Performance Analysis of Red, Blue and Green OLED Spectrum

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Abstract. A mathematical model was analyzed for Organic Light Emitting Diodes (OLED) performance and characteristics for various wavelengths of interest in the visible spectrum. The results for parameters such as luminance decay, power efficiency and current efficiency of OLEDs are analyzed. A correlation between OLED luminance and wavelength has been derived to propose the most suitable wavelengths for which the lifetime of OLED is longest. Analysis is also done on two more correlations between luminance, voltage, stretch factor and wavelength. Furthermore, current efficiency and power efficiency of OLEDs have also been analyzed for different visible wavelengths.

Keywords: OLED, luminance decay, power efficiency, current efficiency, lifetime.

1 INTRODUCTION

Organic Light Emitting Diodes commonly known as OLEDs are one of the most promising efficient and cost effective devices in its category. An OLED is basically a solid state device which consists of thin films of electroluminescent organic layers sandwiched between two electrodes which are conducting anode and metallic cathode. At least one of the electrodes is transparent. With the application of suitable voltage to the device, electron hole recombination occurs resulting in electroluminescence (Van, Chen, Tang 1996). Unlike LEDs, OLED lighting devices are thin panels that emit light across the entire surface area. At present, researchers and manufacturers are more interested to use OLED for display purposes. The lifetime of OLED is the main challenge. In the practical level the lifetime of blue OLED is very short compared to red and green OLED (Hung, Chen 2002).

2 MATHEMATICAL MODEL OF OLED LIFETIME

The lifetime of OLED is defined as the time required to decay the luminance to half of its initial value under steady state condition (Buckley, Yates, Underwood 2009). There are lifetime models that can be used to describe the luminance decay of OLED. The steady state luminance decay of OLED is described by a stretched exponential function or Kohlrausch function (Buckley et al. 2009) (Meerheim, Walzer, Pfeiffer, Leo 2006)

$$\mathrm{L(t)} = \mathrm{L_{\circ}} \exp\left[\left(-\frac{\mathrm{t}}{\tau}\right)^{\beta}\right] \qquad (1)$$

Here L(t) is the luminance at time t, $L_{\circ}$ is the initial luminance, τ is the decay time constant which depends on the temperature, β is the stretch factor which shows the steepness of the initial drop. Secondly, a model which is purely mathematical is used to describe the luminance decay (Kristukat, Gerloff, Hoffmann, Diekmann, 2013)

$$L(t) = L_\circ\,(1 - bt^{\gamma}) \tag{2}$$

Here L(t) is the luminance at time t, $L_\circ$is the initial luminance, t is time, β is a fit parameter, γ is a fit parameter. The fit parameter γ is in the range of 0 to 1 and the function's graph therefore has the shape of a negative non-integer root function. Thus it is called the generalized root (GR) model. Its obvious drawback is that it may yield negative values and therefore it has no physical meaning (Kristukat et al. 2013). There is another equation that describes the OLED lifetime. It is a differential equation in time. It has to be solved and fit to the experimental data by means of numerical integration (Féry, Racine, Vaufrey, Doyeux, Cina, 2005)

$$\frac{1}{\tau}\frac{d}{dt}\left(\frac{N}{N_S}\right) = \exp\left(-A\frac{N}{N_S}\right) - \frac{N}{N_S}e^{-A} \tag{3}$$

Here N_S and N are the total number and the number of quenched emission centers respectively, A and τ are fit parameters. In this paper a relation between OLED lifetime and wavelength has been made. Luminous flux Φ(λ) at wavelength λ is (Tsujimura 2012)

$$\boldsymbol{\emptyset(\lambda) = \mathrm{Pk_m y}(\lambda)} \tag{4}$$

Here P is the emission intensity, k_m is the maximum luminosity factor, y(λ) is relative luminosity. On the other hand Luminance is defined as (Tsujimura 2012):

$$\mathrm{L} = \frac{\emptyset}{\pi} \tag{5}$$

Substitution of ∅(λ) from equation 4 to equation 5 gives:

$$\mathrm{L}(\lambda) = \frac{\mathrm{PK_m y}(\lambda)}{\pi} \tag{6}$$

This equation gives a relation between Luminance and wavelength. Since equation 6 is not time dependent, therefore this equation yields the maximum value of luminance at a particular wavelength. It was hypothesized that L(λ) of equation 6 is the initial luminance of equation 1. Therefore

$$\mathrm{L}_\circ = \frac{\mathrm{PK_m y}(\lambda)}{\pi} \tag{7}$$

Substituting $L_\circ$ in equation 1 gives:

$$L_t = \frac{\mathrm{PK_m y}(\lambda)}{\pi}\,\exp\left[\left(-\frac{t}{\tau}\right)^{\beta}\right] \tag{8}$$

Equation 8 shows the relation between Luminance at a particular time and the wavelength of the light. Simulation of equation 8 for red, blue and green OLED shows the wavelengths for which the corresponding lifetime is highest. It should be noted that all the simulation of this paper has been simulated for a specific OLED for which the emission intensity P is already known (Pais, Banerjee, Klotzkin, Papautsky 2008). This OLED has a 10 nm layer of EB390 as hole injection layer, 10 of nm NPB layer as hole transportation layer, 15 nm of AlQ as electron emitting layer, 100 nm of aluminum as the cathode layer and a 1 nm layer of LiF as the shadow mask (Pais et al. 2008). For this device the value of emission intensity is given in Fig 1. For blue OLED, equation 8 was simulated for 460 nm, 470 nm, 480 nm and 490 nm.

Results show that for blue OLED, 490 nm is the best wavelength of operation [Fig. 2]. On the other hand, 540 nm is the best wavelength for green OLED according to the results [Fig. 3]. It is also evident that the lifetime of red OLED is higher if it is operated for a wavelength of 620 nm [Fig. 4].

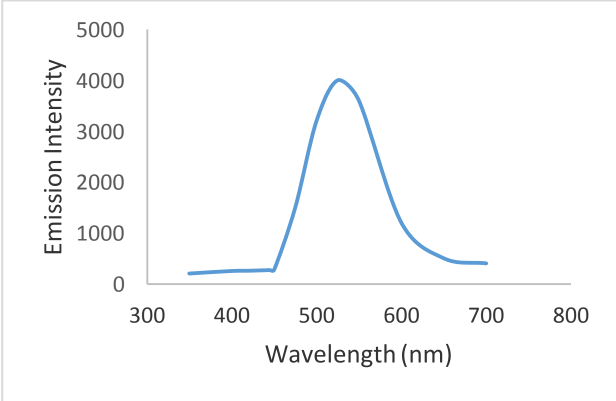

Fig. 1. Emission intensity at different wavelength for the

Corresponding OLED (Pais et al. 2008)

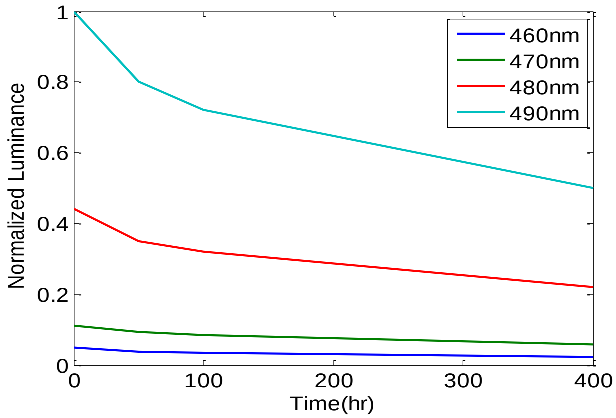

Fig. 2. Luminance decay of blue OLED

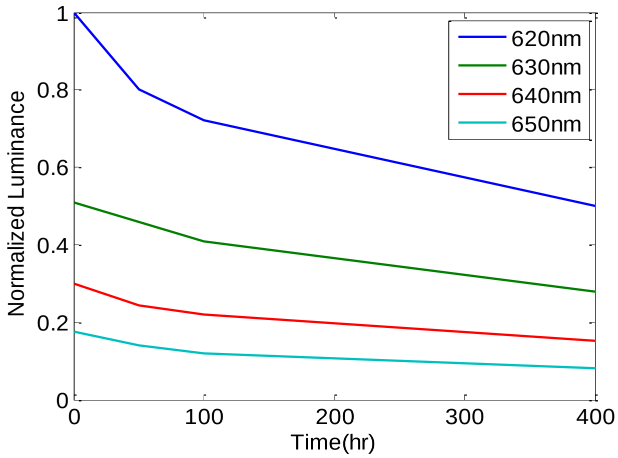

Fig. 3. Luminance Decay of green OLED

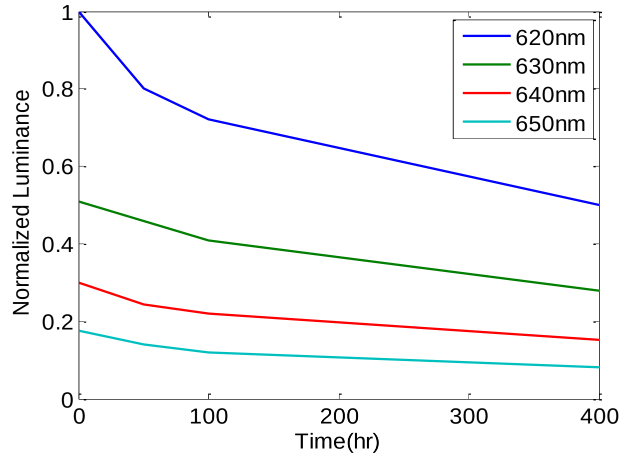

Fig. 4. Luminance Decay of red OLED

3 CORRELATION BETWEEN OLED LUMINANCE AND VOLTAGE

Although the results show that the luminance of OLED decays with time, it should also be noted that the voltage rises with time (Weon, Kim, Lee, Jung 2006). Though the basic principle of luminance and voltage during operation is not yet properly understood, a relation can be established between luminance and voltage during operation. Equation 9 describes normalized luminance (Weon et al. 2006).

$$L(t) = \frac{L_t}{L_\circ} = V(t)^{-\delta(t)} \tag{9}$$

Here $L(t)$ is normalized luminance at time t, L_t is luminance at time t, $L_\circ$ is the initial luminance $V(t)$ is internal voltage of OLED at time t, $\delta(t)$ Indicates a decay exponent. $\delta(t)$=At^B. Here A=exp $(\alpha_1 - \alpha_2)$ (Weon et al. 2006), B=exp $(\beta_1 - \beta_2)$. Researchers measured the values of α_1, β_1, α_2 and β_2 for some specific current density by experimental method. Here the experimental value of α_1 and β_1 for the current density of 12.8 mA/cm^2 are estimated as −1.4574±0.1041 and 0.2566±0.0161 (Weon et al. 2006). The experimental value of α_2 and β_2 for the current density of 63.8 mA/cm^2 are −4.6626±0.1227 and 0.3806±0.0219 (Weon et al. 2006). From equation 8 and 9

$$L_t = \frac{\mathrm{PK_m y(\lambda)}}{\pi} \exp\left[\left(-\frac{t}{\tau}\right)^{\beta}\right]$$

$$L_t = L_\circ V(t)^{-\delta(t)}$$

Substituting $L_\circ = \frac{\mathrm{PK_m y(\lambda)}}{\pi}$ in equation 9

$$L_t = \frac{\mathrm{PK_m y(\lambda)}}{\pi} V(t)^{-\delta(t)} \tag{10}$$

Equation 10 is a new correlation between voltage, luminance and wavelength. This is the second equation that has been proposed. In Fig. 5, a simulated graph using equation 10 has been shown. It should be noted that the voltage level at different time has been taken from another research (Weon et al. 2006). Fig 5, Fig 6 and Fig 7 are simulated graphs for equation 10. For a wide range of wavelength the equation was simulated and it was seen that for blue, a higher initial luminance was achieved for 490 nm wavelength, for green and red it is 540 nm and 620 nm respectively.

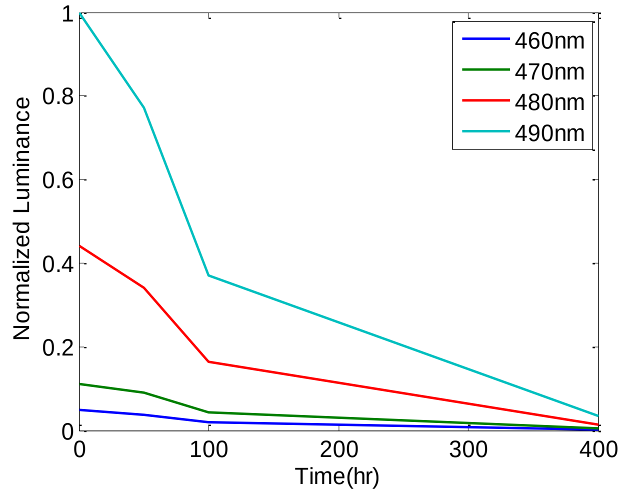

Fig. 5. Luminance decay curve for the blue OLED

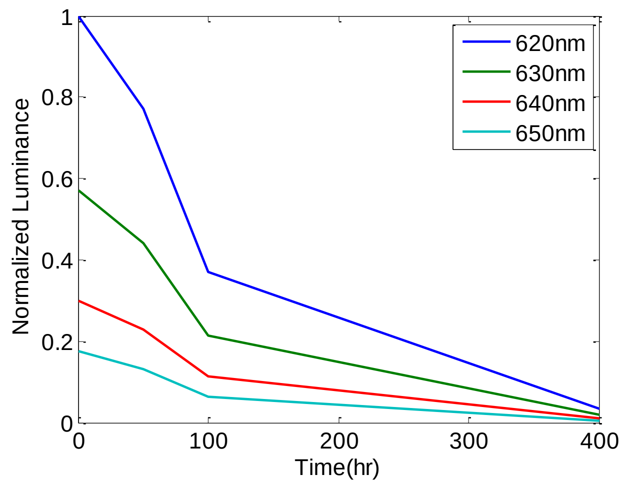

Fig. 6. Luminance decay curve for red OLED

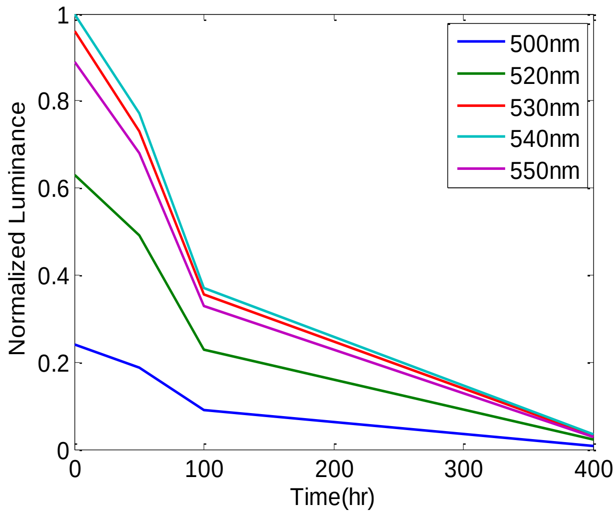

Fig. 7. Luminance decay curve for the green OLED

4 CORELATION BETWEEN OLED LUMINANCE, VOLTAGE, WAVELENGTH, STRECH FACTOR AND DECAY TIME CONSTANT

In this paper another new correlation between luminance, voltage and wavelength has been proposed. Multiplying equation 8 and 10:

$$L_t^{\,2} = \left[\frac{\mathrm{PK_m y(\lambda)}}{\pi}\right]^2 \exp\left[\left(-\frac{\mathrm{t}}{\tau}\right)^{\beta}\right] V(t)^{-\delta(t)} \tag{11}$$

$$L_t = \frac{\mathrm{PK_m y(\lambda)}}{\pi} \sqrt{\exp\left[\left(-\frac{\mathrm{t}}{\tau}\right)^{\beta}\right] V(t)^{-\delta(t)}} \tag{12}$$

Equation 12 is also a correlation between luminance, voltage and wavelength. From this equation one can measure the lifetime of OLED at a certain frequency for a certain voltage. The difference between equation 10 and 12 is that equation 12 includes the stretch factor β and decay time constantτ. Using equation 12 we can analyze the effect of wavelength, voltage, stretch factor and decay time constant on the OLED lifetime. This relationship was further simulated to establish which wavelength will produce the highest initial luminance and better lifetime.

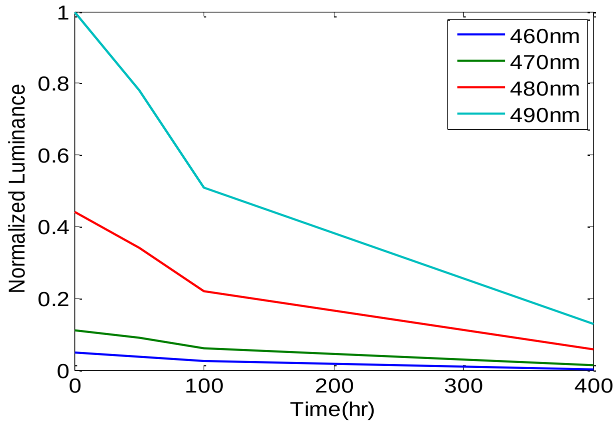

Fig. 8. Luminance decay curve for blue OLED

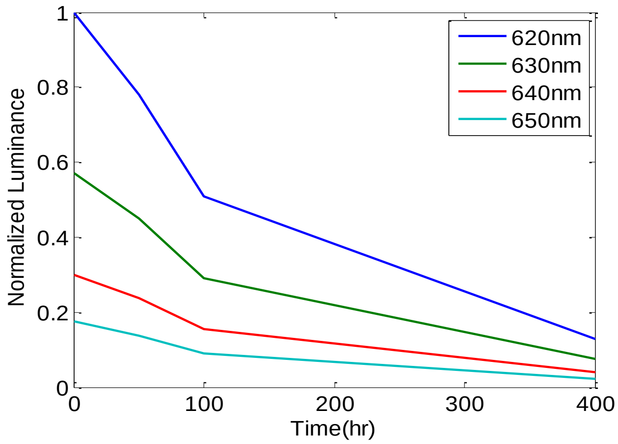

Fig. 9. Luminance decay curve for red OLED

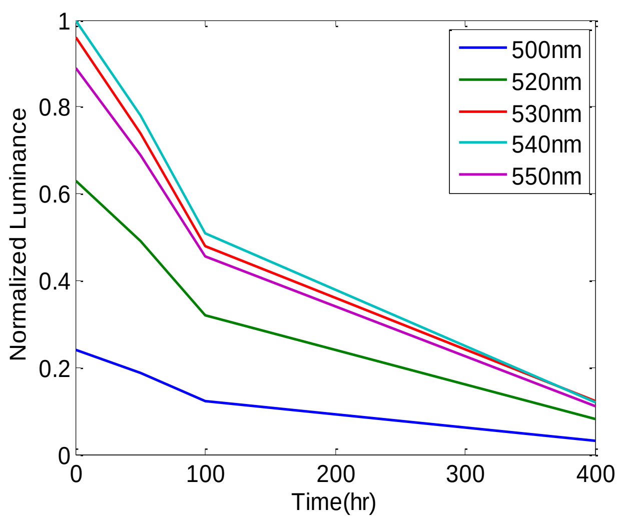

Fig. 10. Luminance decay curve for the wavelength of 530 nm which is simulated using equation 12

From the simulated graphs of equation 12 it is clear that the highest initial luminance exist for 460 nm wavelength in case of blue light. For green and red it is respectively 500 nm and 620 nm. Equation 8, 10, 12 are giving similar results and they are also giving same range of wavelength for each color of light.

4 OLED CURRENT EFFICIENCY

Current efficiency η_c (cd/A) is defined as the luminance divided by the current density (Tsujimura 2012). Mathematically:

$$\eta_c = \frac{L}{J} = \frac{PK_m y(\lambda)}{\pi I} \tag{13}$$

From this equation it can be said that the current efficiency of OLED depends on the wavelength of the light. Fig. 11, 12 and 13 are generated graphs for current efficiency equation. It is seen that for red light at 620 nm wavelength, the highest value of current efficiency is yielded.

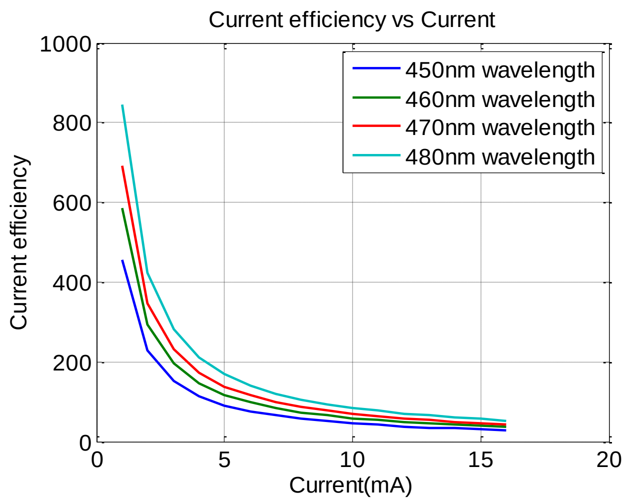

Fig. 11. Current efficiency curve for blue OLED

For green light and blue light at 540 nm and 480 nm wavelength respectively, the highest values of current efficiency are produced. After simulating the current efficiency equation for blue light from 450 to 480 nm, for green light 500 to 560 nm and for red light the range was 620 to 670 nm wavelength, the above values give best values of current efficiency.

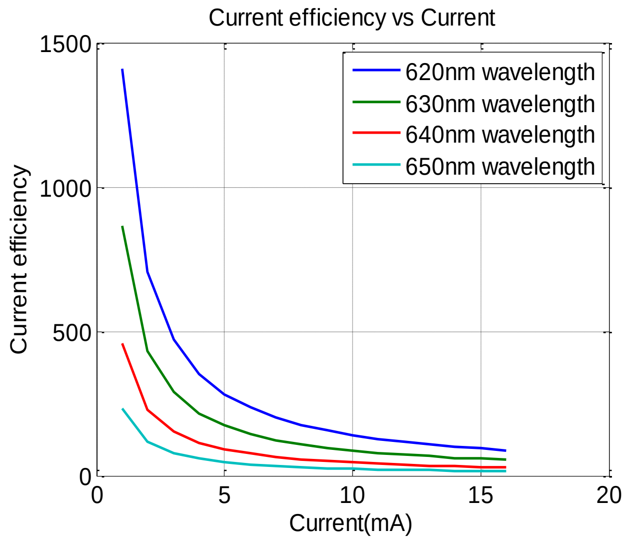

Fig. 12. Current efficiency curve for red OLED

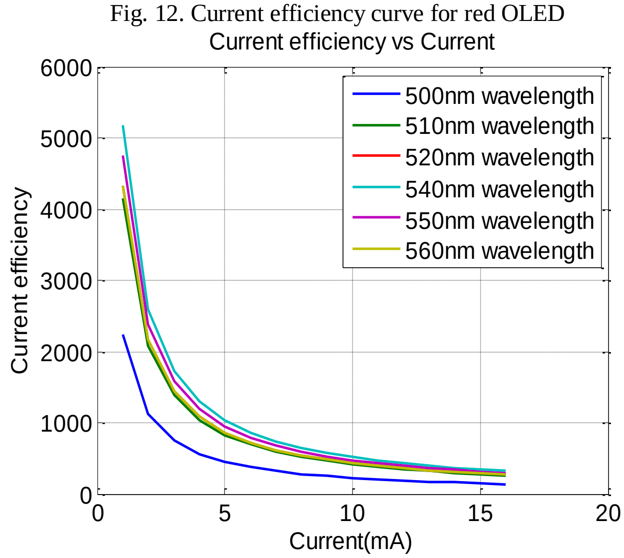

Fig. 13. Current efficiency curve for green OLED

5 POWER EFFICIENCY OF OLED

Power efficiency is another important factor for OLED. The luminance produced by OLED for every unit of power is called the power efficiency of OLED. The Power efficiency or luminous efficiency can be defined as (Tsujimura 2012).

$$\eta_e = \frac{\emptyset}{W} = \frac{PK_m y(\lambda)}{IV} \quad (14)$$

It also shows power efficiency depends on the wavelength of light, because intensity depends on the wavelength of light. Power efficiency changes with the change of luminance.

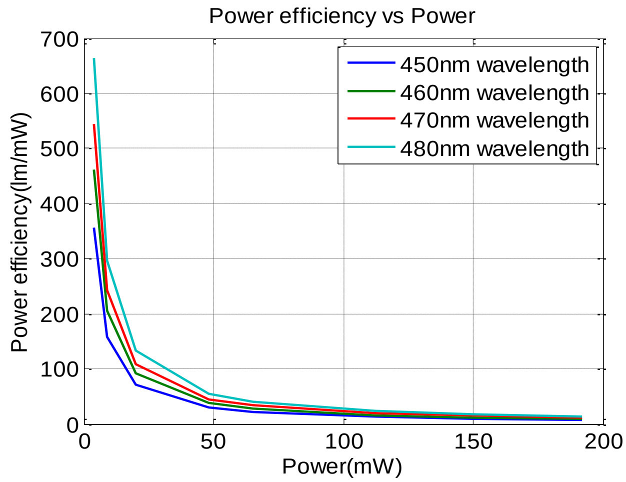

Fig. 14 Power efficiency curve blue OLED

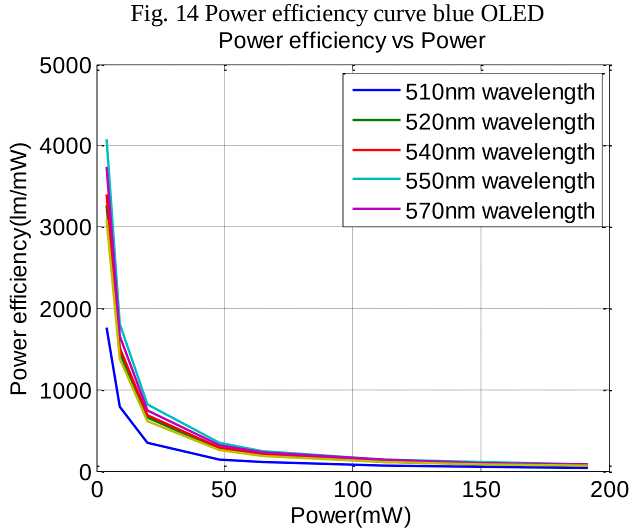

Fig. 15. Power efficiency curve for red OLED

For the power efficiency equation, another simulation for a range of wavelength was performed. And from Fig 14, 15 and 16, it can be seen that blue has the highest power efficiency at 480 nm wavelength, and red has the highest power efficiency at 620 nm wavelength, and green has the highest power efficiency at 540 nm wavelength. It is also observed that blue light has less power and current efficiency than red and green light. And green light has the most power and current efficiency. Analyzing all these graphs, it is clear that for 480 nm, blue has best initial luminance, lifetime, power efficiency and current efficiency. And for green light it is in 530-540 nm range and for red light it is at 620 nm wavelength.

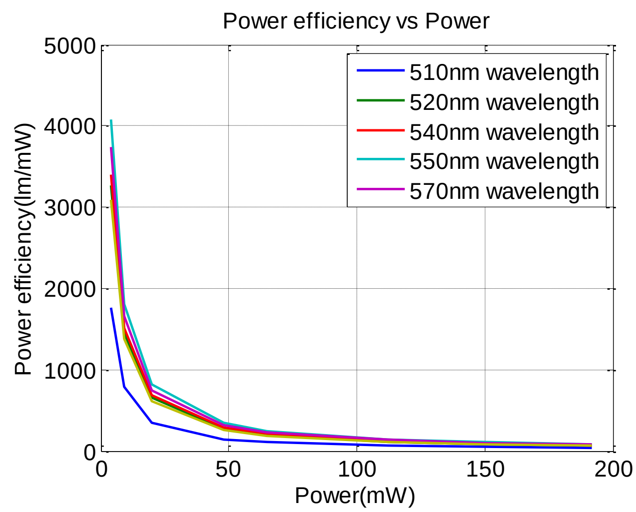

Fig. 16. Power efficiency curve green OLED

6 EFFECT OF TEMPERATURE ON OLED LIFETIME

The two terms τ and β are temperature dependent (Ishii 2003). The value of τ and β at different temperature has been shown in Table 1. Since these two parameters are part of equation 8 and it depends on the temperature, the lifetime of OLED also depends on the temperature. Equation 8 was again simulated for the optimum wavelengths using these two parameters.

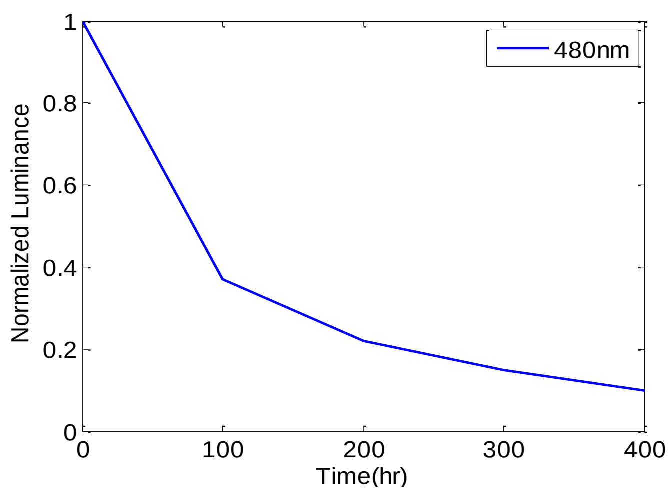

Fig. 17. Luminance Decay for the light of wavelength 480 nm at 85℃

In Fig 17 and 18 luminance decay curve has been shown for the light of wavelength of 480 nm. But in Fig 17 the value of τ and β at 85℃ has been taken and in Fig 18 the value of τ and β at 120 ℃ has been taken. It should be noted that in the previous sections the value of τ and β at 25℃ has been taken. Only these 3 temperature values were considered due to lack of available data from relevant research. Comparing Fig 17 with 18 it is evident that the luminance decay rate is faster when the temperature is high.

Table 1. Values of $\boldsymbol{\tau}$ and $\boldsymbol{\beta}$ at different temperature (Ishii 2003).

Temperature ($°C$)	τ	β
25	757	0.56
85	102	0.59
120	31.8	0.57

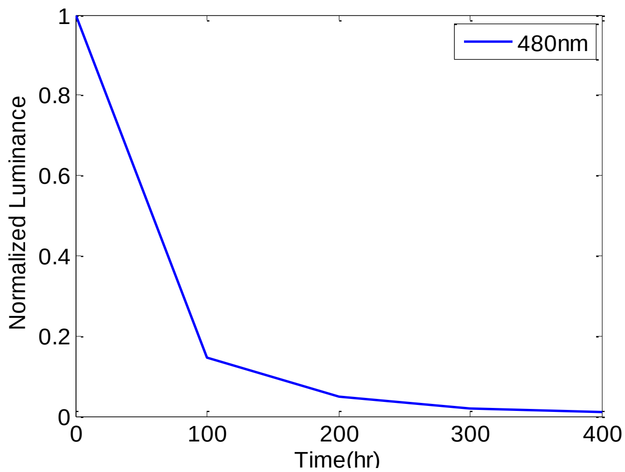

Fig. 18. Luminance Decay for the light of wavelength 480 nm at 120℃

7 CONCLUSION

The initial goal was to find a range of wavelengths for which best results can be achieved. For every color, a range of wavelengths which gives best values of initial luminance, life-time, current efficiency has been presented in the earlier sections. Also shown are three correlations (equations 8, 10 and 12) for OLED parameters on interest. Although these correlations were not verified experimentally, they are producing results similar to experimental results achieved by other researchers. The results for optimum wavelength for the red and green lights are similar to the wavelengths of red and green lights which are used in current applications. This paper also analyzed two important parameters called current efficiency and power efficiency for different values of wavelengths and proposed the optimum wavelengths these two parameters.

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