An organic solution to the Kelvin myth? White light with true color temperature via exciplex formation

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Abstract

Many white light sources are described as having a “color temperature”, a practice that has been termed the “Kelvin myth”, since, in general, only incandescent light-emitters have a spectral distribution which closely approximates that of a black-body curve. We show that the white light emitted, via exciplex formation, from blends of two blue-emitting organic materials, has the same spectral form as black-body light, as perceived by the human eye. The color temperature is tunable, depending on the relative concentrations of the two materials. This suggests that organics could provide a white light source with a tunable, true, color temperature.

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The range of spectral distributions which the human eye perceives as white is rather large and, in its simplest definition, “white” light can be considered as merely a broad spectral distribution in the visible range. A more quantitative approach is clearly required for the comparison of the color of different light sources. The spectral distribution of an incandescent light source is very close to that of a black-body, and therefore, its color can be simply defined in terms of the temperature of the equivalent black-body. For non-incandescent sources a direct color temperature cannot be defined, as the spectral distribution does not have the continuous form of a black-body radiator. In order to define a color temperature for such a source, a series of functions are used to map its Commission Internationale L'Eclairage (CIE) co-ordinates onto the nearest equivalent point on the black-body curve [1]. The resulting temperature is described as a *correlated* color temperature. The problem here is that sources with the same correlated color temperature can have widely different spectral distributions, different again from an incandescent source with the same (true) color temperature. The apparent color of objects illuminated by these sources will therefore be different.

This is the reason why the color of a product purchased after viewing under fluorescent strip lights, correlated color temperature of 5500 K, often appears different under noon sunlight (color temperature ~ 5500 K). Fig. 1 shows the actual CIE co-ordinates of a typical strip light, far removed from the black-body curve. This problem is not unrecognized, and indeed the use of color temperature to describe non-incandescent light sources has been described as the “Kelvin myth” by a leading lighting supplier to the entertainment industries [2]. There is thus clearly a need for white light sources whose spectral distributions lie on the black-body curve.

While a number of organic-based devices employing a combination of different color-emitting materials to produce white light have appeared in the literature [3–6], there also exists the possibility to combine two blue-emitting molecules in a single, spin-coated layer, to produce white light via exciplex formation [7–9]. The CIE co-ordinates of the luminescence from several different relative concentrations of a blend of two such materials are plotted in Fig. 1. The materials used in this study were *N,N'*-bis(3-methylphenyl)-*N,N'*-diphenylbenzidine (TPD) and 2,5-bis(trimethylsilylthiophene)-1,1-dioxide (STO). TPD was obtained from Aldrich and used without further purification, while STO was synthesized and purified as described by Barbarella et al. [10]. Solutions of different relative molar concentrations of STO and TPD were prepared in toluene, with a constant

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Fig. 1. CIE chromaticity diagram showing the co-ordinates of the emission from selected blends of STO and TPD, with the STO molar percentages shown. Also indicated are the co-ordinates of the emission from a typical fluorescent strip light.

overall concentration of 0.04 M. Films were spin-coated onto quartz glass substrates. Photoluminescence spectra were excited by a He:Cd laser ($\lambda = 325$ nm), and corrected for the response of the monochromator.

The co-ordinates of the luminescence from these blends lie on the black-body curve, showing that the emitted light is a good approximation to that produced by an incandescent source. The luminescence spectrum for one of these blends is shown in Fig. 2. The spectrum has two main components—a blue peak at around 425 nm, due to the intrinsic blue emission of the individual molecules, and a much broader peak in the green/red due to exciplex formation. An exciplex [11] is a charge transfer complex formed between the excited state of one molecule and the ground state of another molecule. The resulting complex electron hole pair decays via photon emission, considerably red shifted and broadened compared to that from either of the individual molecules. Here, the combination of two blue-emitting molecules leads to an exciplex emission in the green/red, giving an overall white spectrum [7,8].

The question is then, how does a clearly non-continuous spectrum of the form shown in Fig. 2(c), i.e. a peak in the blue with a broad peak in the green/red, mimic that of an incandescent, or black-body, emitter. The answer lies in Fig. 2(a), where the sum of the three CIE color matching functions [12] has the same form. A continuous emitter, such as a black-body radiator, modulated by the CIE color matching functions will therefore have a spectrum of the form shown in Fig. 2(a)—in other words a

Fig. 2. (a) Sum of the CIE matching functions. (b) Emission spectrum from a fluorescent strip light. (c) Luminescence spectrum from an STO/TPD blend with 33% STO.

continuous spectrum is perceived by the human eye as the combination of a blue peak and a broad red/green peak. Note the difference between the relatively smooth forms of the exciplex spectrum and the sum of the CIE functions compared to that of the fluorescent strip light, Fig. 2(b).

A white exciplex-based LED has been already been demonstrated [9], as have both high intensity [13] and high efficiency [14] in, admittedly non-white, exciplex-based LEDs. This suggests that a tunable, white-emitting, organic-based light source with a true color temperature is a realistic future product.

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