\right] \quad (1)$$

$$luminous\ efficiency \equiv \frac{\int_{\lambda_1}^{\lambda_2} spectrum_{oled-GMRF-PV}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} spectrum_{oled}\, d\lambda} \quad (2)$$

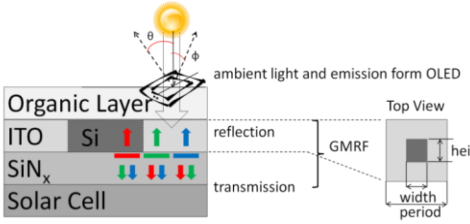

Fig. 1 Schematic diagram of the OLED integrated PV device with the GMRF design.

III. RESULTS

Considering the integration of PV device and OLED [2], the GMRF was made between organic layer (n~1.79) and SiN$_x$ layer (n~1.9), as shown in Fig. 1. The reflection spectrum of GMRFs and emission spectrum of PV-OLED are shown as Fig. 2(a). The reflection spectra of RGB-GMRFs split into two peaks due to p- and s-wave incident on the rectangular shape. We designed the GMRF1 to have specific reflection peaks corresponding to the emission peaks of PV-OLED, respectively. The luminous efficiencies are improved form 50% for the device without RGB-GMRF1s to 57.6%, 59.0% and 60.7%. As we increase the incident angle, the luminous efficiency decreases to 56.9, 57.8, and 59.7 for φ =5^o and 56.4%, 58.1%, and 60.6% for θ=5^o. Because of the difference response between p- and s-waves, we increased the height of rectangular grating to broaden the reflection band of GMRFs to recycle this broad OLED emission spectrum efficiently. As shown in Fig. 2(a), the reflection spectrum of GMRF2 indeed broader while the reflectance decreases. The luminous efficiencies for RGB-GMRFs are improved to 64.7%, 63.2%, and 61.6%. As the incident angle increases, the luminous efficiency still maintain at 63.6%, 62.7%, and 61.8% for φ=5^o and 60.9%, 61.7%, and 60.7% for θ=5^o. As shown on Fig. 3(a) and Fig. 3(b), the color deviation for the RGB-GMRF1 and GMRF2 are negligible. The period, width, height and thickness of the gratings are listed in Table 1 and the CIE coordinates and luminous efficiency of GMRFs are listed in Table 2.

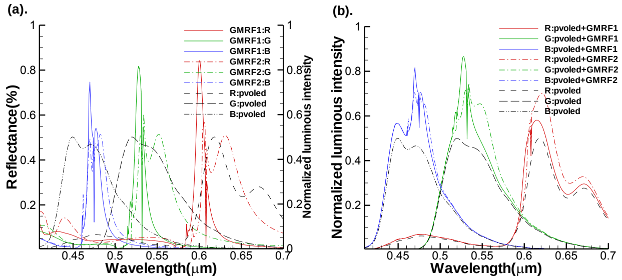

Fig. 2 (a) Reflection spectra of GMRF1 and GMRF2. (b) Emission spectra of PV-OLED with GMRFs. (black lines: emission spectrum of PV-OLED).

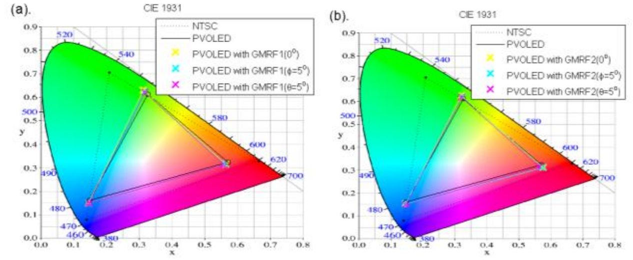

Fig. 3 Color reproducibility of PVOLED with (a) GMRF1 and (b) GMRF2 under oblique incident conditions (θ =5^o,φ =5^o).

IV. CONCLUSION

A novel method was demonstrated to improve the decreasing of luminous efficiency for PV-OLED. We designed the RGB-GMRFs of unified thickness but with different period, width and height to replace the complicated DBR structure used in our previous study. And we broaden the reflection band by modulating the response of p- and s-waves to the grating shape but not increasing layers. The color deviation can also be made negligible. The novel filter based on RGB-GMRFs is of simpler structure and can be more compatible to the fabrication process of PV-OLED.

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Table 1 Geometrical parameters of grating: GMRF (a) with and (b) without cladding layer.

	GMRF1			GMRF2		
Color	Red	Green	Blue	Red	Green	Blue
Period(μm)	0.32	0.28	0.25	0.32	0.28	0.25
Width(μm)	0.11	0.09	0.07	0.11	0.09	0.07
Height(μm)	0.12	0.10	0.09	0.2	0.15	0.1
Thickness(μm)	0.06	0.06	0.06	0.06	0.06	0.06

Table 2 CIE coordinates and luminous efficiency of GMRFs

	GMRF1		
Color	Red	Green	Blue
PVOLED	0.573,0.324	0.328,0.617	0.149,0.161
PVOLED with GMRF	0.567,0.318/ 1.153	0.313,0.634/ 1.181	0.146,0.150/ 1.215
PVOLED with GMRF (φ =5^o)	0.564,0.316/ 1.138	0.317,0.626/ 1.155	0.147,0.149/ 1.194
PVOLED with GMRF (θ =5^o)	0.562,0.316/ 1.128	0.318,0.625/ 1.161	0.146,0.149/ 1.213
	GMRF2		
PVOLED with GMRF	0.580,0.313/ 1.294	0.324,0.628/ 1.263	0.145,0.153/ 1.233
PVOLED with GMRF (φ =5^o)	0.577,0.313/ 1.272	0.325,0.624/ 1.253	0.146,0.152/ 1.235
PVOLED with GMRF (θ =5^o)	0.567,0.316/ 1.217	0.323,0.622/ 1.233	0.147,0.151/ 1.214