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# Laser – driven white light generation by mixing blue (BAM), green (GYAG) and red (nitride) phosphors

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## ABSTRACT

In the present work, a purple laser diode of 405 nm is employed for the excitation of different types of phosphors for the purpose of building a white light source. Three different types of phosphor materials were synthesized – a blue phosphor (BAM), a green phosphor (GYAG) and a red phosphor based on nitride. These samples were synthesized in the form of silicone pellets, having different thicknesses and different concentrations in the silicone matrix. In this study, two different approaches were followed. First, the three different samples were stacked together in various combinations to study the colorimetric parameters of the emitted converted light, particularly the correlated color temperature (CCT) and the color rendering index (CRI). In the second approach, the three types of phosphors were merged in the same silicone pellet. Pellets with different thickness and ratio of the three phosphors were prepared, and their CCT and CRI parameters were measured under laser excitation. In the first case, a CCT of 2264 K and a CRI of 74 were achieved while with the second approach, an average temperature of 4500 K and a CRI of 85 were reached. While the difference between the CRI values for both cases is not big, the CCT value of the mixed samples is twice as high as the value of the stacked pellets, something attributed to simultaneous excitation of phosphors in mixed samples while, when stacked, each material is irradiated in a specific order.

**Keywords:** laser diode, white light, CCT, phosphors, CRI

## 1. INTRODUCTION

Ever since the development of the first blue light emitting diode<sup>1</sup>, solid state lighting has gained tremendous interest, offering an energy efficient alternative, especially when compared to more traditional light sources. LEDs characteristics such as their small size, their relative long lifetime as well as their low energy consumption have led to their adoption as a major light source, with their usage increasing in the near future. While white light generation can be achieved by mixing the light of red, green and blue diodes<sup>2</sup>, the most common practice is the combination of a blue LED diode with a yellow phosphor material<sup>3</sup>.

While the approach of white light generation by phosphor conversion is effective, there are issues with the system’s performance, most notably the efficiency droop. This refers to a drop of the internal or external quantum efficiency of the device due to an increase of the current density and/or the operating temperature, the former called current droop while the latter thermal droop<sup>4</sup>. The outcome of such an increase of the current density usually causes a shift of the peak emission to higher wavelengths while on the same time, an increased temperature is responsible for the broadening of the emission spectrum. The above have a direct effect on the contribution of the wavelength components to the phosphor conversion by moving the color point away from the white light coordinates and decreasing the overall device efficiency.

To counter the droop effect, various solutions have been proposed, with one of them being the replacement of the LED with a laser diode<sup>5</sup>. A laser diode is characterized of the color stability of its laser emission while also its output power and external quantum efficiency follow a linear increase with current. Additionally, the properties of a laser such as its high brightness, the monochromaticity, the directionality of the beam along with the coherence and the polarization render the laser diode a versatile tool for white light generation systems.

While the contribution of the laser diode is very important to such a device, the phosphor probably has the most significant role in order to achieve efficient white light generation. Phosphor properties such as the thickness, the concentration, the particle size, the geometry of the material and the number of particles are important parameters to consider.

In the present study a laser diode of 405 nm is used for the excitation of two groups of phosphor samples. The first group is consisted of blue, green and red phosphors, all mixed together in the same silicone resin. For the second group, different pellets for each phosphor were synthesized and they were stacked together in various combinations to study their colorimetric properties such as the CCT and the CRI.

## 2. MEASUREMENTS OF STACKED PHOSPHORS

### Material preparation

For the synthesis of the materials, a Dow Corning<sup>®</sup> EI-1184 high optical transparency silicone was used as the matrix. Its two parts were mixed with the different phosphor powders and then placed in a vacuum pressure chamber to remove the air. Then the mixtures were put to a form in order to acquire the appropriate thickness (1 mm and 2 mm) and diameter (15 mm). To obtain the final solid samples, the mixtures were heated at 180 °C for 10 minutes. The three types of phosphor powders used were: blue phosphor BAM ( $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$  Sigma Aldrich), cerium doped yttrium aluminum garnet as green phosphor (GYAG Intematix) and red nitride phosphor. Two phosphor concentrations of 5% and 10% were prepared for the GYAG and nitride samples while four concentrations of 10%, 20%, 30% and 40% were prepared for the BAM samples.

### Emission spectra

The laser diode which was employed was an USHIO (HL40085G, 405nm, 1000mW). A lens was used in the experimental configuration in order to focus the laser beam on the sample. The laser diode was supplied with a direct current of 1.3 A. As the laser illuminates the phosphor, the phosphor absorbs the laser light and then it starts emitting white light. A part of the laser beam, which is not converted to white light, traverses the sample. Laser light can be harmful for the human eye so a filter was placed after the sample to cut off the remnant of the laser beam. A spectroradiometer (SpecBos 1201) was used as a measuring tool to record the emission spectrum and calculate the colorimetric properties of the light. The image (Figure 1) below depicts a graphical representation (left) of the experimental configuration employed in our measurements and the experimental setup (right).

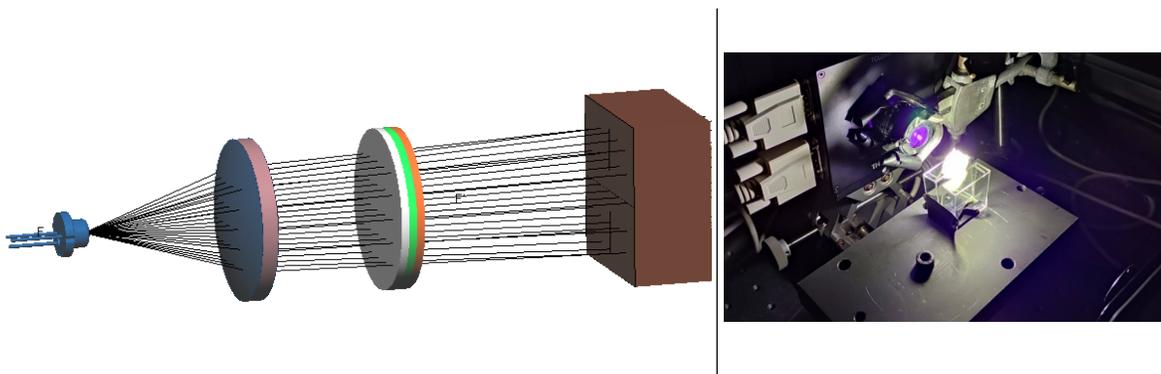


Figure 1. (left) Graphical depiction of the setup with the laser diode, the lens, three stacked samples and the spectroradiometer, (right) samples under excitation.

The three types of phosphors, i.e. blue, green and red were stacked in various combinations, with an average CRI of around 74 and an average CCT of 2264K. However, two combinations were the most promising regarding their colorimetric properties. The first combination, designated as sample 1, was composed of two consecutive BAM phosphors with a concentration of 40% and thickness of 1mm, followed by a GYAG phosphor of 10% concentration and 1mm thickness and a nitride phosphor of 5% concentration and 1mm thickness. The second combination was designated sample 2 and was the same as the above with the difference being that the green phosphor had a concentration of 5% and a thickness of 2mm. The following figures (Figure 2) depict the emission spectra of the two samples.

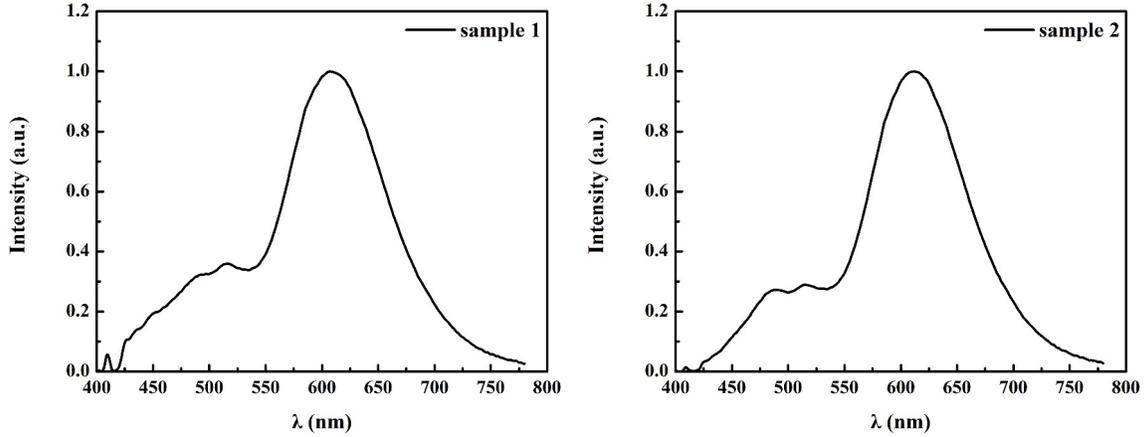


Figure 2. Emission spectra (normalized) of stacked phosphors.

Regarding the colorimetric properties of the above, sample 1 exhibited a CCT of 2491K, a CRI of 82 and its chromaticity coordinates were  $(x, y) = (0.4686, 0.3988)$ . Sample 2 had a CCT of 2236K with a CRI of 80 and the chromaticity coordinates being  $(x, y) = (0.4945, 0.4043)$ . The CCT for both samples is relatively low and as a result the generated light is slightly red. This can be attributed to the fact that part of the blue light is trapped between the phosphor pellets while on the same time red light, coming from the nitride phosphor, is dominant at the end of the phosphor stack. The following table (Table 1) contains the above results.

Table 1. Colorimetric parameters of stacked phosphors.

Sample	CCT (K)	CRI	Chromaticity coordinates (x,y)
Sample 1	2491	82	0.4686, 0.3988
Sample 2	2236	80	0.4945, 0.4043

### 3. MEASUREMENTS OF MIXED PHOSPHORS

#### Material preparation

In the case of mixed phosphors, two samples with an overall phosphor concentration of 5% were made. The first had an equal ratio of blue and green phosphor (BAM/GYAG = 1), while the ratio of blue and green phosphors with the nitride was (BAM+GYAG)/Nit=40/1. The second sample had a (BAM/GYAG = 1) and a (BAM+GYAG)/Nit=50/1. Pellets with a thickness of both 1mm and 2mm were synthesized.

## Emission spectra

Measurements for the mixed phosphor samples were taken using the same experimental setup employed for the stacked phosphors. The emission spectra of the phosphors along with their colorimetric parameters are presented below (Figure 3). For each phosphor concentration, two pellets with different thickness were studied. It can easily be seen that the thicker the phosphor pellet, the higher the intensity of the produced white light is. This is attributed to the fact that a thicker sample has a higher particle number thus the white light output flux is higher<sup>6</sup>.

The colorimetric parameters of samples with a concentration of 40/1 were measured and the following values were found: the 1mm sample had a CCT of 4029K and a CRI of 85 while the 2mm sample exhibited a CCT equal to 3879 and a CRI of 80. Their chromaticity coordinates were  $(x, y) = (0.3929, 0.4276)$  and  $(x, y) = (0.4080, 0.4546)$  respectively. In the case of the mixed phosphor with a concentration of 50/1, the 1mm pellet had a CCT of 4500K and CRI equal to 79 while the 2mm sample's CCT and CRI were 4299K and 78. The chromaticity coordinates of the two samples were  $(x, y) = (0.3829, 0.4418)$  and  $(x, y) = (0.3902, 0.4512)$  respectively. For an easier comparison, all the above results are shown in Table 2.

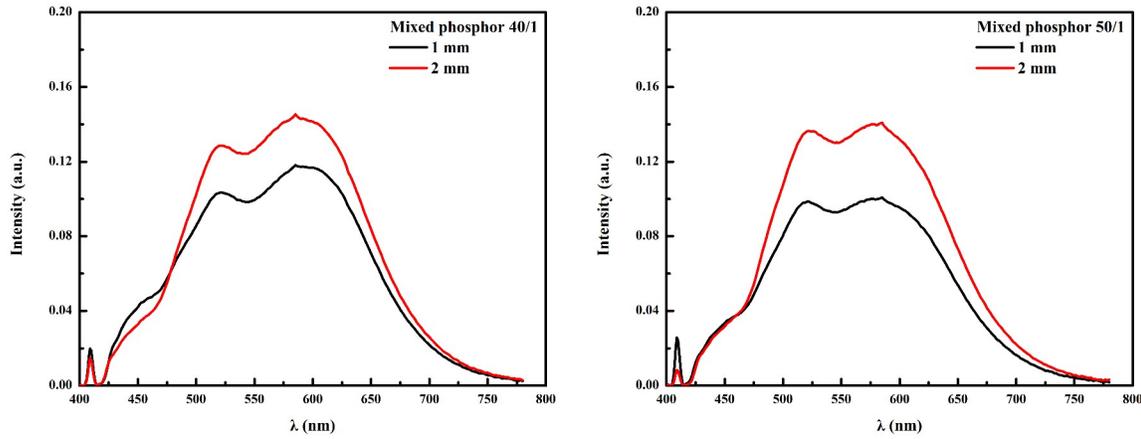


Figure 3. Emission spectra of mixed phosphors.

Table 2. Colorimetric parameters of mixed phosphors.

Sample	CCT (K)	CRI	Chromaticity coordinates (x,y)
Mixed phosphor 40/1 (1mm)	4029	85	0.3929, 0.4276
Mixed phosphor 40/1 (2mm)	3879	80	0.4080, 0.4546
Mixed phosphor 50/1 (1mm)	4500	79	0.3829, 0.4418
Mixed phosphor 50/1 (2mm)	4299	78	0.3902, 0.4512

## 4. CONCLUSIONS

In this study the colorimetric parameters of different phosphor samples were measured under violet laser excitation as potential phosphor materials in an efficient white light generation source. While the usual approach is the coupling of a blue laser diode with a yellow phosphor, we replaced the yellow phosphor with three different colored phosphors (blue, green and red) to achieve better light quality. Two methods were employed; first stacks of different colored phosphor pellets were measured while, on the second part, all three phosphor particles were mixed in the same pellet.

Both methods showed promising results regarding the CRI, with the sample of 40/1 concentration reaching a CRI value of 85. All the other phosphors, both stacked and mixed, had a value of around 80. On the contrary, the CCT values for the two sample categories followed a different trend. While mixed phosphors exhibited a color temperature of around 4000K white light, the CCT of stacked phosphors was significantly lower and ranged around 2300K, generating white light with a dominant red component. This is a direct result of the phosphor arrangement in the stack, with the red phosphor being placed last and emitting more red light, while also a lot of blue light, which is generated first, is trapped between the different layers, thus resulting in a weaker blue component. The above show that stacked phosphor arrangements are better suited for warm light applications while mixed phosphors are better employed when cooler light is needed.

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