Luminous power efficiency optimization of a white organic light-emitting diode by tuning its spectrum and its extraction efficiency

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We show an increase of the luminous power efficiency of a white organic light-emitting diode (LED) with three emitters by optimizing its spectrum and its extraction efficiency. To calculate this efficiency we use a model with four parameters: the spectra, extraction efficiencies, internal quantum efficiencies of three emitters, and the driving voltage. This luminous power efficiency increases by 30% by use of a spectrum close to the spectrum of the MacAdam limit. This limit gives the highest luminous efficacy for a given chromaticity. We also show that a white organic LED with an inefficient deep blue emitter can give the same luminous power efficiency as a white organic LED with a more efficient light blue emitter, because of their different fractions in the radiant flux. Tuning the extraction efficiency with a microcavity to the spectrum also increases the luminous power efficiency by 10%.

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1. Maximizing the Luminous Power Efficiency

Any future light source should have a high efficiency with sufficiently high color reproducibility. These parameters are usually given by the luminous power efficiency [1] and the color rendering index (CRI). [2] One promising technology for future lighting and display applications is the white organic light-emitting diode (WOLED), because of its ease of fabrication and (potentially) high efficiency. Most WOLEDs are fabricated by the deposition of a stack of thin organic layers on a glass substrate. The total thickness of these layers is approximately 100 nm, which provides a large area that generates diffuse light. Although the first WOLED by Kido *et al.* [3] had a luminous power efficiency of only 1.1 m/W at most, present day WOLEDs already exceed the luminous power efficiency of the classical incandescent bulb (15 lm/W) by a factor of 2–3 [4–7]. The WOLEDs discussed in these papers usually have three emitters in the stack organic layers. These papers also indicate several routes to increase the overall luminous power efficiency. On the one hand one can improve the electrical behavior to gain efficient generation of photons. On the other hand one can increase light extraction, which should ensure that most of the generated photons can escape through the substrate to air. Here, we focus on an optimization of the spectral behavior of optical and electrical properties.

We put forward three statements with regard to how the spectral behavior of electrical and optical properties of the emitters in a WOLED can increase the overall luminous power efficiency. This luminous power efficiency gives the ratio of the luminous flux to the electrical power. We also use the luminous efficacy, which gives the ratio of luminous flux to radiant flux. Note that both properties are in units of lumens per watt (lm/W). Moreover, these two properties are related by the wall plug efficiency that gives the efficiency at which electrical power is converted to radiant flux (W/W).

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Our methodology to illustrate these three statements uses a model of a three-color WOLED with four parameters. To calculate the luminous efficacy and the luminous power efficiency, these four parameters are used: the emission spectra of the three emitters, the internal quantum efficiencies of the three emitters, a wavelength-dependent extraction efficiency of three emitters, and the driving voltage. We first give a short overview of the three statements. We then discuss the relation of these four parameters to our three statements. Moreover, this overview gives typical values for these parameters.

The first statement is about optimization of the spectrum. Different spectra can give the same chromaticity but with different luminous efficacy, which is also called metamerism. But one spectrum yields chromaticity with a greater luminous efficacy than any of the other spectra [8]. Because of the close relationship between luminous efficacy and luminous power efficiency, we show that a spectrum with higher luminous efficacy yields an OLED with higher luminous power efficiency. For the second statement, we examine the conversion efficiency of electrical energy to photons by these emitters as a function of the spectrum of these emitters. In our example, we use a deep blue emitter or a light blue emitter in a three-color OLED while we maintain the same white chromaticity. We show that the WOLED with a deep blue emitter requires a smaller fraction of blue than the WOLED with a light blue emitter [9]. Then the WOLED with the deep blue inefficient emitter has the same overall luminous power efficiency as a WOLED with a more efficient light blue emitter. Third, we show that the wavelength-dependent behavior of the extraction efficiency needs to be tuned as a function of the internal quantum efficiencies and the spectra of the emitters.

The first parameter of the model is the spectrum of each emitter. The spectra of the emitters illustrate the first statement. Although different spectra exist for any given chromaticity (metamerism), only one spectrum exists with the highest luminous efficacy, the MacAdam limit [8]. Thus, the MacAdam limit also gives the highest luminous power efficiency of any light source. For example, the MacAdam limit for illuminant A is 512 lm/W. This MacAdam limit can be found for all chromaticities; see Fig. 1. Because the spectra of most WOLEDs do not resemble this spectrum, the luminous efficacy of these spectra is at most 350 lm/W. Changing the spectrum of one of the emitters in a WOLED can increase the luminous efficacy. A typical spectral width of an emitter is approximately 100 nm. Nevertheless, some red emitters based on europium can have a wavelength bandwidth equal to one-fourth of this width [10].

The second parameter is the internal quantum efficiency of each emitter. This internal quantum efficiency gives the fraction of electron– hole pairs that radiatively decay. This parameter, together with the first parameter, is used to illustrate the second statement, which states that a WOLED with a less efficient deep blue emitter can have the same luminous power efficiency as a WOLED with a more efficient blue emitter. Note that the focus of our example is the internal quantum efficiency of the blue emitter. Why? The most efficient emitters are phosphorescent emitters. Theoretically, these emitters can reach an internal quantum efficiency (IQE) of $\eta_{\mathrm{IQE}} = 100\%$ [11,12]. Although a light blue phosphorescent emitter, FIrpic, with high IQE has been demonstrated [13], the stability of deep blue phosphorescent emitters is still a limiting factor of the lifetime of complete phosphorescent white OLEDs [14,15]. Note that green and red emitters are also phosphorescent emitters, but their lifetime is not the limiting factor with regard to the lifetime of the device. Thus, the reason to focus on the blue emitter is the lack of stability of deep blue efficient emitters, especially when compared with the stability of efficient green and red emitters. However, WOLEDs with a long lifetime have been shown, but these use a less efficient deep blue fluorescent emitter [16,17]. Theoretically, the upper limit of the internal quantum efficiency of a fluorescent emitter is $\eta_{\mathrm{IQE}} = 25\%$. Alternatively, some stacks with a blue fluorescent emitter and green and phosphorescent emitters get around the low internal quantum efficiency of the blue emitter [18]. A fraction of the triplet excitons, some of the electron–hole pairs, which normally would decay nonradiatively as a result of the fluorescent blue emitter, can transfer to the phosphorescent emitters. These excitons can then decay radiatively on these phosphorescent emitters.

The third parameter of the model is the wavelength dependence of the extraction efficiency of a WOLED. This parameter, together with the first two parameters will be used to illustrate the third statement. The wavelength-dependent behavior of the extraction efficiency can be tuned as a function of the IQEs and the spectra of the emitters. Light extraction has a straightforward effect on the luminous power efficiency of a WOLED; increasing the radiant flux by 50% for all wavelengths increases the luminous power efficiency by 50%. However, most techniques will show a wavelength-dependent extraction efficiency. Several techniques use a corrugation of the planar layers to increase light extraction. These techniques are a grating between glass and air [19] and microlenses or a diffusive layer between substrate and air [20–22]. Adding interlayers between glass and air also increases light extraction [23–25]. In [24,25] the authors used microcavity effects that greatly influenced the wavelength-dependent behavior of extraction efficiency. Thus, extraction efficiency at one wavelength can be much higher than the extraction efficiency at other wavelengths. Because a silver cathode has a higher reflectance than an aluminum cathode for red light, the former gives greater microcavity effects and higher extraction efficiency than the latter [26]. Nevertheless, each technique to increase extraction efficiency was examined for only one wavelength or a small wavelength region, but it is still unclear how they would change the luminous power efficiency of a WOLED. To show the luminous power efficiency for different wavelength-dependent extraction efficiencies, we compare two WOLEDs, one with and one without strong microcavity effects. Although this example is limited to one method of improving the extraction efficiency, the example clearly shows the influence of the wavelength dependence of the extraction efficiency.

The last parameter of the three-color WOLED model is the driving voltage. Although this parameter has no direct effect on the discussion, a low driving voltage directly increases the luminous power efficiency. Lowering the driving voltage can be done by doping the transport layers in the organic stack [17,27]. The lowest voltage is limited by the thermodynamic limit [28].

In Section 2 we discuss the model of the three-color WOLED. In Sections 3 s4 s5 we discuss the three statements. Our conclusions are given in Section 6.

2. Three-Color White Organic Light-Emitting Diode Model

Our goal is to optimize the luminous power efficiency of a three-color WOLED by changing its optical properties: the spectra and the external quantum efficiencies of the three emitters. This luminous power efficiency (η_P, lm/W) is defined as the ratio of luminous flux (F) to electrical power (P_{el}). To calculate the luminous power efficiency, we use a generic model of a three-color WOLED that requires four parameters. These four parameters are the internal quantum efficiency that gives the conversion of excitons in photons ($\eta_{\mathrm{int},i}$), the extraction efficiency of these photons ($\eta_{c,i}$), and the power normalized radiant flux of the emitters [$E_{\mathrm{el},i}(\lambda)$]. One last relevant parameter is the driving voltage of the OLED. Index i of each of the three emitters is either b(lue), r(ed), or g(reen). This model will be used to show three ways to improve the luminous power efficiency in Sections 3 s4 s5. A small adaptation of the model that is needed for Section 4 will be discussed at the end of this section.

The luminous power efficiency is calculated with the luminous flux (F_i) and electrical power ($P_{\mathrm{el},i}$) of each of the three emitters:

$$\eta_P = \frac{\sum_{i=b,g,r} F_i}{\sum_{i=b,g,r} P_{\mathrm{el},i}}. \tag{1}$$

For a given chromaticity of the WOLED, the contribution of each emitter is determined automatically. Thus, the first step is to determine the spectrum that corresponds with the given chromaticity. Also, the total spectrum then gives the luminous flux. The emitted spectrum in air of each emitter is given by

$$E_{\mathrm{op},i}(\lambda) = E_{\mathrm{el},i}(\lambda)\eta_{c,i}(\lambda). \tag{2}$$

Each spectrum corresponds to tristimulus values in the CIE color space of 1931 [29]:

$$X_i = \int E_{\mathrm{op},i}(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda, \qquad Y_i = \int E_{\mathrm{op},i}(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda,$$
$$Z_i = \int E_{\mathrm{op},i}(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda. \tag{3}$$

Given the chromaticity of the WOLED and its color coordinate, (X_w, Y_w, Z_w), and the three emitters and their color coordinates, the following conditions need to be satisfied:

$$X_w = \sum_{i=b,g,r} A_i X_i, \qquad Y_w = \sum_{i=b,g,r} A_i Y_i,$$
$$Z_w = \sum_{i=b,g,r} A_i Z_i. \tag{4}$$

The prefactors (A_b, A_g, A_r) determine the mutual ratio of radiant flux inside the organic layers. We assume that we can change prefractors A_i without changing any other property or parameter of the OLED. The luminous flux of one emitter is then given by

$$F_i = 683.0 \int A_i E_{\mathrm{op},i}(\lambda) V(\lambda)\mathrm{d}\lambda. \tag{5}$$

Calculating the denominator of Eq. (1) is the next step. Equation (1) is a function of the IQE and the power injected into the organic layers:

$$P_{\mathrm{el},i} = \int A_i E_{\mathrm{el},i}(\lambda) \frac{1}{\eta_{\mathrm{int},i}} \frac{qV\lambda}{hc}\mathrm{d}\lambda. \tag{6}$$

The parameter $1/\eta_{\mathrm{int}}$ gives the amount of excitons needed to create one photon. The ratio $hc/\lambda qV$ gives the relation between the optical power of the photon and the energy of the creating exciton [30]. As stated in Section 1, one can use doped layers to minimize $P_{\mathrm{el},i}$ by minimizing the required voltage.

A small variation of this model is the creation of white light with three distinct monochrome OLEDs, which differs from the previous approach, which has an OLED with the three emitters in the same organic layer stack. Generating white light with three distinct monochrome OLEDs has the advantage that each emitter can be optimized independently. This principle is also known as a horizontally stacked WOLED [7]. The only parameters used to calculate the luminous power efficiency are the spectra and the wall plug efficiency ($\eta_{\mathrm{W/W},i}$) of each of the three emitters. This wall plug efficiency of an emitter can be calculated with its spectrum and its overall luminous efficacy ($\eta_{P,i}$).

The overall wall plug efficiency of the complete WOLED ($\eta_{\mathrm{W,W}}$) can then be calculated with

$$\eta_{\mathrm{W/W}} = \frac{\sum_{i=b,g,r} A_i}{\sum_{i=b,g,r} \frac{A_i}{\eta_{\mathrm{W/W},i}}}. \tag{7}$$

The fraction of radiant flux of each emitter (A_i) is directly given by Eq. (4). The luminous power efficiency of the white OLED is finally given by

$$\eta_P = \frac{683 \int E_{\mathrm{op}}(\lambda) V(\lambda) \mathrm{d}\lambda}{\int E_{\mathrm{op}} \mathrm{d}\lambda} \eta_{W/W}. \qquad (8)$$

The optical spectrum of the WOLED E_{op} is determined by the spectrum of each emitter ($E_{\mathrm{op},i}$) and its relative fraction (A_i).

3. Spectrum to Increase the Luminous Power Efficiency

The luminous power efficiency can be increased with spectrally narrow emitters because of the MacAdam limit. This limit gives the highest luminous efficacy for a given chromaticity. To determine the luminous efficacy, one must take the ratio of luminous flux to radiant flux (lm/W). We will show that this MacAdam limit can be used to increase the luminous power efficiency. For illuminant A, this limit gives a luminous efficacy of 512 lm/W. The corresponding spectrum has 15% of its radiant flux emitted at 450 nm and 85% at 579.5 nm, see Fig. 1. On the other hand, a spectrum of a typical WOLED with this chromaticity is shown in Fig. 2(a). This spectrum has a ratio of luminous flux to radiant flux of only 305 lm/W. If the red emitter of this last spectrum is replaced by a monochromatic emitter that emits at 585 nm [see Fig. 2(b)], the luminous efficacy of this spectrum gives 454 lm/W. Also, Table 1 lists the luminous power efficiency that is calculated with the model discussed in Section 2.

In addition to the luminous power efficiency, the color quality is also important. Therefore, in the remainder of this section we discuss color quality as a function of luminous power efficiency. To measure the quality of a light source and to measure how good colors are reproduced when illuminated with this source, the CRI is often used. Recently, visual experience has shown that the current CRI based ranking of a set of light sources containing white LED light sources contradicts the visual ranking. [31]. Spectral narrow LEDs can have good light quality but a low CRI. Nevertheless, we will use the CRI to determine the color quality even for a light source with a spectrum with narrow peaks. Because the CRI of the WOLED with the monochromatic yellow emitter is well below 80, the rest of this section looks at the trade-off between the CRI and the increase of overall luminous efficacy of emitters with narrower spectra. It should be mentioned that a CRI of 80 is greater than that of the majority of fluorescent lamps.

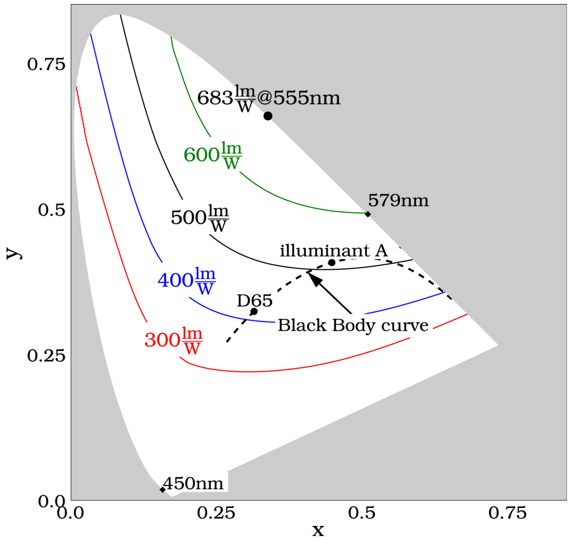


Fig. 1. (Color online) Maximal luminous efficacy of a color point in CIE 1931 *xy* color space; for example, illuminant A can achieve 512 lm/W[8].

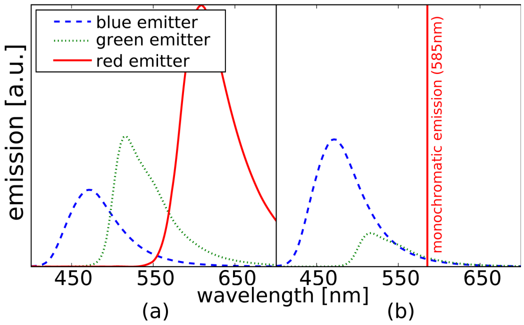


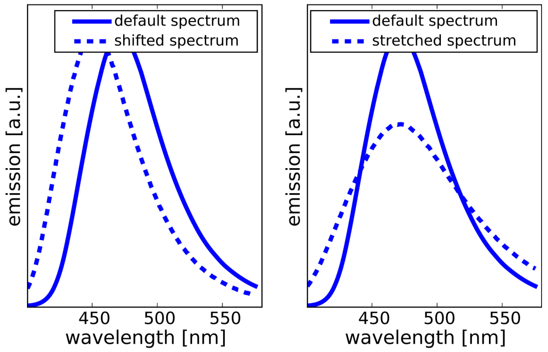
Fig. 2. (Color online) Spectra of three emitters that yields illuminant A. (a) Spiro-DPVBi, Ir(ppy)3 in TCTA, and Ir(MDQ)(acac) in alpha-NPD. (b) The red emitter was replaced by a monochromatic emitter at 585 nm.

The goal of the next discussion is to find a spectrum that still has a higher luminous power efficiency than the default spectrum but with a sufficiently high CRI. To achieve this, we vary the spectrum of one of the emitters. Two possible methods to change the spectrum of an emitter are shifting its peak position or narrowing the spectrum. The

Table 1. Luminous Properties of the Spectra in Fig. 2(a)[a]

Luminous Properties	Fig. 2(a) (lm/W)	Figure 2(b) (lm/W)
$\frac{F}{P_{\mathrm{opt}}}$	305	454
η_P for $(\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r}) = (1.0, 1.0, 1.0)$	39	66
η_P for $(\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r}) = (0.25, 1.0, 1.0)$	30	42

[a] The driving voltage is 3.075 V and the extraction efficiency is 20% for all wavelengths and all the emitters.



(a) (b)

Fig. 3. (Color online) (a) Shifting and (b) stretching of the spectra of the blue emitter were obtained, respectively, with expressions (9) and (10).

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shift of a spectrum is shown in Fig. 3(a) and expression (9); the narrowing of a spectrum is shown by Fig. 3(b) and expression (10). The spectrum of an emitter is given by $\phi(\lambda)$, a shift by λ_0. A narrow factor of 0.5 means that the spectrum is half as wide in wavelength as the default spectrum:

$$\phi_i(\lambda) \to \phi(\lambda - \lambda_0), \tag{9}$$

$$\phi_i(\lambda) \to \phi\left(\lambda_{\max} + \frac{\lambda - \lambda_{\max}}{\text{narrow factor}}\right). \tag{10}$$

Let us now define the boundary conditions that we used in Eqs. (1)–(8) to calculate the luminous power efficiency (η_P) and the CRI for a basic OLED model. The extraction efficiency is 20% and the driving voltage is 3.075 V, which is close to the thermodynamic limit to emit deep blue. Moreover, the green and red emitters have an internal quantum efficiency of $\eta_{\text{int},g} = \eta_{\text{int},r} = 100\%$. Because no phosphorescent deep blue emitters with a long lifetime are known, we again make a distinction between a WOLED with a blue fluorescent emitter ($\eta_{\text{int},b} = 25\%$) and a blue phosphorescent emitter ($\eta_{\text{int},b} = 100\%$). Table 1 shows that replacement of the red emitter by a monochromatic red emitter indeed improves the luminous power efficiency by 30%.

With the previous values, Fig. 4 shows the different luminous power efficiencies of the WOLED for the illuminant A chromaticity (CIE *xy* 1931: 0.4475 and 0.4074) for variations of the blue and red emitters. Because the properties of the WOLED are independent of most variations of the green emitter, variations of the green emitter are not shown. Moreover, variations of the green spectrum are significant only when the shift is large enough to overlap with the spectrum of either a blue or a red emitter.

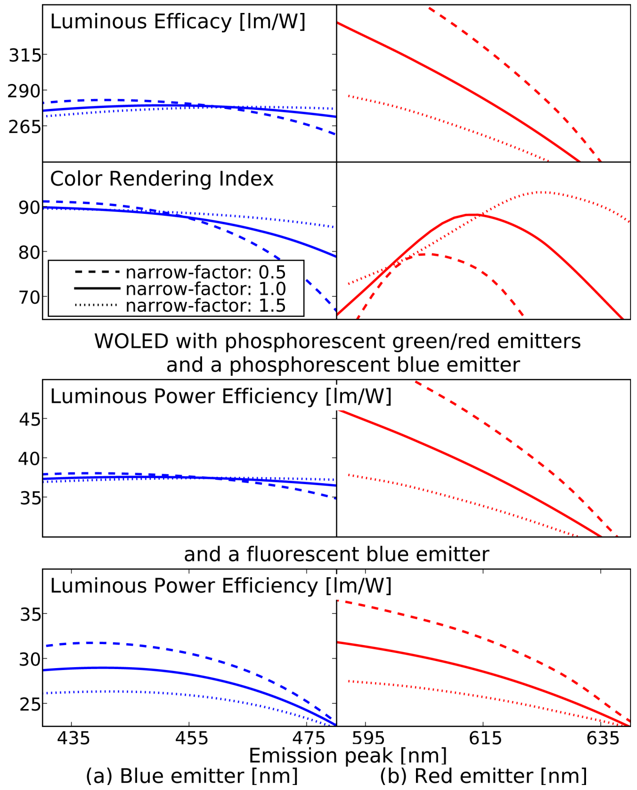

Fig. 4. (Color online) Variation of the spectral intensity of each of three emitters, as defined in Fig. 3. These variations affect the luminous efficacy, the CRI, and the luminous power efficiency.

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Varying the red emitter has the largest influence on the luminous efficacy and the luminous power efficiency because of the chosen warm chromaticity. We compared two WOLEDs with a CRI above 80: a red emitter with its peak at 600 nm and with a narrow factor of 0.5 and a default red emitter. The narrower red emitter in the WOLED still gives a satisfying CRI of 80 but increases the luminous power efficiency ($\eta_P = 47\,\text{lm/W}$) for a WOLED with a blue phosphorescent emitter. The default red emitter in a WOLED gives a CRI of 90 and an overall luminous power efficiency of 39 lm/W (phosphorescent blue); see Table 1. Although this effect is slightly smaller in a WOLED with a blue fluorescent emitter, we again see a relative improvement.

For a WOLED with a blue fluorescent emitter, also variations of the blue fluorescent emitter show an increase of the overall luminous efficacy. We see that a variation of the blue phosphorescent emitter of the WOLED with a blue phosphorescent emitter does not influence the overall luminous efficacy. The increase of the overall luminous efficacy is caused by a decrease in the amount of light emitted by the blue emitter, which is the least efficient emitter. This effect is discussed in more detail in Section 4.

In conclusion, the MacAdam limit plays an important role in this hypothetical WOLED. The maximal luminous power efficiency has been found by replacing the red emitter with a monochrome red emitter. Although the WOLED with the monochrome red emitter has a low CRI, the CRI can be improved by using slightly broader emitters, while maintaining an increase in the overall luminous efficacy.

4. Fraction Radiant Flux of the Emitter

The second statement relates to the conversion efficiency of electron–hole pairs to photons by use of these emitters, which is the IQE. We can use two emitters with roughly the same color to create a WOLED of a given chromaticity. For example, we can use a deep blue emitter or a light blue emitter in a three-color OLED to create the same white chromaticity. But a deep blue emitter requires a smaller fraction of the total light than does a light blue emitter [9]. Therefore, the luminous power efficiency of WOLEDs with either emitter can be equal.

Here we show a comparison of a less efficient deep blue fluorescent emitter versus a more efficient light blue phosphorescent blue emitter. For this comparison a hypothetical WOLED is created by combining the three distinct monochrome OLEDs in Fig. 5. These OLEDs are described in the litarature; see Fig. 5. To explain the second statement, we therefore make use of the wall-plug efficiencies of monochrome OLEDs instead of their IQEs. Nevertheless, the conclusions based on the wall plug efficiency can be extended to the IQE. Figure 5 and Table 2 give the properties of these emitters.

Equations (7) and (8) give, respectively, the wall plug efficiency and the luminous power efficiency of a hypothetical three-color WOLED. The OLEDs in Fig. 5 have a driving voltages larger than 6 V. Thus lowering the driving voltage in some of these OLEDs could increase the wall plug efficiency by a factor of 2.

Table 3 lists the results for the WOLEDs with either b_{I}, b_{II} or b_{III}. Though the wall plug efficiency of the phosphorescent b_{III} is almost twice that of fluorescent b_{II}, the luminous power efficiencies of the WOLEDs are equal. This is caused mainly by the lower fraction of the required blue when the blue is more deep. It should be noted that a WOLED with a more efficient blue phosphorescent, such as recently presented in [13], would outperform both the WOLEDs described in this section. Nevertheless, a factor of almost 1.66 in wall plug efficiency, 3% versus 5%, is compensated because of the lower fraction of the blue emitter in the radiant flux.

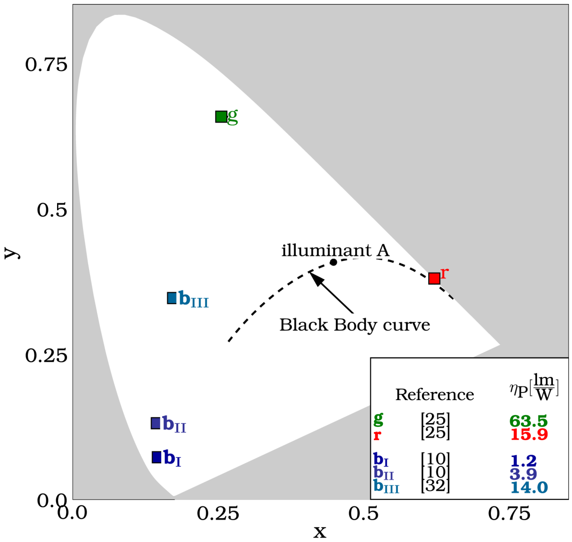

Fig. 5. (Color online) Monochrome emitters found in the literature for the CIE *xy* 1931 chromaticity diagram. The luminous power efficiencies of these emitters are also shown.

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5. Tuning the Extraction Efficiency

The third statement relates to the wavelength dependence of the extraction efficiency and its relation to the electrical properties of a WOLED. Although the different strategies mentioned in Section 1 increase the extraction efficiency, most of the cited papers discuss this increase only for one wavelength or a small wavelength range. Our focus here is to match a strong wavelength-dependent extraction efficiency with other properties of a WOLED. To achieve a strong wavelength-dependent extraction efficiency, we use microcavity effects in

Table 2. Properties of the Emitters shown in Fig. 5

	b_I	b_{II}	b_{III}	g	r
	Undoped MADN	Doped MADN with BD1	PhOLED		
Color Coordinates in the CIE 1931 Color Space	(0.15,0.66)	(0.14,0.13)	(0.17,0.35)	(0.25,0.66)	(0.62,0.38)
Luminous Power Efficiency $\eta_{P,i}[\frac{\mathrm{lm}}{\mathrm{W}}]$	1.2	3.9	14	63.5	15.9
Wall Plug Efficiency $\eta_{W/W,i}$	0.01	0.03	0.05	0.13	0.06

Table 3. Luminous Power Efficiency of the Composed WOLEDs[a]

	b_I Very Deep Blue	b_{II} Deep Blue	b_{III} Light Blue
Wall plug efficiency $\eta_{W/W}$ of the WOLED	0.050	0.060	0.066
Luminous Power Efficiency (η_P) of the WOLED	22.3 lm/W	26.6 lm/W	26.7 lm/W
Relative Fraction of the Emitters to Create Illuminant A (A_b, A_g, A_r)	(0.11, 0.27, 0.62)	(0.125, 0.255, 0.62)	(0.26, 0.13, 0.61)

[a] A WOLED with color point illuminant A can be created by combining blue, green, and red emitters. The WOLEDs have the same green and red emitters as in Table 2, however, each WOLED used only one of the three blue emitters listed in Table 2.

the realistic OLED stack listed in Table 4. The design of the additional interference layers is based on [25]. To calculate the extraction efficiency of this structure, we use a plane wave expansion method [32]. To calculate the luminous power efficiency we use Eqs. (1)–(8).

To show the influence of the extraction efficiency of WOLEDs on the luminous power efficiency, we compare four different WOLEDs. Two basic WOLEDs have no interference layers between indium tin oxide (ITO) and glass, the other two WOLEDs have additional interlayers. The difference between the two basic WOLEDs is their blue emitter, which is either a phosphorescent or a fluorescent emitter. The green and red emitters in both devices are phosphorescent emitters. To maximize the luminous power efficiency, two parameters ($t_{\mathrm{NET5}}, t_{\mathrm{NHT5}}$) are varied. The other two WOLEDs have three additional layers. Again, there is a distinction between a complete phosphorescent device and one with a blue fluorescent emitter. These structures have four parameters ($t_{\mathrm{NET5}}, t_{\mathrm{NHT5}}, t_{\mathrm{low}}, t_{\mathrm{high}}$). The optional layers have parameter t_{low} for the layers of low refractive index and the parameter t_{high} for the layer of high refractive index. In addition to the IQE of the emitter and the layer stack, the model in Section 2 uses the emitters spectra [Fig. 2(a)] and a driving voltage of 3.1 V.

The global optimization of the two basic WOLEDs is a brute force method in which we look for the highest luminous power efficiency in a two dimensional parameter space. The calculation of the extraction efficiency of one OLED for one wavelength takes a few seconds on a system with a 2 GHz Opteron Processor (AMD, Sunnyvale, California). Moreover, a complete scan of the parameter space takes at least one day. Therefore, a global optimization of four parameters would take too long, and we optimize the parameters of the interference layers ($t_{\mathrm{low}}, t_{\mathrm{high}}$) only locally for the previous organic layer stack optimized by brute force. The organic layer stack is the optimized basic stack. The results of the optimization of all four WOLEDs is given in Table 5 and Fig. 6.

These optimizations show that adding interference layers on a basic WOLED increases the overall luminous efficacy by at most 10%; see Table 5. This is true for both WOLEDs with a fluorescent blue emitter and the WOLEDs with a phosphorescent blue emitter. For example, Figs. 6(a) and 6(c) show the extraction efficiency of the basic WOLED with a phosphorescent blue emitter and the basic WOLED with interlayers. Although the difference in the luminous power efficiency is only 10%, the relative change of the extraction efficiency is approximately 50% at some wavelengths. Although

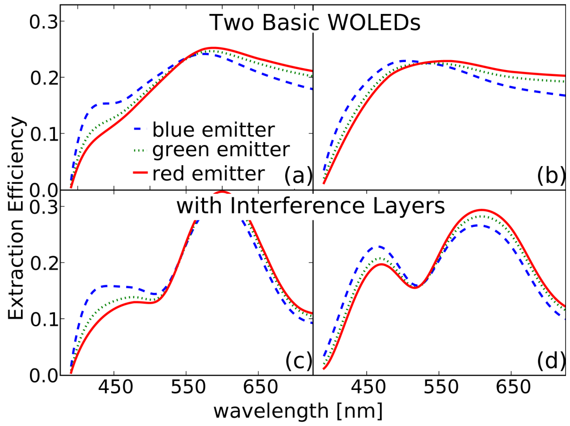

Fig. 6. (Color online) Wavelength-dependent extraction efficiency that corresponds with the values listed in Tables 4 and 5 for different stack configurations. Basic WOLED with (a) a blue phosphorescent emitter and (b) a blue fluorescent emitter. WOLEDs with additional interference layers with (c) a blue phosphosrescent and (d) a blue fluorescent emitter. The green and red emitters are always phosphorescent.

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Table 4. Typical stack of a three color White OLED[a]

Material	Refractive Index at 550 nm	Thickness
Al	0.96–6.69j	100 nm
NET5	1.76	t_{NET5}
ETL	1.75–0.0092j	10 nm
Blue emitter	1.80	10 nm
Interlayer	1.78	5 nm
Green emitter	1.78	3 nm
Red emitter	1.80	10 nm
HTL	1.75–0.0092j	10 nm
NHT5	1.75–0.0092j	t_{NHT5}
ITO	1.82–0.0113j	90 nm
	Begin optional interference layers	
SiO_2	1.46	t_{low}
Nb_2O_5	2.38	t_{high}
SiO_2	1.46	t_{low}
	End optional interference layers	
Glass	1.52	mm
Air	1.0	

[a] Each color is generated by one layer. The optional layers provide a stronger wavelength-dependent extraction efficiency than the default stack.

Table 5. Basic White OLEDs with and without Interference Layers[a]

Basic White OLEDs	
$\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r} = 1.0, 1.0, 1.0$ Fig. 6(a)	$t_{\mathrm{NET5}}, t_{\mathrm{NHT5}} = 48\,\mathrm{nm}, 60\,\mathrm{nm}$ $\eta_P = 48\,\mathrm{lm/W}$
$\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r} = 0.25, 1.0, 1.0$ Fig. 6(b)	$t_{\mathrm{NET5}}, t_{\mathrm{NHT5}} = 45\,\mathrm{nm}, 30\,\mathrm{nm}$ $\eta_P = 32\,\mathrm{lm/W}$
Basic White OLEDs with Interference Layers	
$\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r} = 1.0, 1.0, 1.0$ Fig. 6(c)	$t_{\mathrm{low}}, t_{\mathrm{high}} = 125\,\mathrm{nm}, 90\,\mathrm{nm}$ $\eta_P = 53\,\mathrm{lm/W}$
$\eta_{\mathrm{int},b}, \eta_{\mathrm{int},g}, \eta_{\mathrm{int},r} = 0.25, 1.0, 1.0$ Fig. 6(d)	$t_{\mathrm{low}}, t_{\mathrm{high}} = 190\,\mathrm{nm}, 80\,\mathrm{nm}$ $\eta_P = 35\,\mathrm{lm/W}$

[a] Additional layers between ITO and glass increase the luminous power efficiency compared with the default white OLED. The thicknesses and the overall luminous power efficiencies are given for two WOLEDs with different internal quantum efficiencies. The corresponding extraction efficiencies are listed in Fig. 6

we see a decrease of the extraction efficiency in the blue emitter, the luminous power efficiency is increased because of the increase of the extraction efficiency in the red emitter. This improvement is explained by the larger radiant flux needed for the red emitter than for the blue emitter. Increasing the efficiency of the red emitter compensates for the decrease in efficiency of the blue emitter. Moreover, if the peak extraction efficiency had been placed at 500 nm, the luminous power efficiency would have been approximately 33 lm/W, a decrease of 30%. The WOLED with a blue fluorescent emitter, Figs. 6(b) and 6(d), show an increase of 10% in the luminous power efficiency. However, because the blue emitter is much less efficient, the luminous power efficiency also requires an increase in extraction efficiency of the blue emitter.

Although the increase in luminous power efficiency by use of these microcavities is limited, we have shown the importance of tuning the extraction efficiency to some parameters of a WOLED. Although the relative improvement of the luminous power efficiency is limited to 10%, the increase of the extraction efficiency at some wavelengths is greater than 50%. Placing this peak of extraction efficiency at another wavelength can decrease the luminous power efficiency by 30%.

6. Conclusion

We have shown an increase in luminous power efficiency of a three-color white OLED by optimizing the spectra and the extraction efficiencies of three emitters. This optimization considers optical and electrical parameters. The optical parameters are the spectra and extraction efficiencies of the emitters; the electrical parameters are the driving voltage and the internal quantum efficiencies of the emitters. The model has been used to validate three statements.

First, we have examined variations of the spectrum of the MacAdam limit that have the highest luminous efficacy for a given chromaticity. The spectrum of the MacAdam limit has only two infinitely sharp peaks. By changing the spectrum to be closer to the spectrum of the MacAdam limit, we can increase the luminous efficacy and also the luminous power efficiency by 30% while retaining a sufficiently high CRI of 80. A spectrum with narrower peaks would not have a sufficiently high CRI. On the other hand, recent work has shown that the CRI might underestimate the color quality of spectra with narrow peaks.

The second statement was demonstrated by a comparison of two WOLEDs for which we use emitter values found in the literature. Using a WOLED with a deep blue fluorescent emitter instead of a WOLED with a light blue phosphorescent emitter lowers the fraction of radiant flux emitted by the blue emitter. This lower fraction compensates for the lower efficiency of the deep blue emitter. Thus, the overall luminous power efficiency of the two WOLEDs is almost equal.

Third, tuning the extraction efficiency with the spectrum of a WOLED can also increase the luminous power efficiency. To demonstrate this, we compared two WOLEDs: a basic three-color WOLED and the WOLED with additional interference layers with strong microcavity effects. Although the relative increase of the overall luminous power efficiency is limited to 10%, the increase in the extraction efficiency at some wavelengths is greater than 50%. Placing this peak of the extraction efficiency at the wrong wavelength can decrease the overall luminous efficacy by 35%. Although this example is limited to one method to increase extraction efficiency, it clearly shows the importance of tuning the extraction efficiency to other parameters of the WOLED.

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