Determining colour coordinates of colourful light generated by three laser sources

Isnaeni1,*, Selvina2 and D Tahir2

1Research Center for Physics, Indonesian Institute of Sciences, Building 442, Puspiptek, South Tangerang, Banten, 15314, Indonesia
2Department of Physics, Hasanuddin University, Perintis Kemerdekaan Road, KM.10, Makassar, South Sulawesi, 90245, Indonesia

*E-mail: isnaeni@lipi.go.id

Abstract. Colourful lighting can be generated using various light sources, such as filament lamps, light emitting diodes (LED), and laser. In this work, we present a simple method to generate colourful lighting using three laser sources (red, green, and blue laser) and quantify the generated colours. We set up several laser sources and directed the entire laser beam onto white dove light bulb. We were able to generate 9 different colours and quantify the colour using modified calculation of colour coordinates of colour space diagram CIE 1931. Our simple calculation of colour coordinates agreed with colour appearance. To validate our method, we conducted a simple survey of 25 respondents. 5 out of 9 generated colours show agreement between our calculation method and survey. Thus our modified calculation method can be used to quantify colour lighting generated using three laser sources.

1. Introduction

Lighting is one of important aspects in daily human life, especially indoor or night lighting. People have tried to mimic sunlight, which is assumed as ideal colour of light. White light lamp is the main type of lighting that people need. In addition, colourful lighting sources also important to give special emotional effects to people [1]. Lamps were first developed using incandescent light bulb [2]. Furthermore, different types of lamp have been developed, such as fluorescent lamps, and LED lamps [3, 4]. In the future, people will consider lamp that is generated using laser sources. Using laser, people can create more colour combinations to enhance life. Laser sources can generate more colours indicated by larger gamut area [5].

Colour is strongly related to human feeling; however colour quantification is required. In 1930, the Commission Internationale de l’Eclairage (CIE) has standardized the measurement of light and its response on the human eye. This standard characterizes variations in eye response to visible light with some lighting conditions [6]. Several CIE coordinate standards have been published, ranging from CIE 1931, CIE 1933, CIE 1960, and CIE 1976. Among them, CIE space colour coordinate 1931 is the most used standard until nowadays. A space colour coordinate contains a colour-limited gamut, generated by a tool [7, 8]. Several studies of gamut extensions with various innovations were performed on LEDs [9, 10]. The solution to gain a wider gamut extension and a better colour quality is to use a laser source, which has a monochromatic wavelength. Quantitative analysis of colour mixing using laser sources was done previously; however there was no validation procedure was done [11]. Thus, the
The purpose of this work is (1) to generate multi-colour lighting from three laser sources, (2) to quantify the generated colour using modified calculation of CIE 1931, and (3) to validate our colour quantification using survey.

2. Experimental Methods
Lighting system was built using three kinds of laser sources (red, green and, blue), a white dove light bulb as diffuser, as shown in figure 1. Laser sources and light bulb were assembled in a white box. We used 5 red (wavelength 650 nm) laser sources with 5 mW power each, 3 green (wavelength 532 nm) laser sources with 5 mW power each, and a blue (wavelength 450 nm) laser source with 500 mW power.

Generated light spectrum was detected and recorded using fiber optic spectrometer MAYA from Ocean Optics. Analysis of light spectrum was done using modified calculation and simplified colour matching function to obtain space colour coordinates [11]. Calculated space colour coordinates were then plotted in CIE 1931 colour diagram.

In order to validate our calculation, we conducted a survey, where people were asked to determine space colour coordinate of CIE 1931 of every generated colour lighting, without knowing our calculated coordinates. A pretest was conducted to every respondent to ensure colour-blind free.

3. Results and Discussion
Laser sources were directed onto surface of white dove light bulb, which acts as light diffuser. There was no electric used for the light bulb. The generated colour was confined in a white box. We were able to produce limited colour due to limited combination of laser light sources and unequal power of laser sources and brightness. Since commercial laser sources were used, we have problem in adjusting many colour combinations. In this work, we presented 3 main colours (red, green, and blue) and 6 colour combinations. Figure 2 presents light spectrum and the inset figures show the appearance of colour combination for blue, orange, pink, and white colour.

Blue light in figure 2 (a) came from one type of laser source, which was blue laser source. Orange and pink colours were generated using two types of laser sources. Green and red laser produced orange colour. Meanwhile, blue and red colour produced pink colour. Combination of three types of laser sources produced white colour as shown in figure 2 (d). Due to technical issue in capturing image using ordinary camera, the inset figure of white colour may not look like pure white.

![Figure 1. Schematic of the lighting system using three kinds of laser sources and a white dove light bulb.](image-url)
Figure 2. Light spectrum and appearance (inset figure) for blue (a), orange (b), pink and white (d) colour.

Figure 3. Nine colour combinations generated using three laser sources.

All colour combinations generated using three types of laser sources were shown in figure 3. Single laser source colour (red, green, and blue) are shown in figure 3 (a) to (c). Orange, sky blue, purple, light green, and pink were generated using two laser sources. Lastly, white colour was generated using three laser sources.

Quantization of colour is one big challenge, since colour is strongly related to human feeling and emotion. Colour space diagram CIE 1931 is commonly used to quantize colours. A series of colour matching functions is usually used to calculate colour coordinates for colour space diagram CIE 1931. However, this kind of calculation does not work for light spectrum with Dirac peak such as laser peak spectrum. Our previous work shows an alternative method for calculation of colour coordinates for colour space diagram CIE 1931 [11]. Instead of using a series of colour matching functions, which
covers all wavelength in spectrum, we used only three modified colour matching functions, which correspond to three wavelength of laser sources used in these experiments. The modified colour matching functions used in this calculation are shown in table 1. The modification of colour matching functions are required since when we used complete series of colour matching functions, the calculated colour coordinates in colour diagram CIE 1931 did not match with real colour appearance. In order to calculate colour coordinates, we used simple calculations of equation 1 to 5.

\[
X = x_{\text{red}}I_{\text{red}} + x_{\text{green}}I_{\text{green}} + x_{\text{blue}}I_{\text{blue}} \tag{1}
\]
\[
Y = y_{\text{red}}I_{\text{red}} + y_{\text{green}}I_{\text{green}} + y_{\text{blue}}I_{\text{blue}} \tag{2}
\]
\[
Z = z_{\text{red}}I_{\text{red}} + z_{\text{green}}I_{\text{green}} + z_{\text{blue}}I_{\text{blue}} \tag{3}
\]

where X, Y, and Z are summation of corresponding colour matching functions \((x_{\text{colour}}, y_{\text{colour}}, \text{ and } z_{\text{colour}})\) times colour intensity \((I)\).

\[
x = \frac{X}{X + Y + Z} \tag{4}
\]
\[
y = \frac{Y}{X + Y + Z} \tag{5}
\]

where \(x\) and \(y\) are the colour coordinates that can be plotted in colour space diagram CIE 1931.

| Colour  | Wavelength (nm) | \(x/\) | \(y/\) | \(z/\) |
|---------|----------------|-------|-------|-------|
| Blue    | 450            | 0.11  | 0.01  | 0.85  |
| Green   | 532            | 0.22  | 0.58  | 0.02  |
| Red     | 650            | 0.55  | 0.21  | 0.01  |

*Figure 4. Calculated colour coordinates of 9 generated colours that are plotted in colour space diagram CIE 1931.*
Our calculation of colour coordinates for 9 colours (as shown in figure 3) is shown in figure 4. Our calculated colour coordinates were apparently similar to real colours. For example, in figure 3 (d), orange colour was correctly plotted in orange space in colour space diagram CIE 1931 (spot d in figure 4). Therefore, our calculation method can be applied to quantify colours generated using three laser sources.

In order to clarify our calculation method, we conducted a simple survey. Twenty five respondents were randomly selected. The ages of respondents are between 15 to 50 years old. The number of male and female respondents was approximately equal. Every respondent was given a prepared lighting using three laser sources and a blank colour space diagram CIE 1931. For every lighting, respondent was asked to choose or select position of colour coordinates in colour space diagram according to lighting colour that she/he saw.

Figure 5 show the full results of survey for 9 colour lighting (as shown in figure 3). For some colours, our calculated colour coordinates agreed with survey results. However, for some colours in figure 5, such as orange (d), white (e) and sky blue (f), our calculated colour coordinates were slightly different with survey results. For light green colour, there was not clear conclusion, since all respondents gave different response to the given colour. Nevertheless, for red, green, blue, purple, and pink colours, our calculated colour diagrams were well validated by survey.

4. Conclusions
We have shown generation of colourful lighting using three laser sources. We were able to demonstrate 9 colour combinations and quantify generated colours using our modified calculation to get colour coordinates that can be plotted in colour space diagram CIE 1931. A simple survey had
been conducted to validate out calculation method. In the future, colour combinations using laser sources can be developed using more than 3 laser sources to obtained more colour combinations.

Acknowledgments
This work was supported by Insinas project from Kementrian Riset Teknologi dan Pendidikan Tinggi, Republic of Indonesia No 055/P/RPL-LIPI/INSINAS-1/III/2018.

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