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OLEDs with chromaticity tunable between dusk-hue and candle-light

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A B S T R A C T

We demonstrate in this report the feasibility of using organic light-emitting diode (OLED) lighting device technology to fabricate light sources with chromaticity tunable between that of dusk-hue and candle-light. The resulting color temperature is tunable easily from 1580 K to 2600 K, covering that of dusk-hue (2500 K) and candle-light (1900 K) and providing a physiologically-friendly, melatonin suppression-less emission for illumination at night, along with a respective color rendering index varying from 68 to 91 and power efficiency from 20.9 to 2.7 lm/W at 10 to 23,690 cd/m^2. The color temperature can also be tuned from high to low sequentially, such as from 5200 K to 2360 K, covering that of cool- and warm-white light for daytime illumination, by simply varying emissive layer thickness ratio. The comparatively high color rendering index as well as the large color temperature span and easy color temperature tunability may be attributed to the employment of four blackbody radiation-complementary emitters. The emission ranges from red to sky-blue, which were dispersed into three separated emissive layers coupling with the use of a nano-layer of hole modulation material.

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1. Introduction

Color temperature of light shows a marked effect on human physiology and psychology [1–9]. Bright daylight or intensive artificial light with high color temperature, such as that from cold fluorescent tubes or the latest white LED lamps, can stimulate the secretion of cortisol, a hormone that keeps people awake and active [3,6,7]. High color temperature light, however, also markedly suppress the nocturnal secretion of oncostatic melatonin, increasing the risk of breast, colorectal, and prostate cancers [1,2,4,9], explaining why physicians have long been calling for the development of blue emission free or low color temperature lighting sources for use at night to safeguard human health [4,10].

Besides being crucial to human health, low color temperature light also exhibits many other profound effects. For example, the low color temperature dusk-hue emits diurnally the most charming chromaticity, captivating enormous attention and stirring endless motion of poets. It also affects the migration of birds [11–13], the birds' chorus at dusk [14,15], and the mating of crabs [16] and moths [17].

The importance of light sources with a low color temperature can be further realized by the fact that candle-light which exhibits a color temperature around 1900 K is capable of creating romantic atmosphere during dinner time [18]. The pleasant atmosphere may be originated by the naturally occurring melatonin secretion after dusk [19], which helps people feel relaxed.

Although low color temperature light sources could provide many special functions, current electrically-driven lighting devices show no color temperature smaller than

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2000 K. For examples, the lowest color temperature is around 2500 K for incandescent bulbs, while 3000 K or 5000 K for cold- or warm-white fluorescent tubes or compact fluorescent tubes, or 3000 K or 5000 K for warm- or cold-white LED luminaires. Most importantly, no luminaries with color temperature less than 2500 K are encouraged or justified for receiving the certification of Energy Star according to their specifications [20]. This may mainly, if not totally, explain why almost all the past research and development efforts in general illumination focused on improving the efficacy of white light with color temperature greater than 2500 K [21–25], and little attention had been paid on low color temperature non-white lighting sources. The importance of devising new light sources with color temperature lower than 2500 K or even 2000 K can be further realized by the specific fact that the naturally occurring melatonin generation at night would be much less affected if the employed lighting measures have a color temperature lower than 2300 K, at which the suppression level of melatonin secretion is only 23% as comparing with that at 5000 K, based on the same luminosity [10].

Moreover, current lighting sources provide only a fixed color temperature, seriously mismatching what one truly needs from the standpoint of circadian rhythm; i.e. circadian can be entrained by bright light with high color temperature and melatonin generation be triggered at dark night. Devising a light source with color temperature tunability would hence be highly valuable. In 2009, the first sunlight-style color temperature tunable OLED was reported, which yielded a wide color temperature span, fully covering that of the entire daylight cycle [26]. However, the corresponding power efficiency was low because of the use of purely fluorescent emitters. Although the efficiency has been much improved, such as 13.4 lm/W at 1000 cd/m^2, as electro-luminance effective phosphorescent emitters were employed, the color rendering index was low [27]. To provide visual comfort, high or very-high color rendering index is required. The challenge has now become how to design and fabricate a lighting device with a high color rendering index along with a color temperature tunable character, especially in the low color temperature range for the sake of safeguarding human health.

We demonstrate, in this report, the feasibility of using OLED technology to fabricate light sources with low color temperature as well as chromaticity tunable between that of dusk-hue and candle-light, along with a respective color rendering index up to 91 and power efficiency 20.9 lm/W. The resulting color temperature is tunable from 1600 K to 2600 K, covering that of dusk-hue (2500 K) and candle-light (2000 K). By simply varying the emissive layer thickness ratio, the color temperature can also be tuned from high to low sequentially, such as from 5200 K to 2400 K, covering that of cool- and warm-white light for daytime illumination purpose.

2. Experimental

We fabricated color temperature tunable OLED devices by using four blackbody radiation complementary emitters, i.e. red light-emitting bis(1-phenylisoquinoline)-(acetylacetonate) iridium (III) ($Ir(piq)_2(acac)$), yellow light-emitting Iridium(III) bis(4-phenylthieno[3,2-c] pyridinato-N,C 2′)acetyl-acetonate (PO-01), green light-emitting tris(2-phenylpyridine)irid-ium (III) ($Ir(ppy)_3$), and sky-blue light-emitting bis(4,6-difluorophenylpyridinato-N,C2)-picolinato-iridium(III) (FIrpic), dispersed in three different emissive layers (EMLs). As shown in Fig. 1, the first EML was designated to yield a most energy-efficient sky-blue emission obtained by doping 20% FIrpic in a host of bis-4-(N-carbazolyl)phenyl)phenylphosphine oxide (BCPO), the second EML to yield a brightest green emission obtained by doping 10% $Ir(ppy)_3$ in a host of 4,4′,4″-tris(carbazol-9-yl)triphenylamine (TCTA), and the third EML to yield an intensive orange-red light obtained by doping 3% red dye $Ir(piq)_2(acac)$ into an energy-efficient yellowish green EML composing a 5% yellow dye PO-01 and a 12.5%

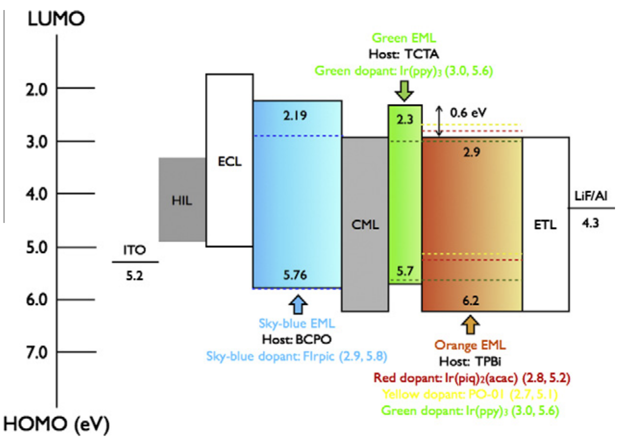

Fig. 1. Schematic illustration of the device structure, in terms of energy-levels, of the color temperature tunable as well as low color temperature OLED devices composing four black body radiation complementary emitters, namely red, yellow, green, and sky-blue, dispersed in three emissive layers with a nano-scale carrier modulating layer. This figure also shows an effective energy barrier, 0.6 eV, at the interface between the green and orange-red EMLs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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