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DEVELOPMENT OF AN EFFICIENT OPTICAL MODEL FOR LEDS-BASED WHITE LIGHT SPECTRUM DESIGN APPLICATIONS

Thi-Minh-Ly Vo
Trong-Nam Tran
Trung-Kien Nguyen
Thi-Hanh Nguyen
Thi-Yen-Nhi Pham
Thien-Bao Huynh
Le-Minh-Khang Tran
Dang-Khoa Pham
Quoc-Cuong Nguyen
Quang-Khoi Nguyen [1]

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A B S T R A C T

We have developed an efficient optical model for simulating the white light spectrum design with high color performance. The optical model began with experimental data collection, simulation with the mathematical model using Gaussian functions, and verifying the similarity between simulation and experiment. In application, the model is applied to study the effect of red light on the optical properties of the generated white light spectrum. The obtained results indicate that the established model is helpful for the solid-state lighting application to fabricate a light source that can emit white light with high optical performance.

1. INTRODUCTION

Light emitting diodes have replaced traditional light sources due to their advanced properties such as energy saving, fast response, environment friendly, and high color performance (Tripathi et al., 2017, Goswami & Shende, 2018; Schubert & Kim, 2005). There are many ways to generate the white light. The first common way is a combination of blue light and yellow light. The blue light is used to excite the yellow phosphor (YAG:Ce), and the absorbed blue light is converted to longer wavelength light of yellow color. The mixing of unabsorbed blue light and converted yellow light will generate white light under the human perceiving (Schubert & Kim, 2005). However the drawback of the first method is blue light hazard, or blue light leakage caused by the stronger thermal decay for yellow phosphor's light emission than that of Blue die's blue light emission (Narendran & Gu, 2005; Schubert, 2006). The second way for white light generation is color mixing blue, green, and red emission spectrum that emits from three types of monochromaticity LEDs including blue, green, and red LEDs. The color pattern of these three types monochromaticity LEDs are shown

[1] Corresponding author: Quang-Khoi Nguyen
Email: nqkhoi@hcmus.edu.vn

in Figure 1. In the field of white light making, design spectrum is an important work in the field of solid-state lighting to obtain a light source with high energy efficiency, and color performance. When mixing the R, G, and B LED to generate the white light, the color performance and optical properties are sensitive to the ratio of Blue, Green, and Red power.

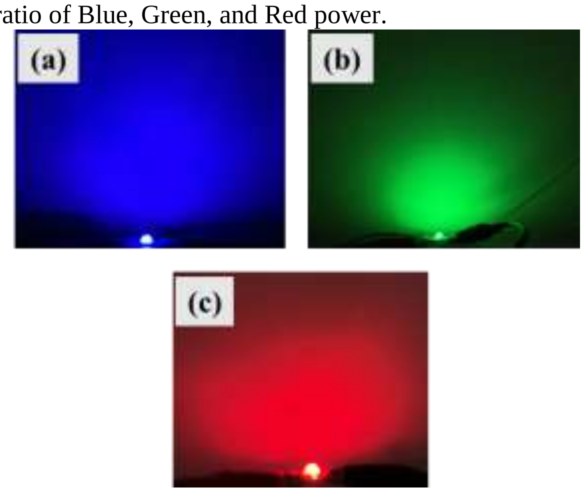

Figure 1. Color pattern of monochromaticity LEDs. (a) Blue LED, (b) Green LED, and (c) Red LED.

Related to the emission spectrum modeling from mixing the R, G, and B LEDs, different topics have been reported. Son et. al. reported a method for the improvement of Color and Luminance Uniformity of the Edge-Lit Backlight Using the RGB LEDs (Sun et al., 2022). Zhao et al. studied the relationship between the driving current of RGB LED chips and the color temperature of the produced white light was investigated. A simple method was proposed to estimate the color temperature output from the electric current input. The proposed method cannot only save a large amount of time for experimental trial-and-error for the color temperature tuning of white light illumination from RGB color mixing, but also reduce the cost of sample preparation (Nguyen et al., 2023). Sun et al. (2022) proposed and experimentally analyzed a novel light luminaire which efficiently mixes and projects the tunable light from red, green and blue (RGB) light-emitting diodes (LEDs). This method is simple and compact; it only uses a short light pipe, a thin diffuser, and a total internal reflection lens. A balance between optical efficiency and color uniformity was studied by changing light recycling and color mixing (Son et al., 2011). Hung et al. (2013) proposed an innovative color mixing technique ased on a linkage mechanism. The individual RGB chips were installed in 3 sets of four-bar linkages to enable color mixing by driving the RGB chips with the crank of the mechanism. The color mixing effects provide a continuing change of colors to meet people's requirements for color mixing fixtures in certain scenarios. Chung et al. (2015) presented a study wherein using a color-mixing cavity, multiple LEDs are used to produce a quasisolar spectrum at a certain band and white light with a color rendering index as high as 97 at around 2800 K (Zhao & Lee, 2012; Sun et al., 2012). Wang et al. (2016) reported an effective color mixing for Red, green, and blue (RGB) light-emitting diode (LED). In this study, three RGB LEDs, each provided with two reflective mirrors, are used to design an all-reflective color temperature-adjustable LED flashlight. The LED flashlight features an adjustable color temperature ranging from 2000 K to 6500 K, a uniformity of illuminance of 0.68, an average difference of uniformity of approximately 25%, and a color uniformity of 0.0042 (Hung et al., 2013). Li et al. 2018 reported a RGB-Stack Light Emitting Diode Modules with Transparent Glass Circuit Board and Oil Encapsulation. Light emitted from each glass circuit board (GCB) stacked LEDs passes through each other and thus exhibits good output efficiency and homogeneous light-mixing characteristics. In this work, the parasitic problem of heat accumulation, which is caused by the poor thermal conductivity of GCB and leads to a serious decrease in output efficiency, is solved by a transparent cooling oil encapsulation (OCP) method (Chung et al., 2015). Huang et al. (2013) studied the R/G/B laser diodes mixed white-lighting source at 6500K performed to implement the WDM VLC system with QAM-OFDM data transmission at 11.2 Gbps. To fit the demand of day-light at CCT of 6500K, the composition of R/G/B output powers needs a precise adjustment; however, the sacrifice between the demand of CCT and data rate is also observed and discussed (Wang et al., 2016). Zhu et. al. (2020) have experimentally fabricated nine types of phosphor layers with patterned RGB pixel array, which consist of tuneable RGB ratio in a planar configuration. In this work, by designing pixel-array phosphor layers with different RGB phosphors, in combination with remote phosphor-converted lighting method, LEDs can realize multi-colour light emission (Li et al., 2016). Wu et al. (2017) reported a white light generation by mixing red, green, and blue laser diodes (RGB LDs) was demonstrated with Commission International de l'Eclairage coordinates of (0.2928, 0.2981), a correlated color temperature of 8382 K, and a color rendering index of 54.4 to provide a maximal illuminance of 7540 lux (Hung et al., 2013). Nie et al. (2021) reported a method to get the high color fidelity for mixed white LED, the other monochromatic LEDs are chosen according to the CIE 1931chromaticity diagram and Grassmann Color Law of additive color mixture. Using the mathematical model of monochromatic LEDs and restrictions of chromaticity coordinates on Planckian blackbody locus, there are only 2 independent variables in the simulation to a certain combination of peak wavelengths. The optimized peak wavelengths of the five monochromatic LEDs are 385, 467, 524, 564, and 632 nm. The blue light hazard efficiency of radiation (BLHER) of the practical mixed white light is always less than 0.06 when its correlated color temperature (CCT) changes from 2500 to 7000 K (Zhu et al., 2020). Das et al. (2021) proposed a novel approach of tunable correlated color temperature (CCT) lighting system with high color rendition using three component color mixing concept. Using Grassmann's color mixing theory, phosphor coated warm white LED source (CCT 2800 K) is mixed with the blue (467 nm) and green (527 nm) LED light sources and a detailed mathematical formulation is derived for easy controlling of variable CCT and experimentally validated (Wu et al., 2017). Bachouch et al. (2021) reported a methodological approach for simulating luminary output radiation, which is achieved by mixing light-emitting diodes (LEDs) in order to match any plant absorption spectrum. Various recorded narrow-band LED spectra of different colors were first characterized and then fitted with a multi-Gaussian model. An optimizing procedure computed the optimal weighting of the relevant parameters so as to minimize the discrepancy between the combined spectrum and the reference target curve. Guarnera et al. (2022) presented two practical approaches for high fidelity spectral upsampling of previously recorded RGB illumination in the form of an image-based representation such as an RGB light probe. Unlike previous approaches that require multiple measurements with a spectrometer or a reference color chart under a target illumination environment, our method requires no additional information for the spectral upsampling step (Das & Mazumdar, 2021). Chen et al. (2022) reported a design method for a high-power optical system based on RGB LED Arrays with multiple channels to achieve high-quality color-mixing and uniform lighting. The high-power optical system consists of a multi-channel reflector and a color-mixing component (Bachouch et al., 2021). Onwukaeme, Lee and Ryu (2023) presented a simple method to obtain a stable correlated color temperature (CCT) for the variation in light output power (LOP) of a light-emitting diode (LED) comprising a trichromatic LED-based white light source. A mathematical model was developed to determine the condition for the stable CCT operation using colorimetric analyses, and the stable CCT condition can be obtained by taking the derivative of the CCT with respect to the power ratio between the LEDs (Guarnera, et al., 2022). In generally, the efficient model for design emission spectra from mixing the R, G, B LEDs is still an demand not only in the field of SSL but also in field of white light making.

In this study, we developed an efficient optical model for simulating the white light spectrum. The model is applied to study the effect of red on the optical properties of the generated white light spectrum. The obtained result is helpful for the solid-state lighting application to fabricate a light source that can emit white light with high optical performance.

2. OPTICAL MODEL PROCEDURES

Firstly, the optical model started with an experiment of taking the emission spectrums of red LED. The main purpose is to determine the parameter of emission spectrums, the wavelength of emission peak, and the value of full width at haft maxima (FWHM). Figure 2 shows the emission spectra of used Red, green, and Red LEDs. Blue LED showed a peak wavelength of 450 nm, and a value FWHM of 20 nm (443 nm to 463 nm). Green LED showed a peak wavelength of 520 nm, and a value of FWHM of 30 nm (508 nm to 538 nm). The Red LED showed a peak wavelength of 630 nm, and a value FWHM of 16 nm (620 nm to 636 nm).

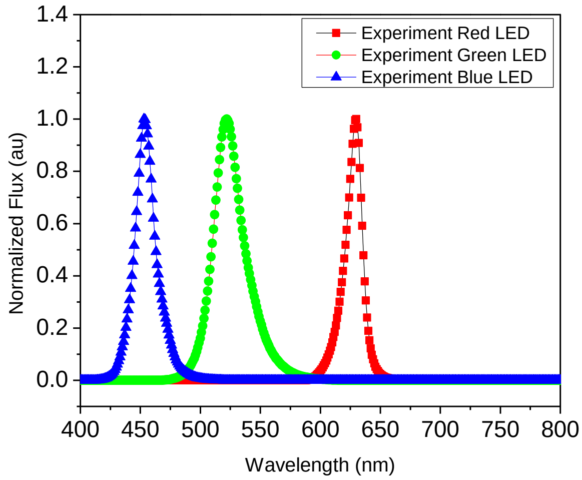

Figure 2. The measured emission spectra of used Red, green, and Red LEDs

For the LED-based white light generation method, white light can be generated by combining blue, green, and red LEDs. The mathematical description for the spectral power distribution (SPD) of LEDs-based white light is

$$P_{white}(\lambda) = P_{blue}(\lambda) + P_{green}(\lambda) + P_{red}(\lambda) \quad (1)$$

Where $P_{white}(\lambda)$ is the SPD of generated white light. $P_{blue}(\lambda)$, $P_{green}(\lambda)$, $P_{red}(\lambda)$ are the SPD of blue, green, and red light that contributes to that white light.

The mathematical description for each component spectrum $P_{blue}(\lambda)$, $P_{green}(\lambda)$, and $P_{red}(\lambda)$ are

$$P(\lambda) = P\,exp\left[-\beta\left(\frac{\lambda - \lambda_{peak}}{\Delta E}\right)^2\right] \quad (2)$$

Where beta β is corrected coeficient, ΔE is the FWHM in nanometers (nm) units, and P is the optical power of LED in watts (W) units.

While the parameter of ΔE is defined in the above experiment, the parameter of beta is defined through an investigation to understand the effect of beta value on the shape of the emission band. Then the optimal value of beta will be defined to ensure the highest matching between the simulated spectrum and the experimental spectrum. The effect of beta value on the shape of the emission band is shown in Figure 3. The optimal value of beta which has the highest matching between the simulated spectrum and experimental spectrum is 2.5. Based on this value, the simulation of the shape of the emission band corresponding to blue, green, and red LED is determined. The simulated emission bands corresponding to beta 2.5 of these LEDs are shown in Figure 4. Quantifily, it is easy to see the similarity between simulated spectra (Figure 4) to experimental spectra (Figure 2).

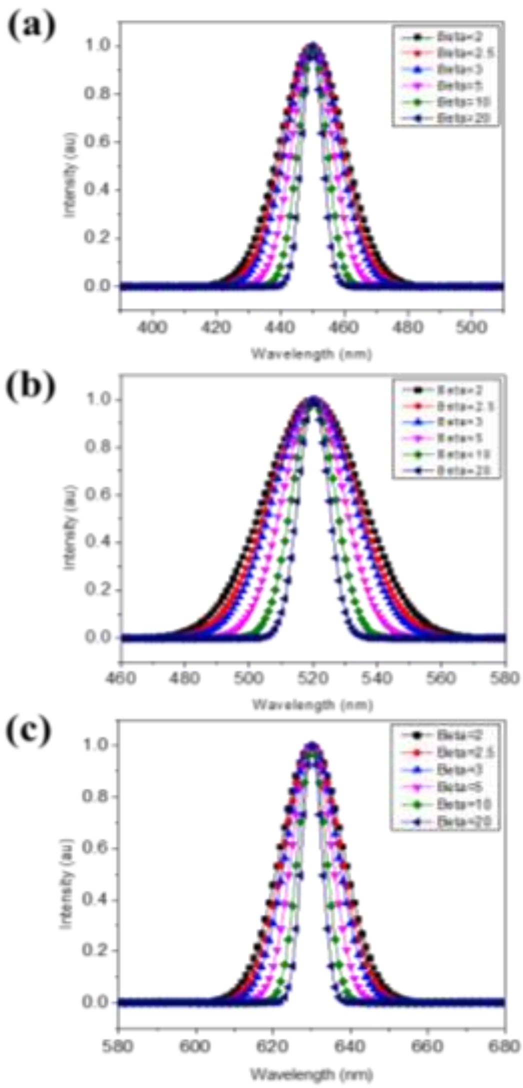

Figure 3. Effect of beta value on the shape of the emission band. (a) Blue LED, (b) Green LED, and (c) Red LED.

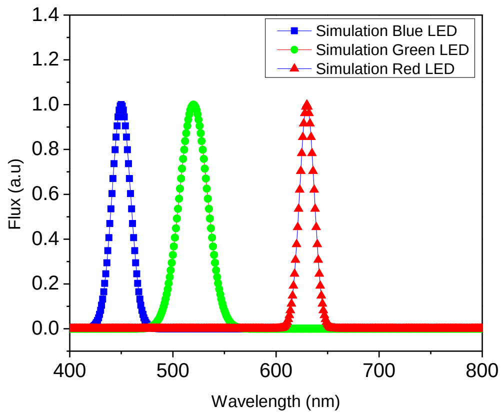

Figure 4: The simulated emission bands corresponds to beta 2.5 of blue, Green, and LEDs.

3. APPLICATION OF MODEL IN SPECTRUM DESIGN FOR LEDS-BASED WHITE LIGHT

After verification of the similarity between the simulation and experiment, the optical model is applied to simulate the spectrum of white light from 2500 K to 5500 K by modification of the power ratio of blue, green, and red LED. The parameter of B:G:R power ratio in simulation is listed in Table 1.

Table 1: Parameters of B:G:R power ratio in simulation

No.	B:G:R power ratio		
	Blue power	Green power	Red power
1	1	2	7.6
2	1	2	6.5
3	1	2	5.55
4	1	2	4.9
5	1	2	4.38
6	1	2	3.9
7	1	2	3.5

The simulation white light spectrum at different B/G/R power ratios is shown in Figure 5 (a).

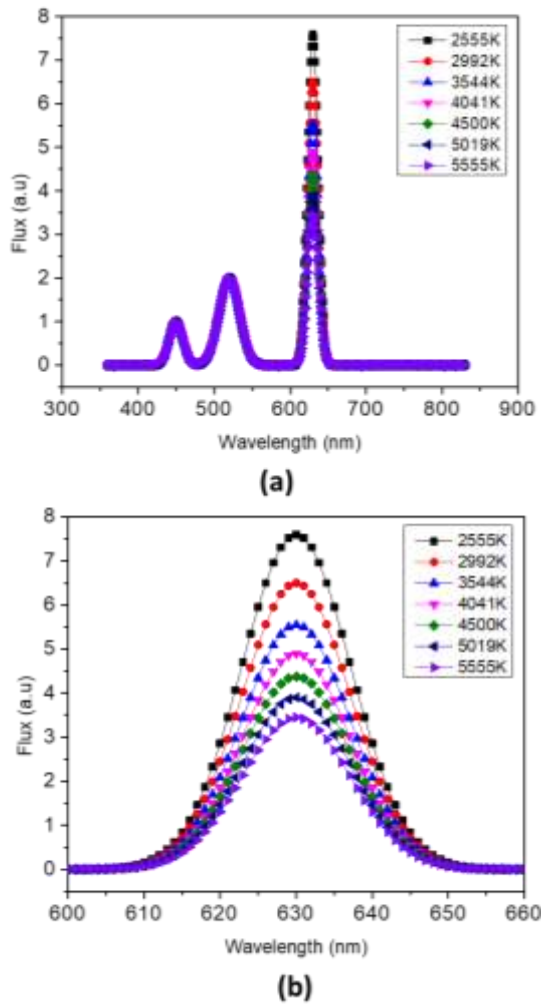

Figure 5. (a) The simulation white light spectrum at different B/G/R power ratio. (b) Enlarged of Figure 5 (a) with in the spectral wavelength range 600 nm to 660 nm.

The CCT of simulated spectrum No.1 to 5 are 2555K, 2992 K, 3544K, 4041K, 4500K, 5019K, and 5555K. These spectra have the same power ratio of blue and green light, but the red power is different. Figure 5(b) is enlarged of Figure 5 (a) within the spectral wavelength range 600 nm to 660 nm to help a clearer seeing of the difference of Red spectral component of 7.6; 6.5; 5.55; 4.9; 4.38; 3.9; and 3.5.

The effect of red light contribution to the CCT value is shown in Figure 6. The larger the amount of red light, the lower the value of CCT is. This results indicates a simple way to control the CCT by adding more red light while still maintaining the amount of blue and green light. For the same power ratio of blue and green light, different red light amounts are added including 7.6; 6.5; 5.55; 4.9; 4.38; 3.9; and 3.5. Then, the corresponding CCT values are 2555K, 2992 K, 3544K, 4041K, 4500K, 5019K, and 5555K. The effect of red light amount on the moving of color points is shown in Figure 7.

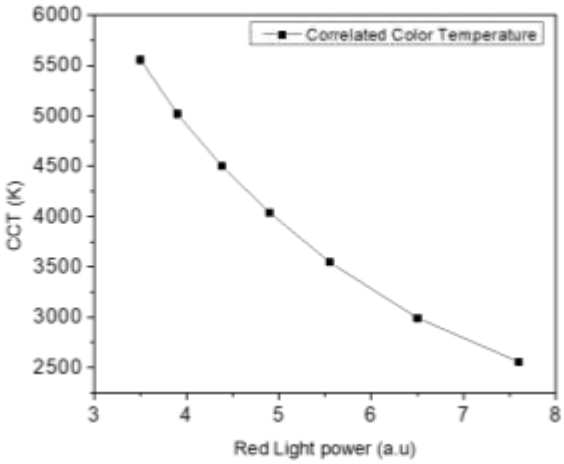

Figure 6. The CCT value of out put white light is a function of red light content.

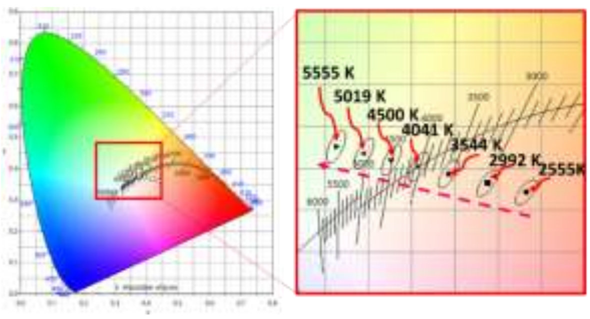

Figure 7. Effect of red light contriution on the moving of color point in color space

In lighting applications, it is always expected to have an output lumen as high as possible. The effect of red light on the output lumen is shown in Figure 8. The result showed that the output lumen is linearly proportional to the amount of red light. This is related to the luminous efficacy of radiation for red light (630 nm) is around 183 lm/W. Thus, as increasing the amount of red light, the output lumen of the overall spectrum is increased. The percentage of increased output lumen for obtained radiation when increasing the red light amount from a value of 3.5. to 3.9; 4.38; 4.9; 5.55; 6.5; and 7.6, respectively, are 3.5%, 7.2%, 11.2%, 16.2%, 23.5%, and 32%, respectively. Figure 9 shows the changes of luminous efficiency for different cases of B:G:R power ratio. In terms of output lumen versus the input power, it can be seen that a higher red light amount is used, and then lower energy efficiency is obtained. For the same power ratio of blue and green light, when the red light amount is added increasing from value of 3.5. to 3.9; 4.38; 4.9; 5.55; 6.5; and 7.6, respectively, then the decreasing of louminous efficiency are 1.8%; 3.5%, 5.3%, 7.0%, 9.1% and 11.6%, respectively.

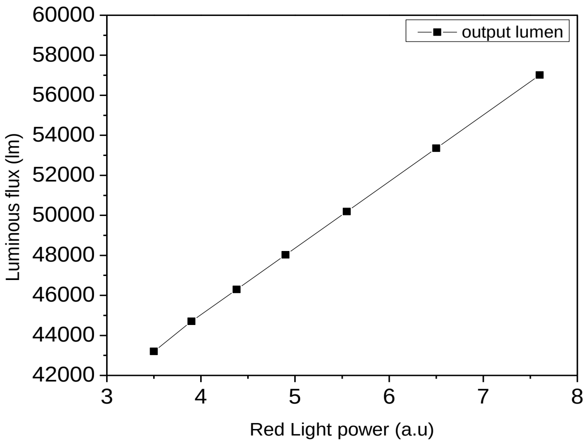

Figure 8: The effect of red light on the output lumen

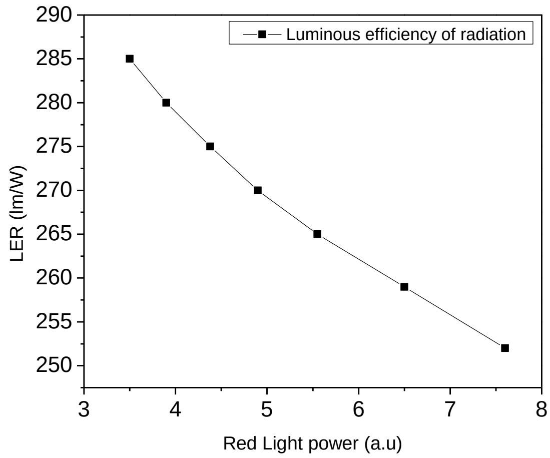

Figure 9. Changing of luminous efficiency for different cases of B:G:R power ratio

In genneral, results in Figure 8 and 9 indicates that, higher efficiency in output lemen will leads to a lower energy efficiency.

4. CONCLUSIONS

In summary, an efficient optical model for simulating the white light spectrum is developed and verified between experiment and simulation. The model is then applied to design the spectrum of LED-based white light. The power ratio B: G: R is determined for making the white light. The model is applied to study the effect of red on the optical properties of the generated white light spectrum. The corresponded power ratio B:G:R for each case are listed and studied. Results showed that the

CCT is easy to control by changing the red light power while keeping the blue and green light unchanged. The obtained formula for making white light is helpful for the solid-state lighting application to fabricate a light source that can emit white light with high optical performance.

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Thi-Minh-Ly Vo
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
22c39004@student.hcmus.edu.vn
ORCID: 0009-0000-8471-4366

Thi-Hanh Nguyen
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130018@student.hcmus.edu.vn
ORCID: 0009-0004-7796-0066

Le-Minh-Khang Tran
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130136@student.hcmus.edu.vn
ORCID: 0009-0008-3144-5324

Quang-Khoi Nguyen
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
nqkhoi@hcmus.edu.vn
ORCID: 0000-0002-6456-365X

Trong-Nam Tran
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
21c38007@student.hcmus.edu.vn
ORCID: 0009-0009-0606-2097

Thi-Yen-Nhi Pham
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130035@student.hcmus.edu.vn
ORCID: 0009-0005-5339-4300

Dang-Khoa Pham
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130142@student.hcmus.edu.vn

Trung-Kien Nguyen
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130144@student.hcmus.edu.vn
ORCID: 0009-0006-3186-9253

Thien-Bao Huynh
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130085@student.hcmus.edu.vn
ORCID: 0009-0005-7802-7195

Quoc-Cuong Nguyen
Faculty of Physics and Engineering Physics, VNUHCM-University of Science;
Vietnam National University Hochiminh City;
Vietnam.
23130009@student.hcmus.edu.vn
ORCID: 0009-0008-3894-8194