International Journal of Engineering and Technology Innovation, vol. 7, no. 3, 2017, pp. 157 - 168

Wireless Low-Power Light-Emitting Device with RGB LED

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Received 22 November 2016; received in revised form 28 March 2017; accepted 13 April 2017

Abstract

Color therapy is a type of alternative medicine. It utilizes the emission of a specific wavelength of light to treat diseased areas. This study presents a wireless, low-power light-emitting device with RGB LED to conduct color therapy. The device is small-sized, adhesive to the skin, and without a tether line for power or communication. Aided by the property of skin adhesiveness, the device provides a therapeutic effect comparable to that of available devices, over a short radiation distance and consumes low power. The therapeutic dosage parameters including color wavelength combination, LED brightness, and illumination time can be regulated through the smartphone application. The wavelength consistency over intensities and the intensity accuracy were validated. With effective calibration, the emission of light by the LED can be effectively regulated to ensure therapeutic effects.

Keywords: color therapy, RGB LED, color combination, light-emitting device

1. Introduction

Color therapy is a type of alternative medicine that utilizes visible spectrum of light to affect health conditions positively. Color therapy utilizes a specific wavelength of light to produce healing effect at a diseased area. Color therapy with red, green, and blue (RGB) light-emitting diode (LED) can be applied in various fields such as treatment, biomedical engineering, and medical cosmetology. Currently, the LED has been introduced as an alternative to low-level laser therapy (LLLT). Therefore, the field of color therapy with LED is being highlighted [1-4].

A number of devices have been developed for color therapy using RGB LED. A pocket-sized RGB LED system has been introduced [5]. Moreover, a device was developed with high power LEDs, which included white light and RGB lights. These high-power LEDs deliver intensity of 10-100 lm, which, at the time of their development, was stronger than that of commercially available LEDs. These LEDs have higher energy efficiencies than that of incandescent and halogen bulbs [6]. Furthermore, a device for irradiating skin by direct treatment with RGB LED is available [7]. In particular, a self-adhesive low-level light therapy device that is small-sized, portable, and suitable for personal use, has been introduced [8-9]. Treatment using this device for 20 min per day over 3 mo has resulted in significant reduction in the severity of menstrual pain, which was measured using a visual analog scale.

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RGB LED can emit a variety of colors through combinations of the three elementary colors. When creating a color light with RGB LED, the ratio and spatial allocation of the elementary colors is crucial. This is because these parameters can affect the energy and therapeutic effect. Therefore, for color therapeutic devices with RGB LED intended to provide therapeutic effect, it is necessary to regulate the intensities of each elementary color precisely [10-12].

Although the color therapy devices mentioned above provide considerable therapeutic effects, several of their aspects are to be improved, particularly regarding personal usability [1-7]. A majority of these devices are large and consume significant amount of power. They have wired communication or do not provide communication. Hence, a majority of them are not portable and unsuitable for personal usage. A small-sized and portable color therapy device could facilitate more frequent personal usage. In particular, considering the proliferation of smartphone usage, wireless communication with a smartphone could provide a user with the advantages of convenient operation and access to his/her therapeutic history. This type of device is expected to eventually provide convenient operation and result in more frequent usage and monitoring of therapeutic history.

This study presents a wireless low-power light-emitting device with RGB LED, which is small-sized, adhesive to the skin, and without a tether line for power or communication. It also provides wireless communication with a smartphone. Aided by the property of skin adhesiveness, the device provides therapeutic effect comparable to that of available devices, over the short radiation distance and consumes lower power. Its design is described considering the color mixture, intensity control, and wireless communication. In particular, the intensity of light emission, which is critical for clinical application, is calibrated for each LED element. By the calibration of each of the LEDs, the intensity and RGB ratio can be regulated with high accuracy.

2. Materials and Methods

2.1. System implementation

The proposed system in this study is configured as illustrated in Fig. 1. The device consists of an RGB three-color LED, micro-controller unit (MCU) module, rechargeable battery, and field effect transistor (FET) switching circuit. The MCU module is a type of radio-on-chip (RoC) device and provides Bluetooth Low Energy (BLE) communication and 32-bit MCU functionality. The RGB LED generates arbitrary colors of various wavelengths. The device communicates with a smartphone application through BLE communication. Color wavelength combination, LED intensity, and illumination time can be regulated by using the smartphone application. Moreover, the percentage of remaining battery capacity is displayed on the smartphone application. The intensity of each LED is regulated by pulse width modulation (PWM).

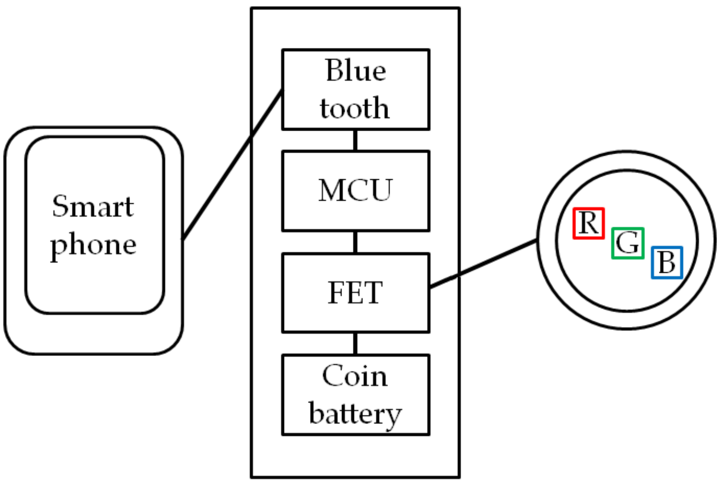


Fig. 1 Proposed system configuration

The proposed system was developed using a development kit (Pioneer Kit, CY8CKIT-042-BLE, Cypress, CA), as illustrated in Fig. 2, and RoC evaluation board with BLE (CYBLE-022001-EVAL, Cypress, CA), as illustrated in Fig. 3. This development tool was selected as the RoC chip on the RoC evaluation board is small and provides adequate functions for this system. To ensure convenient development using the RoC evaluation board, the development kit was utilized as a starter kit. The RoC evaluation board is mounted on the right-upper side of the development kit (Fig. 3). The development kit is connected to a PC on which an integrated development environment (IDE) operates. The IDE offers a number of examples to implement various applications with the development kit and the evaluation board mounted on it.

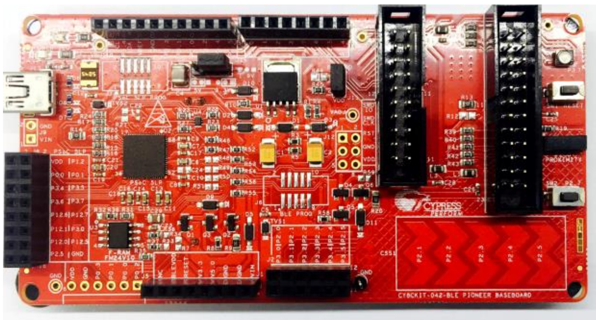


Fig. 2 RoC development kit (Pioneer Kit, CY8CKIT-042-BLE, Cypress, CA)

As the RoC chip is small and inconvenient to be manipulated, the RoC evaluation board was utilized during the early phase of the development (Fig. 3). There are a number of pins on the evaluation board; however, a few of the ports are not connectable to a developer. Debug pins are located in the middle of the evaluation board for connecting to the development kit. With this developmental environment, the basic functions of the proposed system including BLE communication, LED color mixture, intensity control, duration control, and LED driving, were implemented and tested.

Fig. 3 RoC evaluation board with BLE module (CYBLE-022001-EVAL, Cypress, CA)

A prototype was implemented on a circular printed circuit board with diameter 31 mm (Fig. 4). The systems consist of a RoC chip (lower side of Fig. 4) and debug pins with five holes (upper side of Fig. 4). The RoC chip (CYBLE 022001-00, Cypress, CA) was used as it is commonly available and provides simple BLE implementation. The prototype system also includes an FET switching circuit (FDMA1024NZ, Fairchild Semiconductor, CA), a RGB LED, and a voltage regulator (TPS79333, Texas Instrument, TX) to supply stable voltage from the battery. After being attached to the LED side on a body site such as an arm or wrist, the device could undergo relative movement while the user attended to routine activities. Therefore, the entire device was designed as flat as possible. The height of the circuit is 3.95 mm including the populated components. The other side contains a coin battery, which enables portability of the device. The terminals to charge the coin battery are located on the right side, as illustrated in Fig. 4. A rechargeable Lithium ion battery, PD2032 (20 mm × 3.2 mm), with 85 mAh capacity was used. Assuming that each of the RDB LED consumes 10 mA and the MCU's power consumption is negligible in low-power mode, the proposed system could operate for 2 h and 50 min, i.e., 7 therapy times, from fully-charged condition.

Fig. 4 Implemented prototype

Any BLE performance has a specific profile, similar to a data packet, for communication. There are a number of existing profiles for various applications. A profile is defined by adding a data set on the basic BLE protocol. Applications have appropriate profiles according to the activities with a paired device. In the case of hands-free headset device, for example, headset profile is selected as a basic profile.

However, as no standard profile suitable for this study was identified, a customized profile was defined for this application, as illustrated in Fig. 5. The generic access profile and generic attribute profile are basic profiles in all services. The LED control profile is the customized profile implemented in this study. The profile has control data and state data. The client characteristic configuration descriptor (CCCD) is a descriptor for notifying data variation to an application, i.e., BLE central device. As it is necessary for a few characteristics to notify their data update to users in this study, their CCCDs were constructed appropriately.

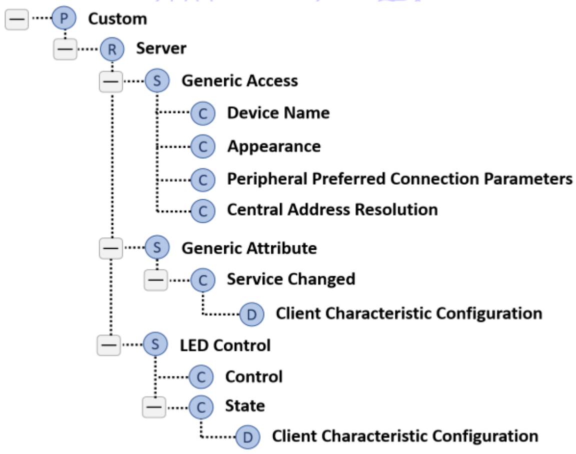


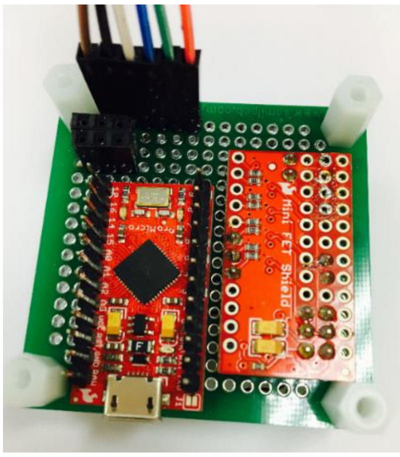
Fig. 5 Customized profile

2.2. *Intensity control algorithm*

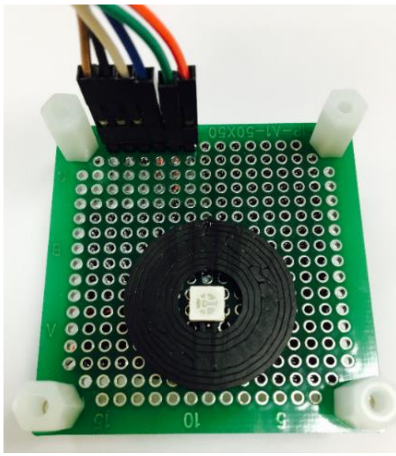
To provide effective therapeutic effects, color mixture and light intensity are critical factors to be regulated. The color mixture, i.e., the color wavelength combination of each color and total light intensity can be regulated by the user with the smartphone application. The intensity control is particularly crucial. To provide color with highly precise light intensity level, proper intensity control and its calibration are to be considered.

There have been several methods for LED intensity control (usually called dimming), such as analog dimming and PWM dimming. Analog dimming method regulates current flow to LED using a feedback circuit, and the current flow in turn regulates the LED intensity. As has been demonstrated, while the analog dimming method regulates current precisely, the peak point of wavelength is varied, which is undesirable for this application. Meanwhile, the PWM dimming method is known to have a drawback that the current regulation is unstable at low levels. However, as control of current level lower than 10% is not required in the proposed system, PWM dimming method is the preferred method considering its simplicity of implementation.

For the intensity calibration, a wired version system comprising an Arduino MCU board (Pro Micro 3.3V/8MHz, Sparkfun, CO), an FET breakout board (Mini FET shield, Sparkfun, CO), and an RGB LED (Fig. 6), was prototyped. This MCU board provides high performance with low-power, AVR 8-bit MCU (Atmega328, Atmel, CA). The MCU was used to set the intensities of RGB LEDs through PWM signals. The PWM signals from the MCU was capable of generating pseudo-analog signals; however, they could not supply sufficient current to LEDs as the output current from the MCU is up to several mA, which is not adequate to activate an LED. Considering this, a FET switching circuit was constructed to supply the required current.



(a) Main controller



(b) LED board

Fig. 6 The Arduino-based prototype for intensity calibration

As the FET switching circuit does not have feedback for sensing the LED current, a calibration algorithm to provide the desired intensity was used, as illustrated in Fig. 7. At first, the output intensity is measured at 10 % incremental PWM commands for each LED probe and each of the three colors. Next, their distribution is estimated by a linear regression expression. Finally, the reverse expression is utilized to obtain PWM values for the desired light intensity command to accompany the 10 % incremental PWM command. These calculated PWM values are stored in a table as calibration data. The desired light intensity is acquired by using the stored calibration data.

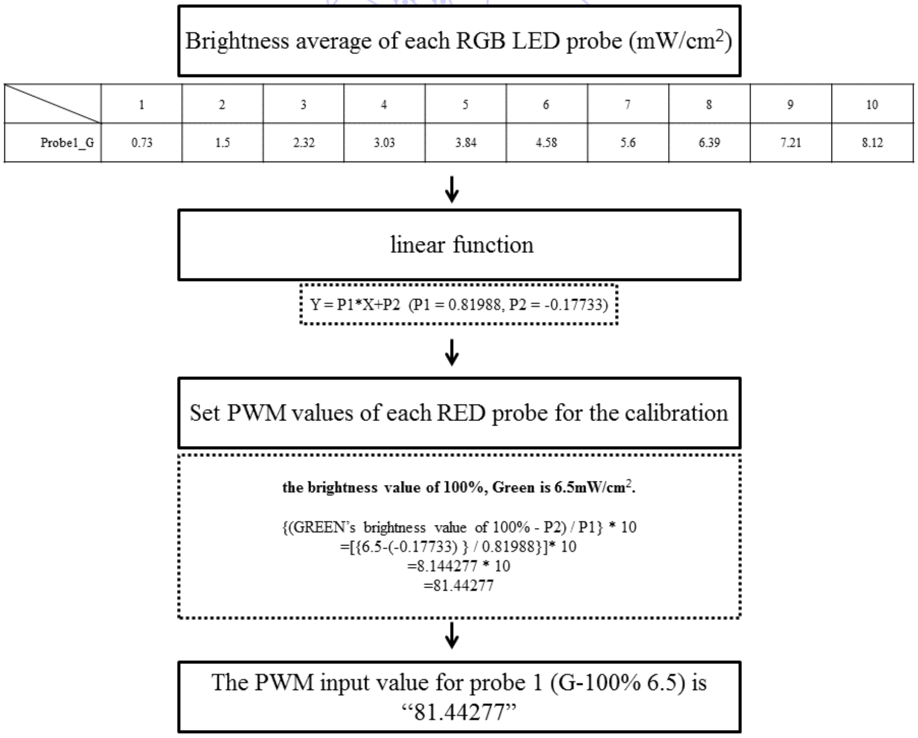
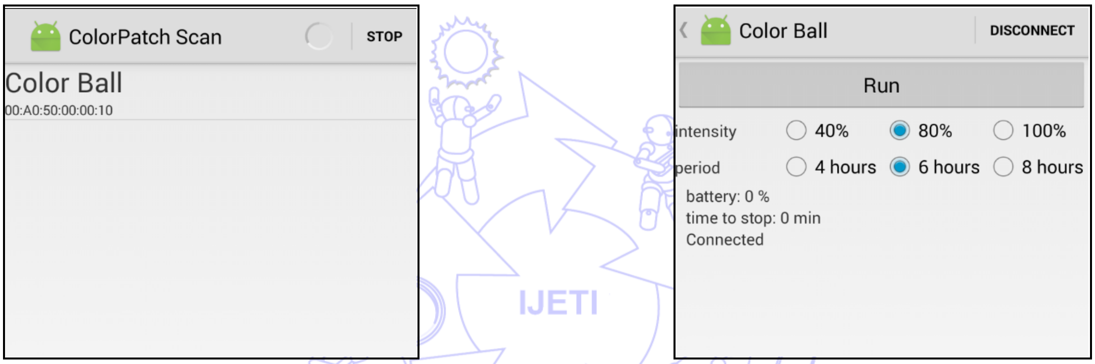


Fig. 7 Intensity calibration

2.3. Android application

An Android application was implemented to regulate the LEDs (color mixture, light intensity, and illumination duration) and monitor the device's state (device name, remaining battery capacity, and remaining illumination time). The application was implemented based on an Android BLE example application provided by Google. The application has been developed with Android Studio, and the targeted version was selected as API 23. Although the API version with the least capabilities suitable for BLE applications is 18, the API version 23 was selected considering the proliferation of API versions.

At first, the application scans devices in the vicinity of the user, using a scanning screen. The detected devices are displayed with their names and media control addresses, as illustrated in Fig. 8 (a). After the user selects a detected device, the application connects to the selected device and transforms into a device control screen, as illustrated in Fig. 8 (b). The device control screen has a button, radio buttons, and text views. If the connection is established successfully between the application and device, an option menu, situated on the right-upper side of the device control screen, shifts from "connect" state to "disconnect" state. The device also can be disconnected if required, by touching a button on the option menu. The radio buttons provide controls for light intensity and illumination time over the connected device. The text views display device information such as remaining battery capacity, remaining illumination time, and connection state.



(a) Device scanning screen (b) Device control screen

Fig. 8 Android application

2.4. Intensity verification method

To verify the light intensity calibration, two optical measurement systems were used. To measure light intensity, a digital optical power and energy meter (PM100D, Thorlabs Inc., NJ) was used, as illustrated in Fig. 9 (a). This equipment can capture wavelength between 400 nm and 1100 nm. The measuring range for power is from 500 nW to 500 mW with a ± 3 % measurement uncertainty and a 10 nW resolution. To measure the relative intensity over the visible light range, a CCD spectrometer (CCS200, Thorlabs, NJ) was used, as illustrated in Fig. 9 (b).

(a) Optical power and energy meter (b) Spectrometer

Fig. 9 Experimental measurement equipment

To measure light intensity accurately and precisely with the optical power and energy meter, a measuring jig was constructed (Fig. 10). The measuring jig aids to locate the LED probe at a specific position for each measurement and shields the jig from ambient light. The jig enables convenient measurement of the light intensity at an identical position on each probe. The jig was designed using a 3D CAD/CAM system (CATIA, Dassault System, France) and fabricated by using a 3D printer. It can be attached to the measurement instrument and measure at an identical position each time.

Fig. 10 Measurement jig

3. Results

The wavelength of each color was measured with the spectrometer and its peak wavelength was checked. The peak wavelengths were 630 nm, 520 nm, and 450 nm for red, green, and blue colors, respectively.

Five RGB LED probes under the control of the PWM command were tested for effective measurement of intensity value. The PWM commands were subdivided into 10 steps of 10 % each. For each PWM value, its corresponding intensity was measured ten times and averaged (Table 1). Each measurement was conducted under similar conditions. Overall, 750 measurements of intensity were conducted. It revealed that the LED probes of similar color yielded significantly different values of average intensity; this demonstrated that the light intensity was not calibrated.

Table 1 Average intensity for each RGB LED probe before calibration (mW/cm^2)

LED set	PWM (%)									
	10	20	30	40	50	60	70	80	90	100
Probe1_R	0.53	1.05	1.52	2.03	2.52	3.01	3.45	4.03	4.50	5.01
Probe2_R	0.60	1.09	1.57	2.36	2.84	3.25	4.01	4.76	5.39	5.85
Probe3_R	0.73	1.36	2.02	2.69	3.23	4.13	4.92	5.51	6.35	7.08
Probe4_R	0.61	1.26	1.82	2.59	3.10	3.72	4.46	5.04	5.87	6.58
Probe5_R	0.62	1.14	1.81	2.25	2.85	3.39	4.14	4.90	5.60	6.33
Probe1_G	0.73	1.50	2.32	3.03	3.84	4.58	5.60	6.39	7.21	8.12
Probe2_G	0.81	1.69	2.61	3.43	4.24	5.07	6.05	7.31	8.20	9.24
Probe3_G	0.66	1.33	2.02	2.65	3.32	4.18	4.90	5.76	6.43	7.23
Probe4_G	0.80	1.67	2.59	3.53	4.24	4.95	6.11	7.23	8.22	9.10
Probe5_G	0.73	1.43	2.33	3.07	3.68	4.59	5.24	6.32	7.49	8.33
Probe1_B	2.20	4.45	6.95	9.15	11.44	13.77	16.26	18.97	21.28	23.48
Probe2_B	2.20	4.59	6.90	9.30	11.39	13.89	16.67	19.31	21.54	23.86
Probe3_B	2.27	4.56	6.65	9.17	11.27	14.12	16.15	19.1	21.35	24.10
Probe4_B	2.22	4.59	6.93	9.19	11.45	14.06	16.48	18.97	21.33	24.00
Probe5_B	2.21	4.58	6.90	9.31	11.51	14.17	16.22	19.22	21.46	23.59

Before the calibration, it is necessary to specify the maximum target intensities for each color. At first, the intensities of the five LEDs of similar color were grouped together. In this group, the minimum of the intensities of the five LEDs at 100 % PWM command was specified as the maximum target intensity that all the LEDs in that group are to provide. Additionally, a marginal value of margin was subtracted from this minimum intensity value. Finally, the maximum target intensities were decided as 4.8 mW/cm^2, 6.5 mW/cm^2, and 22 mW/cm^2 for red, green, and blue groups, respectively. Considering the maximum target intensity, i.e., target intensity at a 100 % PWM command, the target intensity at 10 % incremental PWM command was linearly interpolated.

For the target intensities, the calibrated PWM values for each LED probe were calculated as explained in the earlier section (Table 2). These calibrated PWM values correspond to the PWM commands which provide targeted light intensity for each LED. A highly significant number of the calibrated PWM values are smaller than their uncalibrated PWM commands as the maximum target intensity was specified as the minimum of the measured intensities. However, a few calibrated PWM values are larger than their uncalibrated PWM command. This is because that the LEDs have a certain level of nonlinearity for these PWM commands.

Table 2 Calibrated PWM values of each LED (%)

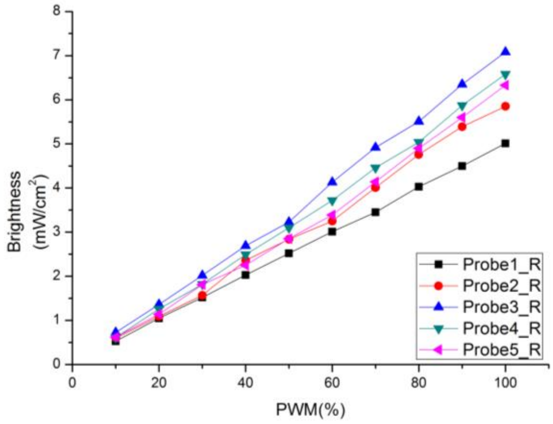
	10	20	30	40	50	60	70	80	90	100
Probe1_R	8.89	18.58	28.26	37.95	47.63	57.32	67.01	76.69	86.38	96.06
Probe2_R	9.98	18.01	26.03	34.06	42.09	50.12	58.14	66.17	74.20	82.23
Probe3_R	8.20	14.96	21.72	28.49	35.25	42.01	48.77	55.54	62.30	69.06
Probe4_R	8.93	16.24	23.55	30.86	38.17	45.48	52.79	60.10	67.41	74.72
Probe5_R	10.33	17.92	25.52	33.12	40.71	48.31	55.90	63.50	71.09	78.69
Probe1_G	10.09	18.02	25.95	33.87	41.80	49.73	57.66	65.59	73.51	81.44
Probe2_G	9.73	16.71	23.69	30.67	37.65	44.64	51.62	58.60	65.58	72.56
Probe3_G	11.44	20.29	29.15	38.00	46.85	55.71	64.56	73.42	82.27	91.12
Probe4_G	9.53	16.58	23.63	30.67	37.72	44.77	51.81	58.86	65.91	72.95
Probe5_G	11.17	18.93	26.69	34.45	42.21	49.97	57.73	65.49	73.26	81.02
Probe1_B	10.53	19.76	29.00	38.23	47.46	56.70	65.93	75.17	84.40	93.64
Probe2_B	10.62	19.69	28.76	37.83	46.90	55.97	65.04	74.11	83.18	92.24
Probe3_B	10.97	20.05	29.12	38.20	47.27	56.34	65.42	74.49	83.57	92.64
Probe4_B	10.54	19.66	28.78	37.91	47.03	56.15	65.28	74.40	83.52	92.65
Probe5_B	10.30	19.47	28.65	37.83	47.00	56.18	65.36	74.53	83.71	92.89

The intensities were measured and compared before and after the calibration as illustrated in Table 3. Before the calibration, the intensity values had a wide distribution. The standard deviation (STD) gradually increases as we shift from 10 % to 100 %, and 100% intensity displays the largest STD. At 100% intensity command, red and green LEDs displayed STD of approximately 0.7 with a wide distribution. However, blue LED displayed an STD of 0.2, which is a distribution narrower than that that of the other colors. However, after the calibration, the measured average intensity values matched their corresponding target intensities. As can be observed in Table 3, the STDs were negligible including at 100 % command intensity, whereas the uncalibrated intensities had revealed large STDs.

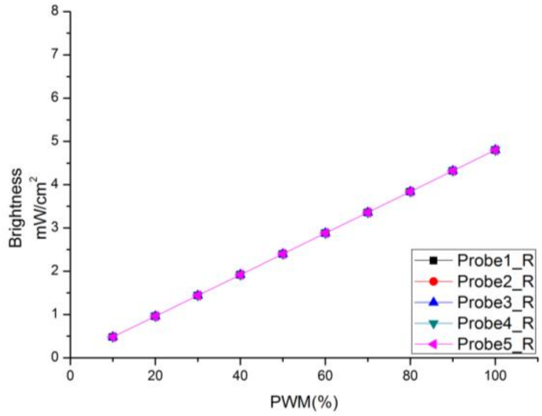
Table 3 Intensity at 100 % PWM before and after calibration (mW/cm^2)

	Before calibration							After calibration						
LED	P1	P2	P3	P4	P5	Mean	STD	P1	P2	P3	P4	P5	Mean	STD
Red	5.01	5.85	7.08	6.58	6.33	6.17	0.703	4.80	4.80	4.80	4.80	4.80	4.80	0.000
Green	8.12	9.24	7.23	9.10	8.33	8.40	0.728	6.500	6.50	6.50	6.50	6.50	6.50	0.000
Blue	23.48	23.86	24.10	24.00	23.59	23.81	0.237	22.00	22.00	22.00	22.00	22.00	22.00	0.000

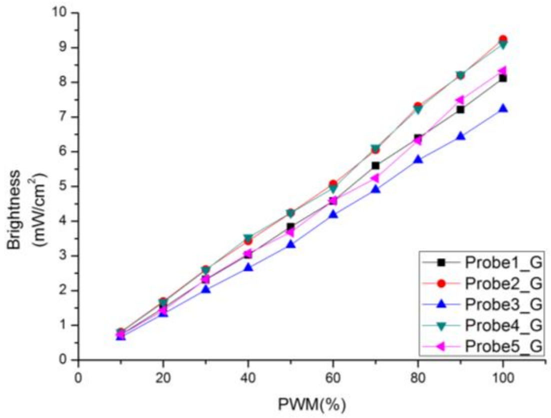
Fig. 11 illustrates the measured intensity values before and after the calibration. Before the calibration, the intensity values reveal a wider distribution; none of the LED probe displayed reasonable linearity. The correlation coefficients were 0.97, 0.98, and 0.99 for red, green, and blue colors, respectively. However, after calibration, each LED probe displayed a very narrow distribution as mentioned before. Moreover, they display excellent linearity. Their correlation coefficients were smaller than 0.00 for all the colors.



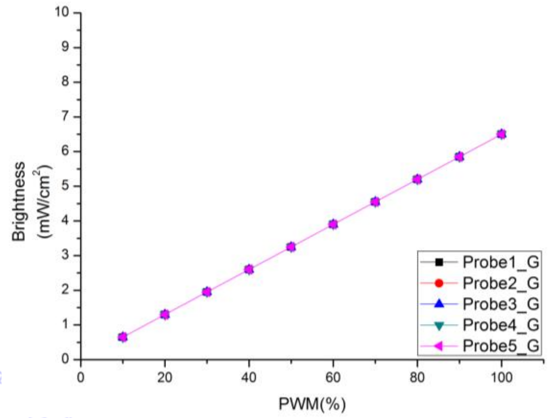
(a) Red color before calibration



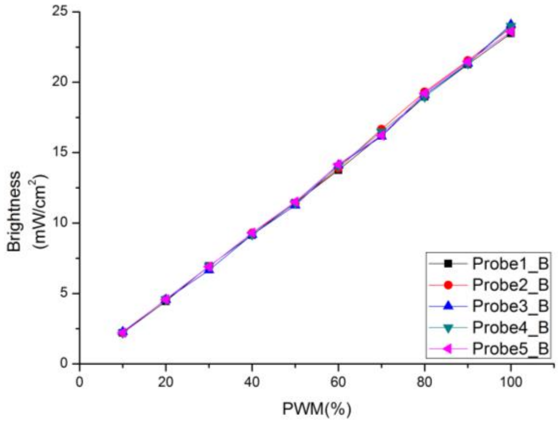
(b) Red color after calibration



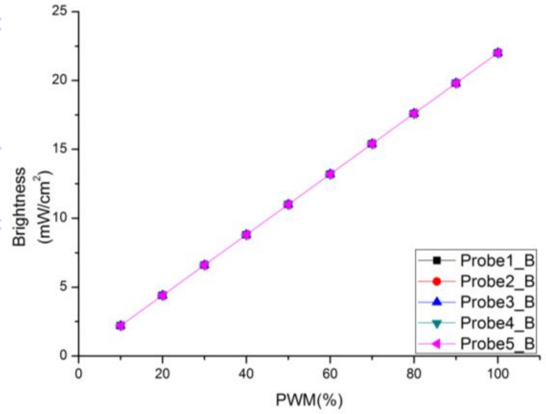
(c) Green color before calibration



(d) Green color after calibration



(e) Blue color before calibration



(f) Blue color after calibration

Fig. 11 Measured intensity values before and after calibration

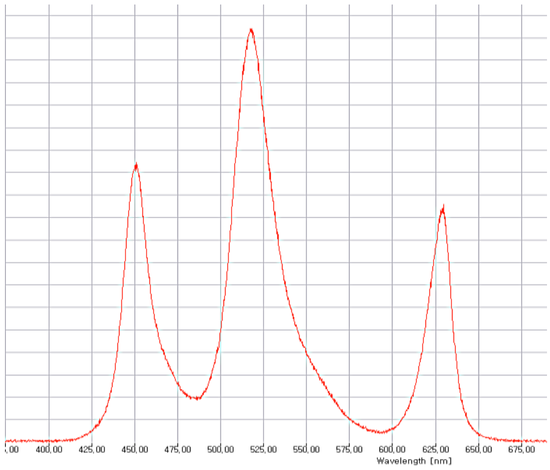
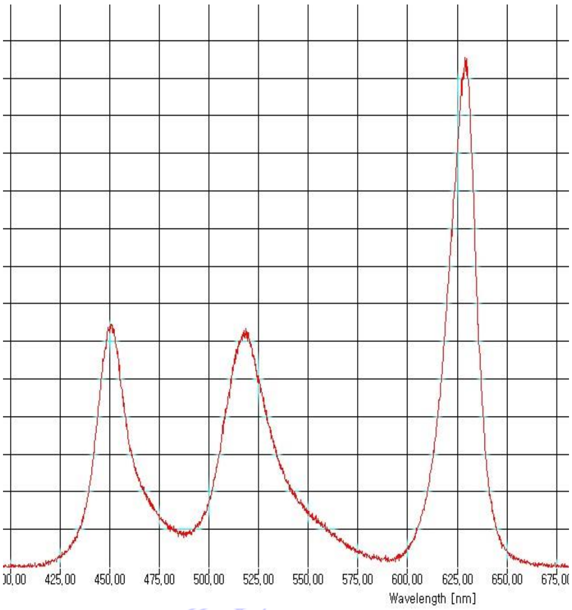


Fig. 12 Before color mixture calibration

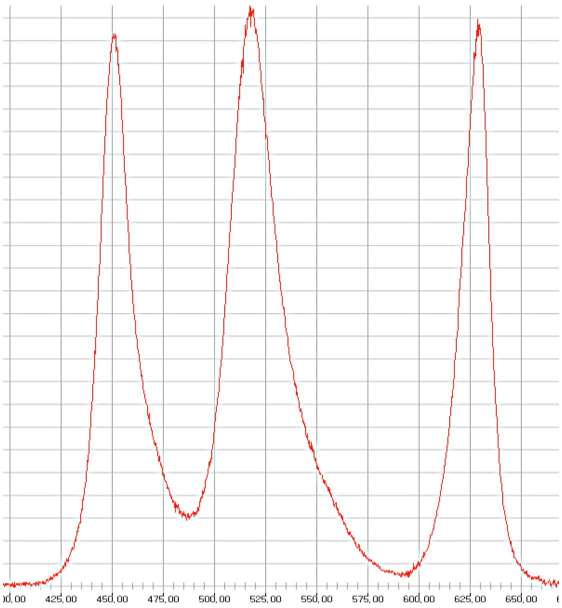
Although the intensity is calibrated for each LED, notable differences in the intensity output between the LEDs remained. This difference is particularly significant between the colors. This could be due to an issue in the context of color mixing. In Fig. 12, three LEDs were commanded with 100 % PWM command. However, the intensity values are different between the colors.

Therefore, each color's intensity was calibrated for color mixture. For this adjustment, a similar method as the intensity calibration explained above, was utilized. The minimum of the maximum target intensity values for the three colors was selected as the target color mixture intensity. Considering this target color mixture intensity, the calibration of each color's target intensity was repeated.

After this process of color mixture calibration, each color's intensity displayed an appropriate intensity ratio according to the desired command, as illustrated in Fig. 13. For this measurement, the spectrometer described in the previous section was used. It is noteworthy that this spectrometer measures only the relative intensity in the spectrum of visible light wavelength. Therefore, the absolute light intensity was not considered in this experiment.



(a) Red: green: blue = 2: 1: 1



(b) Red: green: blue = 1: 1: 1

Fig. 13 After color mixture calibration

4. Discussion

The prototyped wireless portable color therapy device performed satisfactorily. The light intensity, illumination time, and color mixture could be regulated by a smartphone application via BLE communication. The device's information such as remaining battery capacity and remaining illumination time was monitored on the application.

The light intensity of each LED was successively calibrated with the proposed method. Before the calibration, each LED displayed different intensity values and nonlinearity. In particular, the deviation in the light intensities increased as the command intensity increased. The intensity values are different according to color. These characteristics of LEDs could provide useful information that can aid the development of this type of devices. After the intensity calibration, each LED could provide the desired intensity according to command provided in 10 % increments. Moreover, additional calibration in the context of the color mixture was required as each LED, particularly of similar color, displayed different intensity for similar command intensity.

Although the color mixture calibration regulates the intensities of each LED light, it does not provide light of new wavelength. As has been demonstrated, specific wavelengths provide therapeutic effect on particular cell, tissue, or organ. However, effective regulation of intensity of light of each wavelength can enable precise control of therapeutic dosage.

5. Conclusions

This study presented a wireless, low-power light-emitting device with RGB LED for color therapy. The proposed system was prototyped using an RoC module with an MCU function and BLE. An Android application was also implemented. With the application, the operations of the prototyped device including color mixture, illumination intensity, and illumination time could be regulated, and the information from the device could be displayed on the application for users to read. For the precise control of light intensity, a calibration process was conducted, and the effect was verified for each RGB LED probe. For experimental convenience, the intensity calibration and its verification were executed on a wired system based on an Arduino MCU.

The proposed system is small-sized to be adhesive on skin without a tether line for power or communication. Aided by the property of skin adhesiveness, the device provides a therapeutic effect comparable to that of available devices, over a short radiation distance and consumes low power. Using wireless communication through a smartphone, the device enables convenient operation, frequent usage, and monitoring of therapeutic history. The proposed system is expected to be utilized as a portable wireless color therapy device, particularly for personal use.

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