Simulation of Color Shift in Fluorescent LED Cap

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Abstract: Computer investigation and design of light propagation in fluorescent scattering media is considered. Suggested solution provides efficient and physically accurate model of light propagation in the media that allows simulating Stokes color shift effect and design of white LED.

Keywords: scattering media, fluorescence, fluorescence efficiency, LED, Stokes color shift, LED color design.

1. Introduction

Modern, high efficient light source LED emits in very narrow spectral band (often in violet-blue region) that makes these LED unusable for many applications. The task of generation of white LED emission is very important and has different engineering solutions [1]. One of the solutions is generation of white emissions as a result of color shift of the part of initially blue LED emission to red spectral area [2]. In this case output light emission which is mixture of blue and red spectral emissions takes white color. The color shift effect is caused by fluorescence phenomenon. Our work is aimed to design solution to simulate this phenomenon. We elaborated computing model of accurate light propagation in the materials with fluorescence properties. Taking into account that fluorescence material usually has finely grained structure embedded into binding material we supply our computing model with special features of light propagation in the scattering medium with micro particles (including fluorescence ones). The article presents results of simulation of color shift effect in the initially blue LED and design of white LED by means of optimal choice of concentration of scattering fluorescence particles.

2. Physical system

Fluorescence means that particle captures photon of one wavelength and re-emits photons of another, longer wavelength. Angular distribution of emitted photons is assumed isotropic. Polarization is absent.

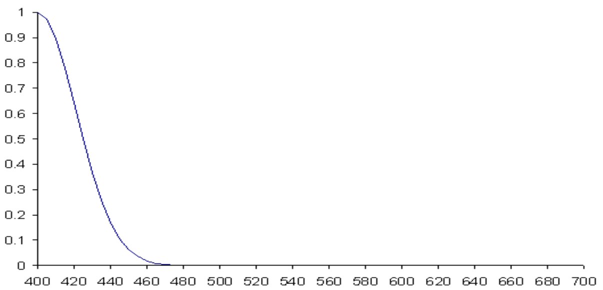

Fig. 1. Spectrogram of LED emission

The remained quantitative measure of fluorescence is its efficiency factor. Let particle is illuminated with incident light of wavelength λ_{in} and unit flux, then spectral density of energy of emitted light near wavelength λ_{out} is

$$dE = \pi r^2 Q(\lambda_{in}, \lambda_{out}) d\lambda_{out}$$

where r is particle radius, $Q(\lambda_{in}, \lambda_{out})$ is fluorescence efficiency factor for particle of particular size and shape and in particular environment. It may be calculated from properties of material or measured.

We investigated the example where fluorescent cap of LED transforms originally blue emission of LED into white output light. The LED is simulated as 1x1 mm area light source with Lambert emission. Spectrogram of emitted light is shown in Fig. 1.

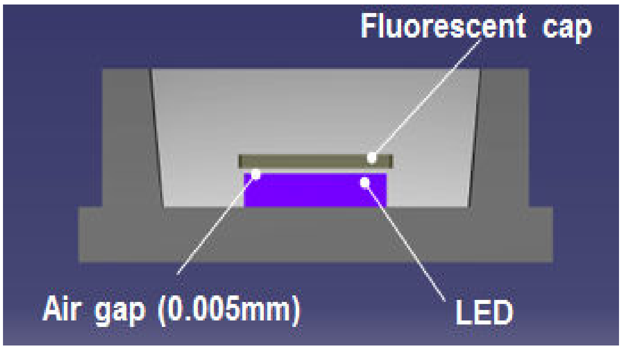

Fig. 2. LED geometry

Fluorescent cap (Fig.2) is simulated as a cylinder of height (thickness) 0.25 mm, and radius 1.25 mm, placed above the LED. There is air gap 5 μm between them.

Material of the fluorescent cap consists of "passive" binder (refraction index 1.5) with particles of diameter 15 μm dispersed in it. They are made of fluorescent substance with refraction index 2.0.

In our simulation the fluorescent efficiency factor was taken as shown in Fig. 3. As incident wavelength (shown by color lines in the Fig. 3) increases, maximum moves to red band and its value decreases. Such function, though artificial, obeys basic physical properties of fluorescent efficiency (Stokes law).

There was no absorption in the particles, i.e. incident light is either scattered or re-emitted in different color.

This is the simplification because usually some captured photons are not re-emitted but gone into heat. This effect reduces overall efficiency of the cap, and thus increases required number of rays to get accurate solution using Monte Carlo ray tracing technique.

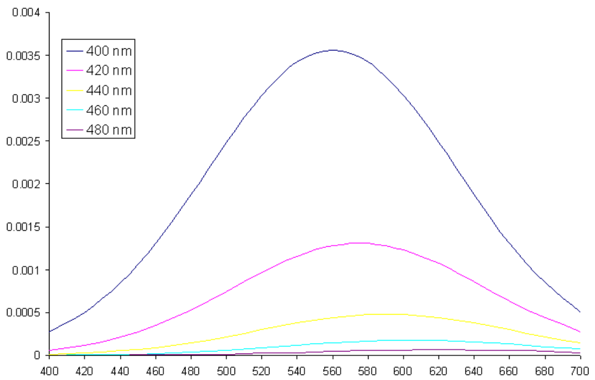

Fig. 3. Fluorescent efficiency factor of used particles for 400 - 480 nm

3. Results of simulation

We did calculations for increasing concentration of particles. When there are no of them, we see original LED color (blue).

One can see that for nonzero concentration of phosphors, scattering (and fluorescence) spread light over whole cap, so its disk is all illuminated and visible, see Fig. 4.

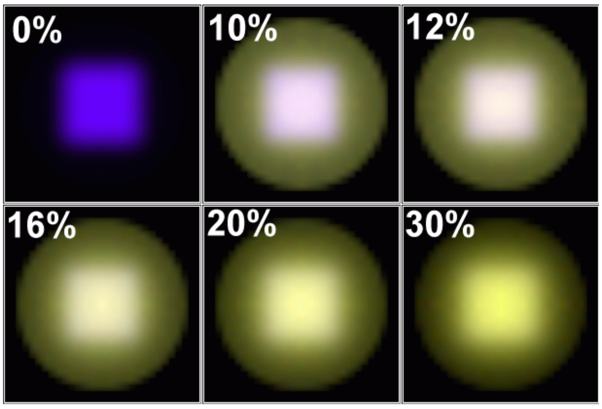

Fig. 4. Luminance distribution over cap's top for different concentration of particles. Bright central square is just above LED's emission area.

In each image, Tone Mapping Operator is applied with maximal luminance taken from the brightest point (center of the image). Thus all images look about the same brightness. It is convenient to investigate change of shade. Actually brightness decreases with concentration, though not strongly. It is price for color shift.

Notice that for low densities light spot reproduces LED emission area while for higher densities because of multiple scattering (i.e. light diffusion) in the layer it spreads approaching symmetric distribution.

4. Design of white LED

Design aim is to achieve the white color. For automatic optimization we need a quantitative criterion. A simple yet reasonable one is deviation of luminance over "central area" (above LED, see Fig. 4) from white: we take averaged R, G, B components and calculate their relative difference:

$$d = ((R - W)^2 + (G - W)^2 + (B - W)^2)^{1/2} / W,$$

$$W = (R+G+B)/3$$

The optimal system parameters would then minimize d. Its plot vs. phosphor concentration is shown in Fig.5.

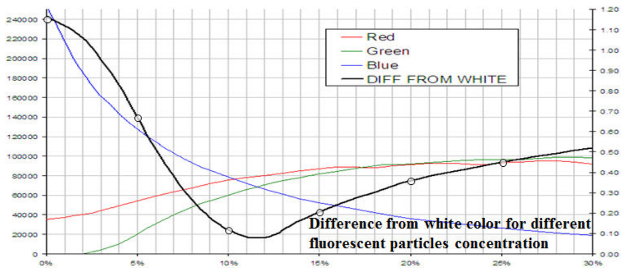

Fig. 5. R, G, B luminance over central area (above LED) and "difference from white" d (secondary axis) as a function of concentration.

The minimum is approximately at PVC=12%. This is result of descent to minimum and thus gives better approximation to white. Luminance values are very high because we assigned unit flux for LED; when concentrated in small area about 10^{-6} m^2 it naturally gave large luminance. Its absolute values are though irrelevant because of linearity.

5. Conclusion

The solution for physically accurate simulation of fluorescence and volume scattering phenomena in complex optical devices like LED is elaborated. It is demonstrated that developed software is capable to design of LED color. The elaborated software is embedded in software package SPECTER [3].

6. References

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http://www.integra.jp/en/specter/index.html