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Design of high-contrast OLEDs with microcavity effect

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Abstract: There is a large demand for Organic Light-Emitting Displays (OLEDs) with higher contrast, particularly for outdoor applications. We show that lowering the reflectance of OLEDs, which is required for increasing the contrast, can also lead to a reduction of their efficiency when a small microcavity effect is not maintained in their structure. We describe in details the design of high-contrast bottom-emitting OLEDs that have low reflectance but still maintain a small cavity effect for efficient emission.

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OCIS codes: (310.6845) Thin film devices and applications; (230.3670) Light-emitting diodes; (160.4890) Organic materials

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1. Introduction

As more electronic devices with display are targeted for outside use (i.e. cameras, telephones, music players), it becomes increasingly important to solve the problem of contrast of the display under strong external lighting, more particularly under sunlight. The contrast can be expressed numerically as a ratio of the brightest and darkest elements of a display, taking into account the ambient light reflected on it. In the case of liquid crystal displays, generally with a white backlight source, this contrast is related to the transmittance values of "on" and "off" pixels [1]. In the case of light emitting devices, such as organic light emitting displays (OLEDs), the transmittance is replaced by the luminance of the brightest and darkest pixels, and the contrast ratio (CR) is expressed as [2]:

$$CR = \frac{L_{on} + R_D L_{ambient}}{L_{off} + R_D L_{ambient}}, \tag{1}$$

where L_{on} and L_{off} are the luminance values of "on" and "off" pixels on the display, respectively, $L_{ambient}$ is the ambient luminance, and R_D is the luminous reflectance of the display, given by

$$R_D = \frac{\int_{\lambda_1}^{\lambda_2} V(\lambda) \cdot R(\lambda) \cdot S(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} V(\lambda) \cdot S(\lambda) d\lambda}, \tag{2}$$

$V(\lambda)$ being the photopic curve (an eye sensitivity spectrum standard defined by CIE 1931 [3]) $R(\lambda)$ is the reflectance of the pixel (on or off), and $S(\lambda)$ is the source of ambient light (for calculation, CIE standards such as D65 are used). A *CR* value of 30 is typical for a television in a living room, while a cinema can achieve a *CR* of 1000. Typical luminance values for ambient light and display devices are given in Table I. As seen in Eq. (1), without ambient light, *CR* is limited by the darkness of the off pixel, which is not as dark for liquid-crystal display (due to its required back illumination) as it is for emitting devices (Table I). When ambient light is considered, the viewer is seeing the light reflected on the pixels and the only way to prevent it from affecting too much *CR* is to increase the ratio $L_{on}/R_D L_{ambient}$ by (i) increasing L_{on} or (ii) reducing R_D to 1% or less (see Table II). Thus an ideal display should have a high L_{on}/L_{off} ratio and $L_{on} >> R_D L_{ambient}$. Emitting displays naturally have a very high

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L_{on}/L_{off} ratio, sometimes incorrectly quoted by vendors as the contrast ratio. Increasing L_{on}, costs power, an important consideration for portable applications.

Table I. Typical values of luminance for different ambient light conditions and display devices [4, 5].

SOURCE	TYPICAL LUMINANCE L [CD/M^2]
Clear day	10^4
Heavily Overcast day	10^2
Bright moonlight	10^{-2}
Moonless overcast night	10^{-4}
CRT	90—150
CRT, "off" pixel	0.01
LCD	400—500
LCD, "off" pixel	0.72
OLED	70—600
OLED, "off" pixel	0

In organic light emitting displays (OLEDs), electrons and holes are brought together from two electrodes to an organic layer in which they recombine and emit light. We distinguish bottom- and top-emission OLEDs, for which emission occurs through a transparent anode/substrate or a semi-transparent top anode, respectively. In most OLEDs, a thick metal layer is used as the electrode material on the non-emitting side; the light reflection from such an electrode is high and results in a low *CR* value. Replacing the metal electrode by a transparent conductor (such as ITO) can contribute to lower the OLED reflectance, but this generally results in lower carrier injection into the organic layers. For example, the cathode requires a material with a low work function (such as Ca, Mg:Ag, or Al/LiF), which generally possesses high reflectance. The anode material is less of a problem, and transparent conductors such as ITO are usually chosen for bottom-emitting devices.

Table II. Values of Contrast Ratio (Eq. 1) corresponding to different values of R_D and $L_{ambient}$ (assuming L_D=500 cd/m^2).

R_D [%]	Contrast Ratio *CR*	
	$L_{ambient}$=10^4 cd/m^2	$L_{ambient}$=10^2 cd/m^2
50	1.1	11
10	1.5	**51**
1.0	6.0	**501**
0.1	**51**	**5001**

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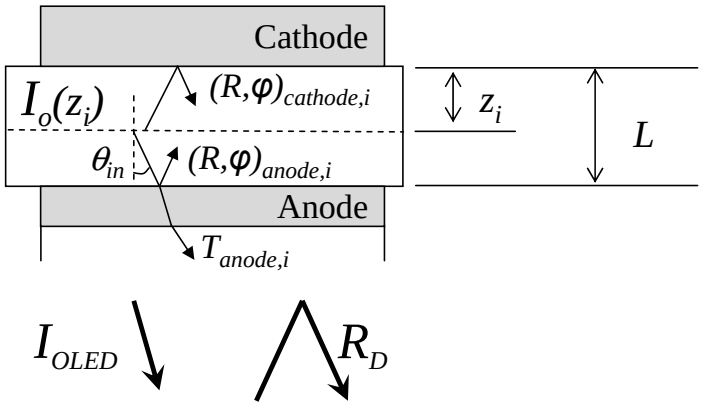

Fig. 1. Schematic view of a bottom-emission OLED showing its Fabry-Perot-like structure and the parameters used in Eq. (3).

2. Theory

2.1. Theory of emission

Several rigorous models for the emission of dipoles in a multilayer structure have been presented in the literature, which take into account the orientation of dipoles in the emitting layer [6]. More simplistic expressions for the emission of a thin-film structure with an emitting layer can also be developed using an approach similar to the one presented by Smith for describing the transmittance of Fabry-Perot structures, using the concept of effective interfaces [7]. We used this approach to obtain the following expression for bottom-emission OLEDs as described in Fig. 1 (similar expressions can be found in the literature, for example Ref. 10):

$$I_{OLED}(\lambda) = \frac{1}{N}\sum_{i=1}^{N} \frac{T_{anode,i}\left[1 + R_{cathode,i} + 2\sqrt{R_{cathode,i}}\cos\left(\frac{4\pi z_i \cos\theta_{in}}{\lambda} + \varphi_{cathode,i}\right)\right]}{1 + R_{cathode,i}R_{anode,i} - 2\sqrt{R_{cathode,i}R_{anode,i}}\cos\left(\varphi_{cathode,i} + \varphi_{anode,i} + \frac{4\pi L\cos\theta_{in}}{\lambda}\right)} I_0(z_i,\lambda), \quad (3)$$

where R_{anode} and $R_{cathode}$ are the internal reflectance values of the two electrodes, φ_{anode} and $\varphi_{cathode}$ are the phase changes on internal reflection from the mirrors surrounding the cavity layers, T_{anode} is the transmittance of the exit anode, L is the total optical thickness of the cavity layer, $I_0(z,\lambda)$ is the irradiance of the emitter, $I_{OLED}(\lambda)$ is the irradiance emitted through the substrate, z_i is the optical distance between the emitting sublayer i and its interface with the cathode, and θ_{in} is the angle of the emitted beam when measured from inside the emitting material. As shown in Eq. (3), the emitting layer can be divided into N sublayers and their contribution summed up (this step is not essential when the electric field intensity does not change significantly over the emitting layer, as with thin emitting layer, or weak microcavity effect). This equation can include the absorption and the dispersion of the optical constants of the materials. Luminance $L(\lambda)$ spectra can be obtained from Eq. (3) simply by modulating $I_{OLED}(\lambda)$ with the photopic curve. Assuming that the phase conditions in Eq. (3) are optimal, the maximum of emission is obtained approximately when $R_{anode}/(R_{anode}+T_{anode})=R_{cathode}$, which reduces to $R_{anode}=R_{cathode}$ when there is no absorption.

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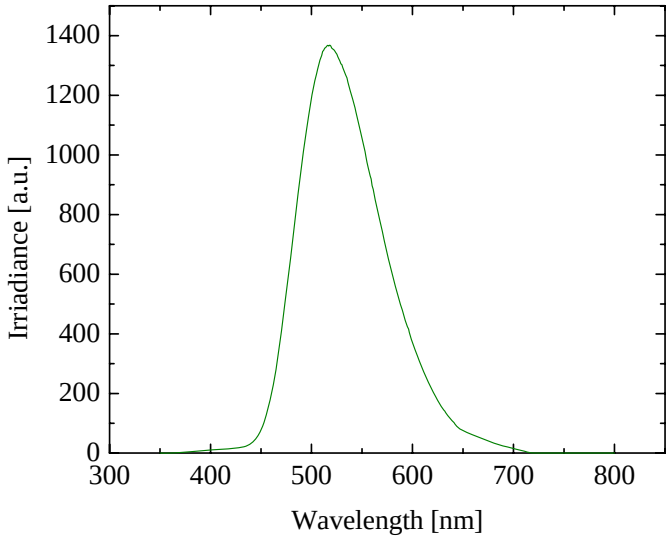

Fig. 2. Emission spectrum of Alq3. The curve was taken as representing I_0 inside the OLED emitting layer.

Equation (3) depends on the value of the internal irradiance $I_0(z,\lambda)$, which is difficult to determine exactly. In this work, we approximated $I_0(z,\lambda)$ with the photoluminescence spectra of a thick Alq_3 layer having a green emission peak (shown in Fig. 2)[8].

As mentioned above, Eq. (3) is similar to the equation describing the transmittance of a Fabry-Perot, except for the cosine at the numerator. As in Fabry-Perot filters, the multiple internal reflections in OLEDs induce, at some specific wavelengths, a resonance of the light electric-field intensity (or more accurately, the irradiance) distribution inside the OLED. The phenomenon known as "microcavity effect" refers to the enhancement or annihilation of the emitted irradiance related to the position of the emitting material relative to this resonance peak of the irradiance [9]. A weak microcavity effect is present in conventional OLEDs [11], and more accentuated in microcavity OLEDs [12]. With Fabry-Perot filters, the phase condition for the appearance of resonance peaks is given by the following equation:

$$\frac{\varphi_{anode}+\varphi_{cathode}}{2}-\frac{2\pi L\cos\theta}{\lambda}=m\pi. \tag{4}$$

For OLEDs, this condition is shifted due to the top cosine term in Eq. (3)**.** When all-dielectric mirrors are used, the phase terms φ_{anode} and $\varphi_{cathode}$ can be set to zero; however, when absorbing materials (such as metals) are used in at least one of the mirrors, the phase terms have to be considered.

2.2. Calculation of the reflectance and design

The reflectance of the OLED, R_{OLED}, is calculated using a well-know iterative approach for multilayer optics (available in many commercial software). It is interesting to note that this approach can also be used not only to optimize (minimize) the reflectance of the OLED, but also to simultaneously optimize (maximize) its emission through the optimization of its transmittance (from the substrate towards the cathode), instead of using an exact expression for the emission, such as Eq. (3). It is the comparison of Eq. (3) with the Fabry-Perot equation that makes it possible; the position of the resonance peak in emission is first

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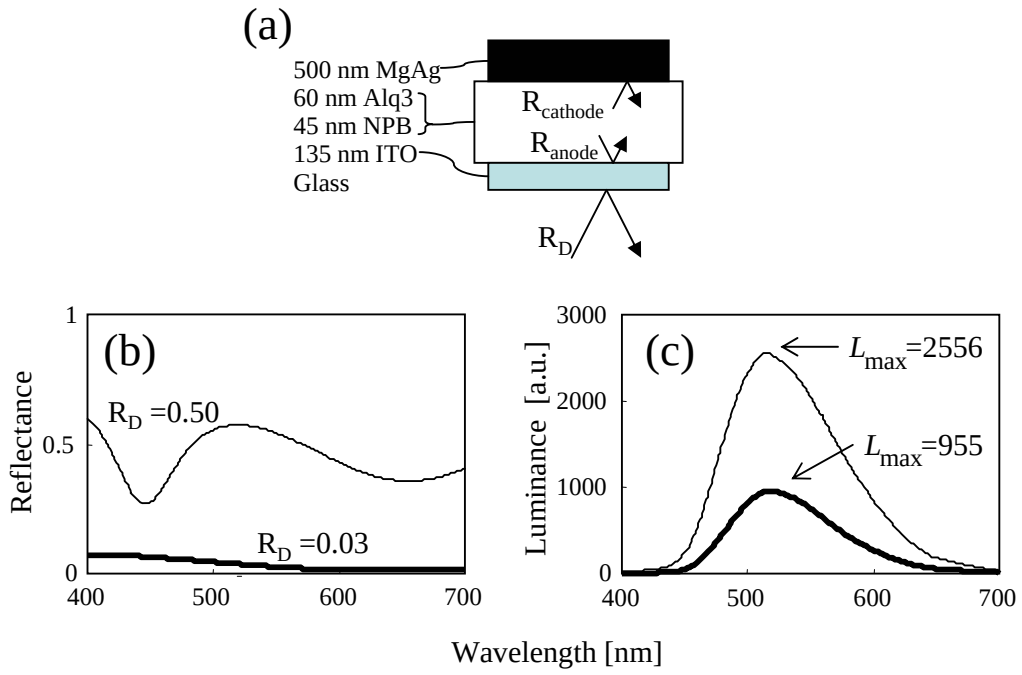

Fig. 3. (a). Structure of a conventional bottom-emission OLED. (b) Reflectance and (c) emission of a conventional OLED (thin line), and of one with $R_{cathode}$=0 (thick line). (R_D is the luminous reflectance, given by Eq.(2)).

approximated by Eq. (4) from the Fabry-Perot transmittance peak, and then refined using Eq. (3) to maximize the emission.

3. Review of current approaches for reducing R_D

As seen in Eq. (1) and Table I, significantly reducing the reflectance of OLEDs is crucial to increase their contrast; several approaches can be used to reduce R_D and increase the contrast ratio.

3.1. Use of a polarizer

A circular polarizer can be used to improve the contrast of OLEDs, a technology borrowed from the LCD industry [13]. This approach does not require the introduction of new layers in the OLED structure and results in a reflectance similar to that of glass. However, polarizers are expensive, generally not flexible, and absorb a substantial amount of the light.

3.2. All-dielectric antireflection coating

Using an all-dielectric antireflection (AR) coating is the proper way to remove the reflection from the front glass surface when the light is emitted through a glass substrate (bottom-emission). However, this front AR coating does not remove the reflectance from the OLED structure, on the other side of the glass substrate.

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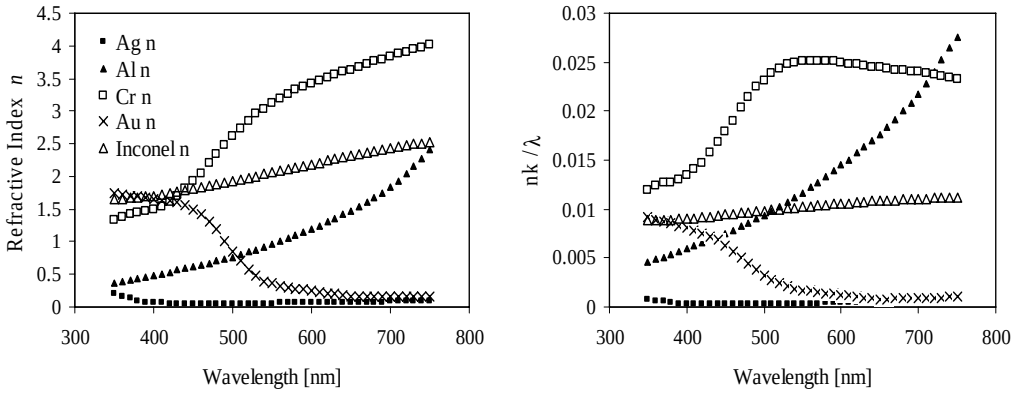

Fig. 4. Refractive index and nk/λ dispersion curves for a few metals.

One can introduce an all-dielectric AR coating inside the OLED structure, i.e. between the anode of a bottom-emitting OLED and a glass substrate. Such a coating will have a limited efficiency in reducing R_D when the cathode is highly reflecting (i.e. Al or Mg-Ag). In such cases, metal-dielectric AR can lead to a better performance.

3.3. Scattering Anti-glare surface

One can reduce the specular reflectance of the display by introducing a non-planar microstructure to its top-surface, an approach that can also enhance the extraction of light from the device. However, the fact that the emitted light is scattered by the surface structure may have a detrimental effect on the resolution of the display [14].

3.4. Black electrode

In the last few years, many attempts have been made to reduce the reflectance of metal-based electrodes, mainly by making the cathode black [15–17] using absorbing materials in it, or covering it with a conductive black layer coating (similar to the metal-dielectric AR coating described below) [16]. The result is a reduced reflectance of the OLED sometimes below 2%, but this comes at the detriment of the emission since half the light is emitted towards it. Using Eq. (3), we can show that a completely dark cathode is not desired because (i) it does not take into account the contribution to R_D from the other interfaces in the OLED structure, and more important (ii) it destroys any beneficial microcavity effect and reduce the emission, as shown in Fig. 3. In typical OLEDs, a weak microcavity effect is generally present and may be beneficial if correctly designed.

3.5. Metal-dielectric antireflection coating

For efficiently reducing the reflectance of highly reflective substrate with a complex admittance (i.e. metals, or coated metals, such as an OLED), it is convenient to use simple metal-dielectric AR coatings similar to those used in black absorbers [18, 20] or heat-reflector in solar-cells applications [21]. This type of coatings has been demonstrated for the contrast-enhancement of electroluminescent (EL) displays [2] and on the cathode side of bottom-emitting OLED (see above) [16].

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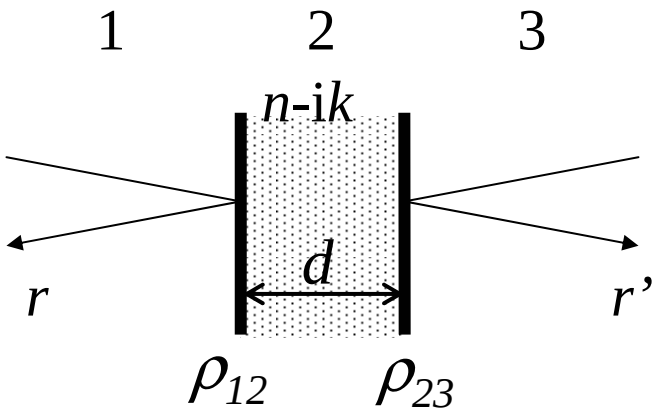

Fig. 5. Schematic view of a metal layer, surrounded by arbitrary materials (ρ_{12} and ρ_{23} can represent the reflection coefficient of multilayers, media 1 and 3 can be different).

4. Our design approach

Of all the approaches mentioned above, none seem capable of combining a low reflectance (R_D), a large emission and a good resolution. Reducing the reflectance of the OLED to a value lower than glass without affecting its emission is particularly challenging. Using a black cathode is efficient for reducing R_D to a low value, but as shown in Sec. 3.4 and Fig. 3, it also leads to a lower emission of the OLED. We proposed to correct this situation with designs that include a new type of anode.

We mentioned in Secs. 2.1 and 3.4 that keeping a weak microcavity effect is important for maintaining a relatively high emission. When designing the high-contrast OLEDs, our goals are thus (i) to minimize the external R_D of the OLED, and (ii) to maintain R_{anode} and $R_{cathode}$ large enough to keep the emission high. In order to achieve these goals, we combine in the OLED structure three types of optical coatings phenomena: antireflection with a metal-dielectric coating on the anode side, microcavity effect at the emitting layer, and an asymmetric reflectance of the anode (high-inside- and low-outside-reflection).

A small microcavity effect, as seen in Sec. 2, is necessary for maintaining a good emission of the device. For that purpose, internal reflections R_{anode} and $R_{cathode}$ must not be reduced to zero, and the organic layers inside the OLED act as cavity layers, so that the position of the emitting layer (the thin recombination layer) must be at a resonance peak of the electric field.

As shown in Fig. 1, the combination of good AR coating and small microcavity effect apparently lead to a contradiction of the anode's role: it must simultaneously have a low external reflectance when seen from the substrate and a relatively large internal reflectance when seen from the cavity layers. It has been observed for a long time in thin-film optics that a thin layer of a material with a large extinction coefficient k can lead to the kind of asymmetric reflectance [22]. In our design, such a layer has thus to be introduced on the anode side of the OLED structure.

Of course, a compromise must still be made between low reflectance and high emission. Also, a too-high microcavity effect is usually not desirable in display application, since it leads to a large dependence of the emission on the viewing angle. The key to our design is the asymmetry of the anode internal and external reflection.

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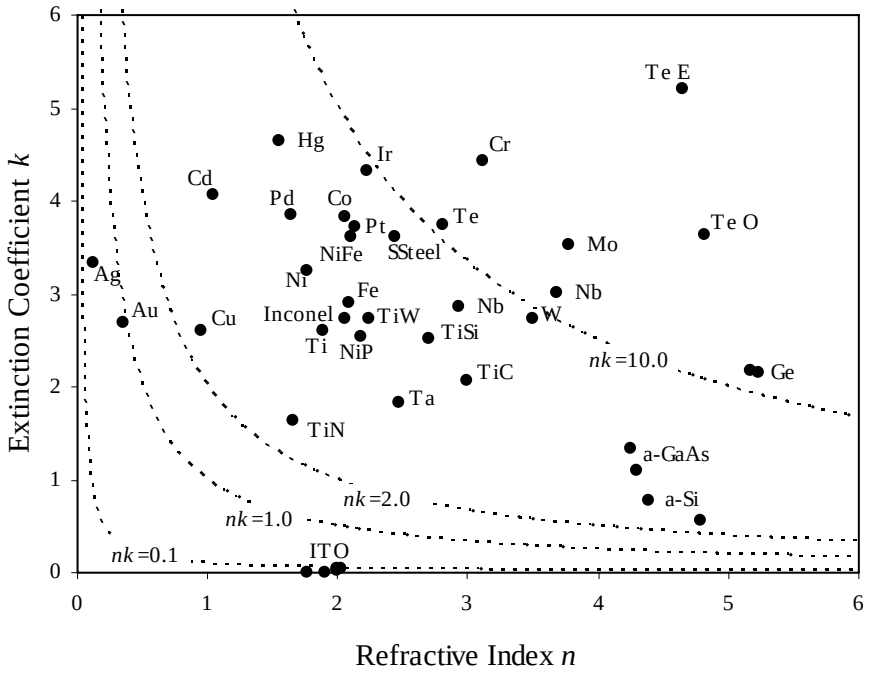

Fig. 6. Refractive indices and extinction coefficients (both given at a wavelength of 550nm) of several metals and semiconductor materials, as found in the literature. Some isovalue-curves of *nk* product are shown (most optical constants values are extracted from Palik [24] and from J.A. Woollam WVASE software [25]).

5. Choice of Materials

5.1. Diode consideration

The selection of materials composing the OLED is important from an electronic point of view. The anode should have a high work-function and the cathode a low-work function, such that they efficiently inject comparable holes and electron currents into the organic layers, respectively. The organic layers should transport one type of carrier efficiently, but their respective energy levels align such that carriers are blocked from drifting through the diode without recombining. Finally, the intrinsic properties of the emitting layer determine the emission wavelength and the charge to photon conversion efficiency.

In the present work, we choose well-known materials for the OLED "core" layers: Mg-Ag as a cathode (electron injection) material, Alq_3 for the electron transport and emitting layer, and NPB as the hole-transport layer [19]. In some cases, ITO was used for the anode (hole injection) material. The other materials included in the design are mentioned in the following sub-sections.

5.2. Optical consideration, metal-dielectric antireflection coating

In metal-dielectric AR coatings, the main role of the metal layers is not to absorb the light but to benefit from its complex admittance *n*-i*k* in order to more efficiently reach to AR condition [20]. For that reason, metals with relatively large *k* are required for this type of coatings (see Fig. 6. Metals that are highly reflecting, such as metals with $n<1$, are usually avoided. In addition, metals with *n* that decreases with decreasing λ (often called "abnormal dispersion") are needed to compensate for the increase of optical thickness in the dielectrics at shorter wavelengths. This type of optical constants dispersion is also needed so that the metal does not introduce chromatic absorption in the device, which requires a constant nk/λ for all the

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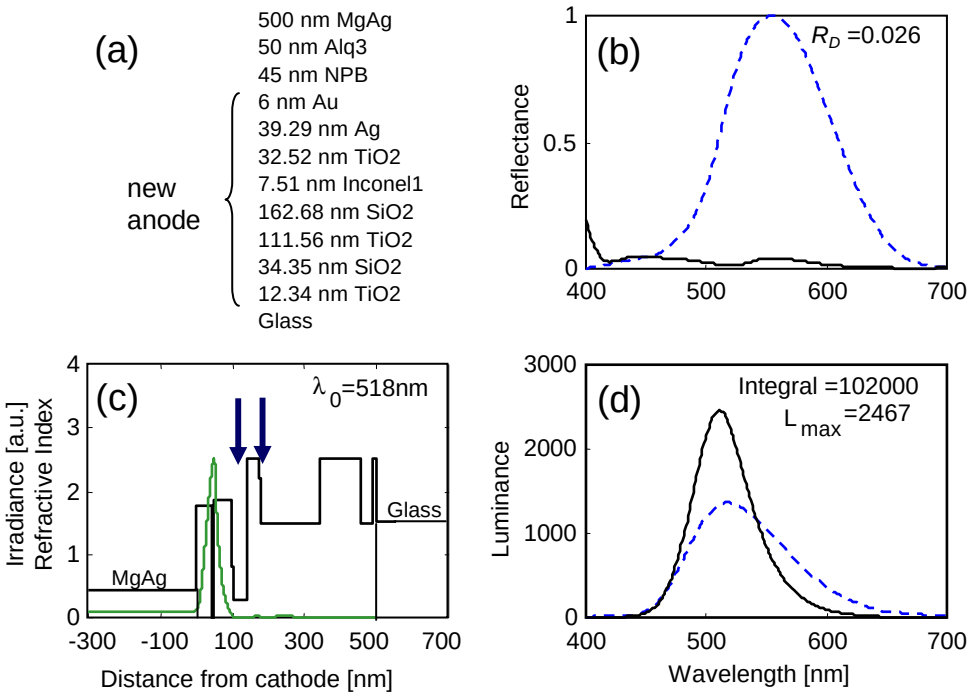

Fig. 7. (a). OLED design. (b). Calculated reflectance (solid line) with the photopic curve (dash line) and the value of the luminous reflectance R_D. (c). Refractive index profile (step) and irradiance profile inside the OLED, with the arrows showing the metal layers, and the thin interfacial emitting layer marked in black. (d). Calculated luminance of the OLED (solid line), compared to that of a conventional OLED [dash line; same as in Fig. 3(c)].

wavelengths of interest. Figure 4 shows n and nk/λ dispersion curves for several metals. Chromium is often used for metal-dielectric black absorbers, but our preferred choice is Inconel (an alloy of Cr-Ni-Fe), which is less absorbing and has a very flat nk/λ curve.

5.3. Optical consideration, electrode with asymmetric reflection

As mentioned in Sec. 4, a material with $k>0$ is required at the anode to maintain a cavity effect in the OLED while reducing its external reflectance, i.e. introducing an asymmetry of the internal and external reflectance of the anode. The optical constants required for that purpose can be found by looking at the reflection coefficients r and r' from both side of an arbitrary layer, with arbitrary interfaces (they could include multilayer), as shown in Fig. 5:

$$r = \frac{\rho_{12} + \rho_{23}\exp(-2i\beta)}{1+\rho_{12}\rho_{23}\exp(-2i\beta)}, \qquad r' = \frac{\rho_{23} + \rho_{12}\exp(-2i\beta)}{1+\rho_{12}\rho_{23}\exp(-2i\beta)}, \tag{5}$$

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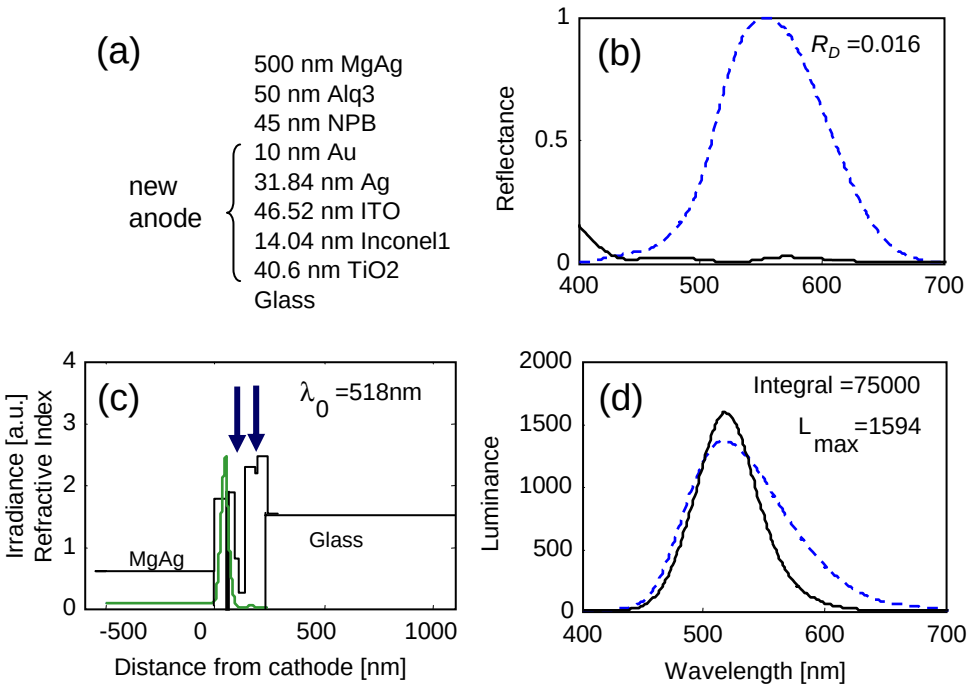

Fig. 8. (a). OLED design. (b). Calculated reflectance (solid line) with the photopic curve (dash line) and the value of the luminous reflectance R_D. (c). Refractive index profile (step) and irradiance profile inside the OLED, with the arrows showing the metal layers, and the thin interfacial emitting layer marked in black. (d). Calculated luminance of the OLED (solid line), compared to that of a conventional OLED [dash line; same as in Fig. 3(c)].

$$\text{with } \beta = \frac{2\pi}{\lambda}\tilde{n}d\cos\theta = \frac{2\pi}{\lambda}(n-ik)d\cos\theta.$$

Clearly, the exponential term differentiates *r* and *r'*. It can be shown from Eq. 5 that a large *k* value is essential to increase the asymmetry in reflectance, with a sufficiently large thickness *d*; a large *n* value will also increase the asymmetry, but is not essential. In the case of the anode (as in many other cases involving asymmetric reflectance), a reduction of the light absorption in the layer is important. The irradiance absorbed by a layer is given by the following relation [23]:

$$I_{abs} = \frac{2\pi}{\lambda}nkd\left|E\right|^2\gamma, \tag{6}$$

where *E* is the average amplitude of the electric field in the film considered and γ is the free space admittance (a constant). From this equation, we see that reducing the thickness and the amplitude of the electric field inside the layer will lead to a low absorption. This can be done when refining the design of the OLED. Equation (6) also indicates that materials with a low *nk* product will lead to small absorption values. Figure 6 shows the optical constants of many absorbing materials, and help to find materials having the required (i) high *k* value and (ii) low *nk* value. We see that semiconductor materials (Ge, GaAs, and Si) have relatively low *k* values, but large *nk* products, while ITO has a low *nk* product, but also a low *k*. Metals, on

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the other hand, have larger *k* values, but most of them are too absorbing (large *nk* product). Only silver (Ag) and gold (Au), two transition metals, have a suitably low *n* value and large *k* value; they are the preferred choice for our application.

6. Examples of design

We used the ideas presented in the previous Section and optimized the layers thicknesses of OLED structures consisting of thick-Mg-Ag|organics|Au/Ag|ITO|metal-dielectric-AR|glass in order to reduce R_D, while keeping $R_{cathode}$ and R_{anode} sufficiently high for maintaining a weak cavity effect and an emission similar or superior to that of a conventional OLED.

During these optimizations, it was important to constrain the thickness values of organic materials to ensure good electrical properties of the OLEDs (the carrier mobility being limited in these materials). As discussed in 5.3, Ag is the best available electrode for assymetric reflection. We added a thin Au layer between Ag and NPB, however, because of its much higher work function (5.1 compared to 4.3, as measured by Kelvin probe). In addition, the thickness of the ITO film had to be large enough to form a low resistivity anode and facilitate the contact with an external electrical source (although in some cases, we found that the Au/Ag layer was thick enough so that no ITO layer was required).

Figure 8 shows two different designs with a different number of layers in the metal-dielectric AR part of the structure, along with their calculated performances (reflectance and luminance spectra). When compared to the performance of a conventional OLED shown in Figs. 3(b) and 3(c), we see that the new designs reduce the reflectance to 2% and less, which is 25 times less than that of a typical OLED, and that the emission is of the same order of magnitude and higher. It thus demonstrates that it is possible to reach a low level of reflectance for an OLED without affecting too much its emission.

Figure 8(c) also shows the distribution of the irradiance inside the OLEDs at the peak wavelength. The maximum of irradiance at the position of the emitting layer indicates that a microcavity effect occurs in the OLED [Not shown here is the fact that the optimization of such designs with absorbing layers involves the adjustment of phase values φ_{anode} and $\varphi_{cathode}$ in Eq. (3) (see Ref. 26)]. In addition, the reduced irradiance values at positions corresponding to the metal layers contribute to reduce the absorption of emitted light in these layers [see Eq. (6)]. These particularities of the designs related to the irradiance are the keys for their good performance and the main novelty of this work.

Figure 9 shows a device that was fabricated following the design of Fig. 8. The details of the fabrication and the performance of the device are reported elsewhere [24]. Part of the sample was made without a metal-dielectric antireflection filter, for comparison of their reflectance (clearly shown in Fig. 9); the complete OLED structure appears at the center of the substrate. The measured performances confirm that the reflectance is reduced and that the emission is high [24].

7. Conclusion

We have demonstrated the concept of a multilayer anode comprising an Au/Ag bilayer and a metal-dielectric AR coating that has both a high internal reflectance and a low outside reflectance. The former property is used to maintain a microcavity effect in the OLED that is tuned to maximize the light out-coupling, and the latter to improve the OLED contrast ratio. Further designs are being considered with varying thicknesses of the Au/Ag layer, and fewer layers in the metal-dielectric coating for a simpler fabrication process.

The novel concept of introducing thin metal layers for maintaining a small beneficial microcavity effect in an OLED while reducing its external reflection, which has been applied in the present work to bottom-emission OLEDs and specific materials, could equally find application in the design of devices based on other materials (i.e. polymer-based), and other device structures (i.e. top-emitting-OLED, tandem-OLED, etc.).

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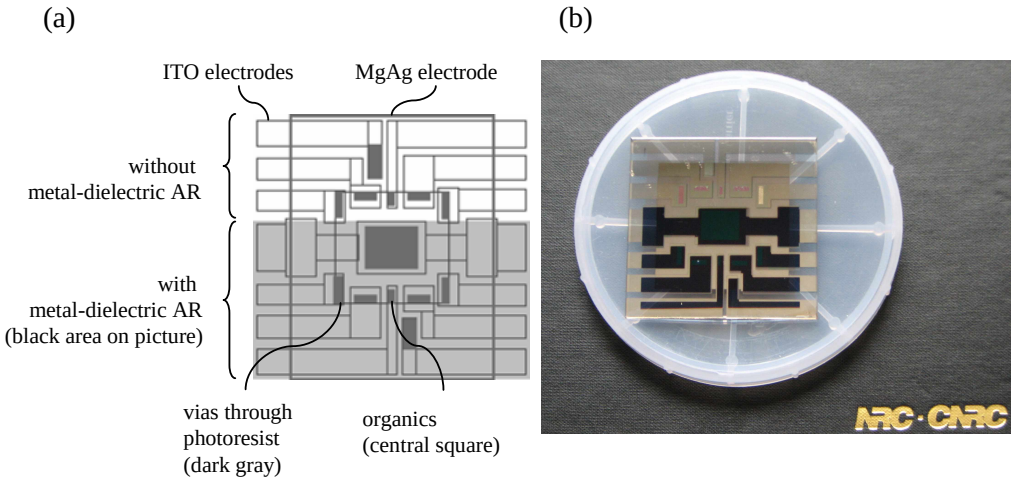

Fig. 9. (a). Schematic bottom view of multi-segment OLED device with and without metal-dielectric AR. (b). Picture of such a device after fabrication. This device corresponds to the design presented in Fig. 8.

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