IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 16, 2020, accepted June 18, 2020, date of publication June 22, 2020, date of current version July 2, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3004142

Improvement of LED Performance With an Integrated Thermoelectric Cooling Package

GUORONG SUI, (Member, IEEE), JIAJUN CHEN, HAO NI, YANYING MA, XIUMIN GAO, AND NING WANG
Shanghai Key Laboratory of Modern System, Engineering Research Center of Optical Instrument and System, Ministry of Education, University of Shanghai for Science and Technology, Shanghai 200093, China

Corresponding author: Ning Wang (nwang@usst.edu.cn)

This work was supported in part by the NSFC under Grant 61804096, in part by the National Key Research and Development Plan–Earth Observation and Navigation Key Special Project under Grant 2017YFB0503102, and in part by the National Key Research and Development Program of China under Grant 2018YFC1313803 and Grant 2018YFA0701800.

ABSTRACT The high junction temperature for a working light-emitting diode (LED) will lead to a decrease in luminous efficiency, redshift in wavelength, and shortened lifetime. Conventional cooling methods such as air cooling and water cooling cannot meet the heat dissipation requirements of highly integrated high-power LED cooling systems. A thermoelectric cooler (TEC) has the characteristics of small size, long life, light weight and high reliability, which can effectively reduce the operating temperature of an LED, obtain higher luminous efficiency and improve its service life. In this paper, LED cooling systems with integrated TEC packaging are studied by experiments. Through the comparison of RGBW LED, the influence of temperature on LED is observed, especially the optical characteristics such as spectrum, irradiance and CRI. By observing the board temperature and regulation of optical parameters, the optical characteristics of an LED with an integrated TEC thermal package are significantly improved. For RGB LEDs cooled by a TEC and large-sized heat sink, the wavelength of the red LED is restored by 5 nm. In the case of a white LED cooled by a TEC with a small-sized heat sink, the illuminance is increased by 3 times from 26,768.93 Lux to 82,962.79 Lux with TEC power increased from 0 W to 14.4 W. As an effective refrigeration device for LEDs, a TEC can supply an extra performance regulation method for realizing a controllable cooling environment. By integrating RGBW LEDs with a TEC, this study provides a solution for LED heat dissipation and studies TEC temperature control for the optical performance of LEDs to provide a basis for adjusting the optical performance of LEDs through a TEC.

INDEX TERMS Light emitting diode cooling system, thermoelectric cooler package, luminescence wavelength, luminous efficiency.

I. INTRODUCTION

Light-emitting diodes (LEDs) are compound semiconductor lighting devices, which have been regarded as one of the most valuable light sources in the 21st century due to their many incomparable advantages over other conventional counterparts [1]. Conventional incandescent and fluorescent lamps will be broadly replaced by LEDs for general lighting in the future due to their potential for substantial energy savings, extremely high efficiency, small size, and long lifetime [2]–[4]. As a result, LEDs have been applied in many applications, such as backlighting for cell phones and other LCD displays, interior and exterior automotive lighting, large signs and displays, signals and projection [5]. Until recently, the power of a modern LED chip is typically above 1 W, even up to 10 W, with a chip area of less than 1 mm^2, which will result in a heat dissipation problem in the LED chip [6]. Approximately 30 to 40% of the LED power consumption can be converted into light, while the remainder will be dissipated as heat focused on the LED p-n junction [7], [8]. Meanwhile, the performance of LEDs is very sensitive to their operating temperature. A high junction temperature will lead to a dominant luminescence wavelength drift, decline in the optical efficiency, as well as degradation of the lifetime of

The associate editor coordinating the review of this manuscript and approving it for publication was Jiajie Fan.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

the phosphor [9]–[11]. Thus, it is crucial to propose effective thermal management to decrease the junction temperature in LED applications.

Existing methods exist for enhancing heat spreading in the heat sink base. For example, vapor chambers with a phase-change heat transfer mechanism and insulating heat dissipating plastics are available to spread the heat. Vapor chamber heat sinks demonstrate advanced thermal performance, which may avoid heat accumulation and achieve a lower rate of increasing temperature. However, the system is filled with air when out of use, probably resulting in inner wall corrosion and short service life. Under transient fluctuation of heating, invalid heat loses occur greatly because of the leaking joint between pipe fitting and radiator. Organic composite heat-conducting plastics are more environmentally friendly. They consume less energy than metal materials and pollute less during production. However, because most heat dissipating plastics are made of PA materials, a slight difference in the formula will probably give rise to cracking problems due to their strong moisture absorption ability. Compared with these schemes, the proposed scheme has a relatively small size, light weight and long life. Through experiments, the optical characteristics of an LED are improved and the luminous flux is increased due to a decrease in the junction temperature with enhanced thermoelectric cooler (TEC) cooling power. Additionally, wavelength shift is effectively prevented.

To create white light from LEDs, two distinct approaches have been adopted: (i) use of multispectral LED systems (such as RGB LED light sources for projectors), and (ii) the combination of a wavelength downconverting phosphor with a blue or ultraviolet LED [12]. The multichip RGB approach allows for high color rendition, chromaticity-point stabilization, and color adjustment [13], [14]. However, it will lead to a strong temperature dependent performance with high cost. Due to the varying temperature dependence of the emissivity of the spectral channels (red, green, blue), the summarized optical spectrum from such a light source will be changed with temperature variation. To solve this problem, some cooling solutions are employed in high-power LED applications, such as use of a fan, heat sink and heat pipe. In addition, many researchers and high-power LED manufacturers have launched a series of new enhanced LED chip cooling methods. Luo and Liu proposed a microjet-based cooling system for the thermal management of high-power LEDs [15]. The substrate temperature remained stable at approximately 36.7 °C for a micropump flow rate of 9.7 mL/s, which demonstrated that the cooling system had good performance. Minseok and Samuel conducted a thermal analysis of high-power LED packages implementing a chip-on-board (COB) architecture combined with a power electronic substrate focusing on the heat spreading effect [16]. Acikalin *et al.* used piezoelectric fans to cool LEDs, which could effectively decrease the heat source temperature [17]. Under optimal conditions, an enhancement in the convective heat transfer coefficient exceeding 375% relative to natural convection was observed, resulting in a temperature drop at the heat source of more than 36.4/spl deg/C. Among the numerous effective methods for LED heat dissipation, thermoelectric cooling is a comparatively excellent way for mainstream applications, showing its merits of cleanness, noiseless, high reliability and high cost performance [18]. Thermoelectric cooling is a refrigeration method based on the ‘‘Peltier effect’’, which is the inverse of the Seebeck effect [19], [20]. P- and N-type thermoelectric legs are connected electrically in series and thermally in parallel, which can drive the thermal energy from one side to the other side. A refrigerating system was designed to cool high-power LEDs with a TEC by Li *et al.*, and the result indicated that the junction temperature could be controlled within 45 °C when the TEC worked at an optimum current [21]. Zhong *et al.* researched an LED integrated with a thermoelectric cooler package. The LED integrated with a TEC achieved an electric energy saving of 22.34% and 44.73% under the condition of 20 W and 30 W power dissipation of the LED chip contrasted to the fluorescent lamp, respectively, but sacrificed 2.71% power under 10 W [22], [23]. Li *et al.* set up an automatic system based on a TEC, a PWM fan, and microcontroller. The result demonstrated that the automatic cooling system had a high cooling efficiency where the maximum LED power cooled by the system was 106.7 W; the total power consumption of the automatic cooling system was only 8.85 W [24]. For further cooling and reduction of packaging, V. Semenyuk and R. Dekhtiaruk designed an improved TEC configuration with an LED based on an IMS-PCB and circuit integrated into the body of the TEC, which reduced the LED operating temperature, provided increased light output and greatly improved the LED lifetime [25]. In the studies above, most of the work involved high-power white LEDs and TECs, but the influence of TEC cooling on the thermal and optical properties of trichromatic LEDs was rarely studied.

In general, researchers have come to some important conclusions through various experiments and simulations. However, there are some shortcomings in these methods: passive cooling solutions cannot fundamentally solve the problem of LED heat dissipation; changing the production process for the LED packaging or the optimization of materials increases the cost substantially. In this paper, experiment RGBW LEDs based on a TEC active cooling system and a passive cooling system without TEC were experimentally studied. The package size of the LED cooling system was effectively reduced by use of a TEC. By observing the junction temperature and the change in the optical parameters, such as wavelength, CCT, CRI, light intensity, and illumination, the optical characteristics of the LED under the integrated TEC thermal package were significantly improved.

II. TEMPERATURE-DEPENDENT RGBW LED

When a LED chip is working, a part of the electrical energy is converted into heat energy. If the generated thermal energy cannot be transmitted to the outside in time, the heat will be accumulated at the PN junction in the LED, which will lead to a rise in temperature. The induced temperature increase will lead to an increase in the junction current, further accumulating an amount of heat, which will result in the LED to temporarily stop shining or even burn out. If the heat dissipation capacity is strong enough, the LED operating temperature will be maintained in a normal range. However, if the working temperature is too high due to weak heat dissipation, the LED characteristics will be degraded.

Red-green-blue three primary colors are emitted by trichromatic LED chips, where the current is regulated by an integrated circuit for each color. By adjusting the current in the LED chips, the luminous intensity of the three chips will change correspondingly. Synchronously, the trichromatic light mixing ratio will be changed. As a result, a variety of colors are converted and generated. RGBW technology is based on the addition of a W white subpixel on the original RGB primary colors, becoming a four-color pixel design, which greatly improves the transmittance of the liquid crystal panel. When displaying the same brightness picture, the power consumption is lower. Under the same power consumption, the brightness is greatly increased. In our work, the LED chip used was a L24-ZRGBW type produced by BIVAR. The package structure of the LED chip is given in Fig. 1, where the numbers 1 to 4 represent red, green, blue and natural white LED, respectively. The LEDs are connected to a supply through the anode and cathode interface, 1+ and 1-, for example. Detailed LED parameters are shown in Table 1. LEDs act as a semiconductor diode with a volt-ampere characteristic whereas the volt-ampere characteristic is temperature dependent. As the temperature increases, the forbidden band width of the material will be decreased, which in turn will result in a decrease in the maximum current. As the temperature increases, the concentration of electrons and holes increases, the band gap decreases, and the electron mobility decreases. Furthermore, the probability of recombination of electrons and holes in the potential well decreases, resulting in non-radiative recombination, thereby reducing the internal quantum efficiency of the LED. In general, the luminous flux will be decreased with increasing junction temperature, the process of which is reversible.

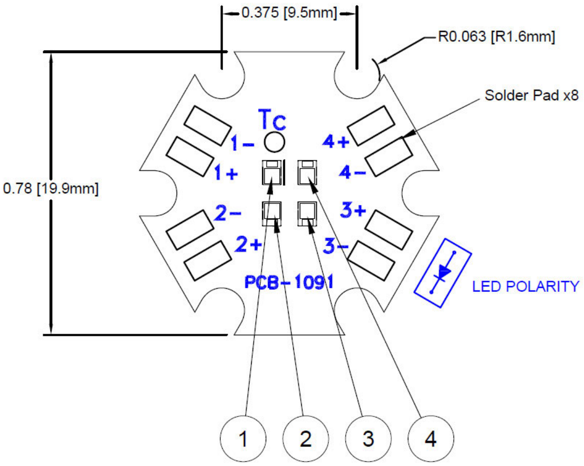


FIGURE 1. LED chip package structure.

TABLE 1. Assembly configurations.

Part Number	LED Location	Color	Wavelength (RGB) / Correlated color temperature (White)	Typical Luminous Flux (lm)	LED P/N
L24-ZRGBW	1	Red	627 nm	40	BDL-1514
	2	Green	530 nm	72	BDL-1515
	3	Blue	470 nm	24	BDL-1516
	4	Neutral White	4000 K	120	BDL-1511

The peak wavelength is the wavelength at which the light intensity is the largest, so it is generally taken as the observed point. Obviously, a change in the wavelength of the LED light caused by the junction temperature will directly affect the perception of the color of the LED by the human eye. For an LED device, the forbidden band width value of the luminescent material directly determines the wavelength or color of the device illumination. As the temperature rises, the forbidden band width of the material will be decreased, resulting in a longer emission wavelength for the device and a bathochromic-shift in color.

Similarly, the LED light distribution, correlated color temperature (CCT), and color rendering index (CRI) will be influenced by the temperature as well. The refractive index of the light-transmitting material is affected by the junction temperature, which changes the spatial distribution of the light emitted by the LED, i.e., the light distribution. When the temperature is high enough, the blue light peak shifts to a longer wavelength position, and the peak of the phosphor becomes flat and deteriorates, which results in a high CCT and deterioration of the CRI.

In general, temperature has a great negative impact on the performance of the LED. Therefore, it is necessary to control the junction temperature of the LED in a reasonable and effective way.

III. LED PACKAGE STRUCTURE WITH AN INTEGRATED TEC

A typical TEC consists of many p-n-doped thermoelectric elements sandwiched between two electrically insulated but heat-conducting ceramic plates [26] and [27], as shown in Fig. 2. When a TEC is applied to an LED, as shown in Fig. 3, its performance needs to be evaluated, and the cooling specification needs to be selected in advance. First, the TEC model needs to meet the cooling requirements for LED heat dissipation. Second, a suitable size and package

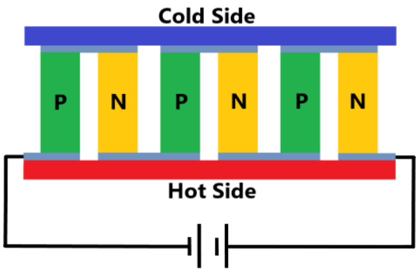


FIGURE 2. The structure of TEC.

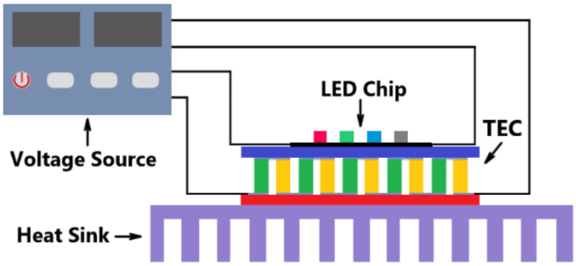


FIGURE 3. The package schematic for an LED and TEC.

are chosen to assemble conveniently. Considering the power and size of the LED, a TEC1-12706 type cooling device was selected in our work. This TEC has 127 pairs of thermocouples, which are arranged in a square array of thermal parallel and electrical series. The detailed parameters for the selected TEC model are given in Table 2:

TABLE 2. The performance of the TEC.

Device Model	TEC1-12706
Hot-side Temperature T_h (K)	300
Maximum Absorbed Heat Power Q_{max} (W)	58-65
Maximum Temperature Difference ΔT_{max} (°C)	Above 60
Maximum Voltage V_{max} (V)	15
Maximum Current I_{max} (A)	5.8
Measured Module Resistance R_e (Ω)	2.5

IV. HEAT DISSIPATION EXPERIMENT

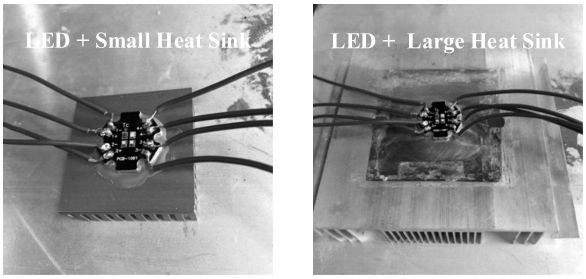
The working conditions for the experiment are shown in Tab. 3.

The devices involved in the experiment are as follows: an RGBW LED chip, commercial TEC, heat sinks with dimensions of 40 mm × 40 mm × 10 mm and 100 mm × 100 mm × 20 mm, MK350N illumination spectrometer, voltage source, thermometer and silicone grease, respectively. The LED spectrometer MK350N is applied to measure LEDs. The LED spectrometer performs a spectral analysis on light, which is emitted by LEDs. The spectrometer measures besides the color spectrum also the illumination level in Lux, the color temperature and many other parameters, which are used for the selection of LEDs.

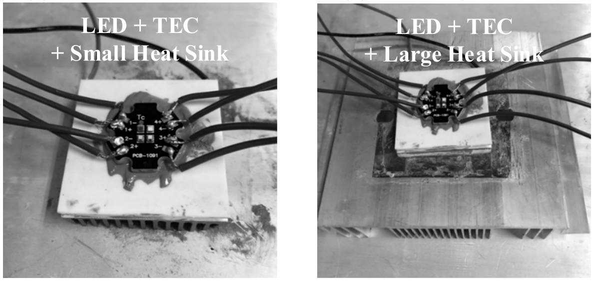
TABLE 3. Working conditions of the experiment.

Experimental Environment	Open, Windless and Dark Surroundings
TEC Operating Voltage Range	0-6 V
LED Operating Current	0.5 A
LED Working Voltage	3.05 V

LEDs, TECs, and different sized heat sinks are bonded by silicone grease. LEDs and TECs are connected together to the same power source. The experimental scheme is divided into 4 cases: 1) LED + Small Heat sink, 2) LED + Large Heat sink, 3) LED + TEC + Small Heat sink, 4) LED + TEC + Large Heat sink, which are shown in Fig. 4.



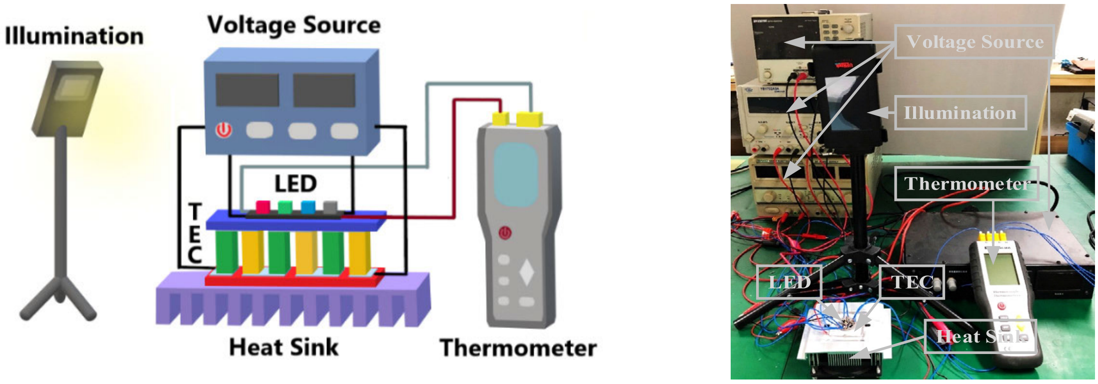
(a) LED + Small Heat Sink (b) LED + Large Heat Sink



(c) LED + TEC + Small Heat Sink (d) LED + TEC + Large Heat Sink

FIGURE 4. Experimental diagram for different combinations of LED heat dissipation.

Based on the four different heat sink combinations, the size of the heat sink, LED with and without TEC, the on-board temperature changes are investigated to analyze the TEC cooling for LED heat dissipation. Then, the board temperature of the LED is measured by a thermometer through physical contact with the T_c of the LED chip. The illumination spectrometer is located approximately 1 cm above the LED, as shown in Fig. 5. After the LED chips for the RGB channel are connected and supplied with the rated power, the board temperature of the LED under different conditions is measured by the thermometer.



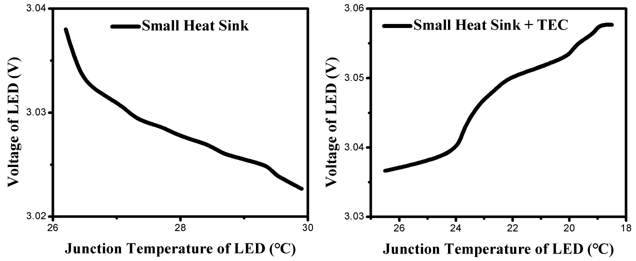
(a)

(b)

FIGURE 5. LED optical parameter measurement. (a) Sketch map. (b) Experimental diagram.

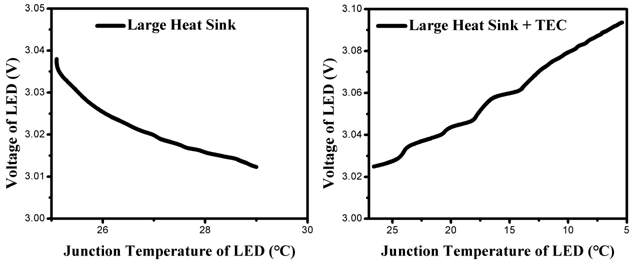
V. RESULTS AND DISCUSSION

Normally, the change of junction temperature of LED will have an effect on the LED voltage. The relationship between the voltage and temperature is illustrated in Fig. 6. As given in Fig. 6(a) and Fig. 6(c), the voltage of LED rises when the junction temperature falls. On the contrary, as shown in Fig. 6(b) and (d), the voltage decreases when the temperature rises. Compared with temperature, the change of voltage is tiny. It probably caused by the change of semiconductor resistance value.



(a) Small Heat Sink

(b) Small Heat Sink + TEC



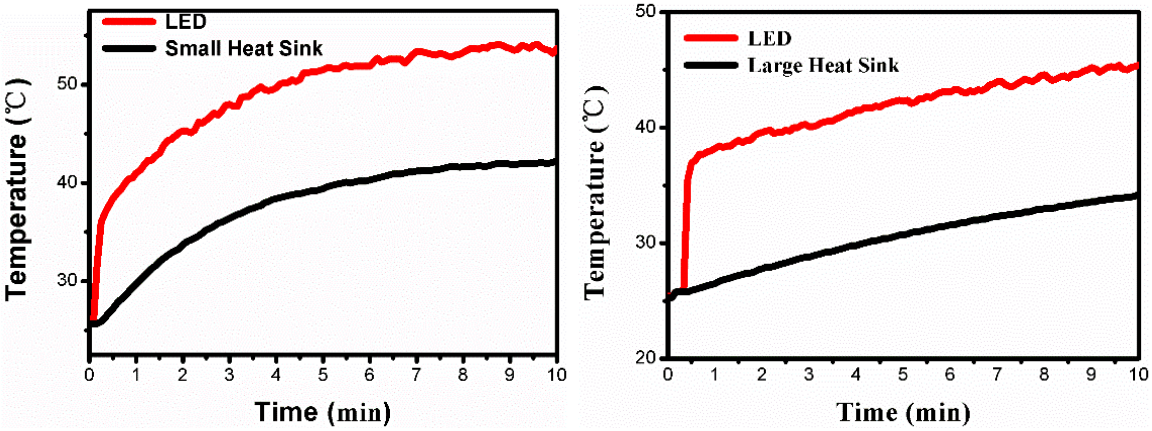
(c) Large Heat Sink

(d) Large Heat Sink + TEC

FIGURE 6. Comparison of LED voltage and temperature.

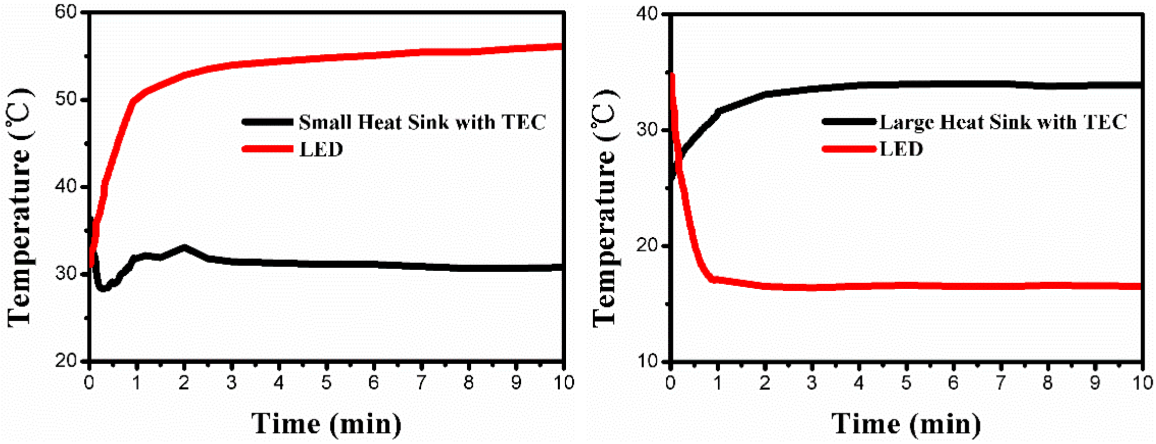
As shown in Fig. 7, the larger the specification, the better the heat dissipation effect. However, an excessive heat sink size affects the packaging and causes inconvenience for the use of the device. Also, it can be seen that no matter large heat sink or small one cannot make LED chip achieve the goal of fast stability. The generated thermal cannot be effectively derived away on passive heat dissipation only by the heat sink. RBGW LEDs work stably for four channels at the rated power. After the TEC is switched on by a voltage of 5 V, the temperature of the LED substrate drops significantly by more than 10 °C compared to the configuration with only heat sink cooling.

In Fig. 7 (a), when the heat is dissipated in the LED only through a small-size heat sink, the LED board temperature is higher than 40 °C at 1 min, and continues to rise. The large-size heat sink illustrated in Fig. 7 (b) has a much better heat dissipation effect than the small heat sink, but the board temperature remains higher than 35 °C. Compared with passive cooling, the LED is then connected to the TEC for active cooling, as shown in Fig. 7 (c) and Fig. 7 (d). Since the TEC has not been powered on and no direct contact between LED and heat sink, its passive heat dissipation is much worse than the heat sink: the initial temperature of the LED is higher than the LED with no TEC connected. Fig. 7 (c) shows that the heat generated by the LED is dissipated by the TEC and small heat sink, where the temperature is maintained at approximately 30 °C, which was determined until the temperature no longer showed a change for approximately 10 min. Fig. 7 (d) shows the LED heat dissipation using a TEC and large-scale heat sink package. This method has a very good heat dissipation effect on the LED, the temperature of which is maintained at approximately 17 °C, even lower than room temperature. As shown in Fig. 8, the board temperature of the LED is approximately 30 °C in the two heat dissipation modes for the size of the heat dissipation package for an LED can be greatly reduced by using a TEC for heat dissipation. Although the TEC is under the heat dissipation conditions of the TEC and the large-scale heat sink, the temperature of the LED is already lower than room temperature. In this way, one can ensure normal use for the LED, while the optical characteristics remain unaffected. For accuracy and authenticity of the experiments, board temperature have be measured 10 times at each node. Transient behavior of LED board temperature and error bar was shown in Fig. 9. Since the heat dissipation requirements for three LEDs are relatively large, the thermal performance of the large-scale heat sink and TEC is chosen as



(a) LED + Small Heat Sink

(b) LED + Large Heat Sink



(c) LED + TEC + Small Heat Sink

(d) LED + TEC + Large Heat Sink

FIGURE 7. Change in LED temperature for different heat dissipation methods.

a research object. In such a condition, the optical performance of the LED is measured by a spectrometer. The RGB channel of the LED chip is turned on with rated power, and the TEC performs cooling at varying voltages of 0 V, 2 V, 4 V, and 6 V, respectively. TEC 0V under nonworking conditions is mainly used for the purpose of conducting a comparison in experiments. As shown in Fig. 8, as the board temperature is continuously decreased, and the spectral curve thereof changes to some extent: the irradiance of the blue light wave gets smaller from 1750 mW/m^2 to 1526 mW/m^2; the irradiance of the green light wave basically remains unchanged; the irradiance of the red light wave goes up and then goes down, and the value of the irradiance at 0 V and 6 V is the sam e. Due to the cooling power of TEC 2V is small, the heat generated by the LED system including the electric power of the TEC cannot be dissipated in time, which causes the irradiance of red light to rise on account of the red light is most affected by the junction temperature, When the TEC cooling power continues to increase, the radiating of LED achieves the cooling effect, as a result the irradiance of red light diminished gradually.

Since the heat cannot be effectively dissipated in TEC 0V, the junction temperature of the LED is too high, and the wavelength will be red-shifted. When the thermal energy is effectively dissipated by the TEC in the LED, the light emission wavelength shifts to shorter wavelengths. As a result, the redshift phenomenon caused by the high board temperature is alleviated.

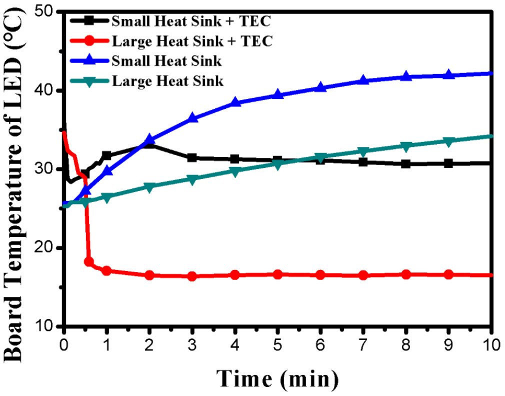
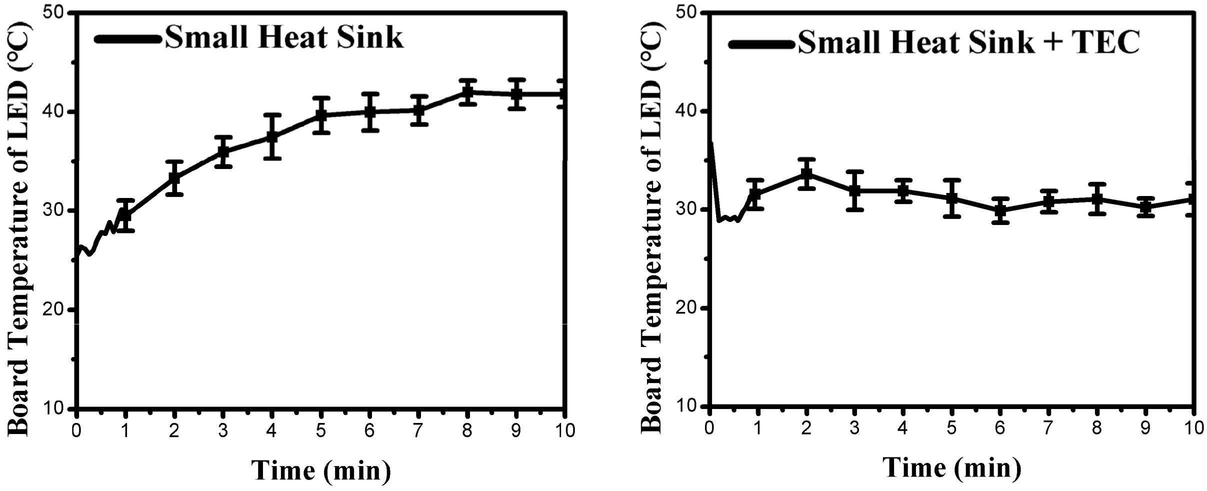


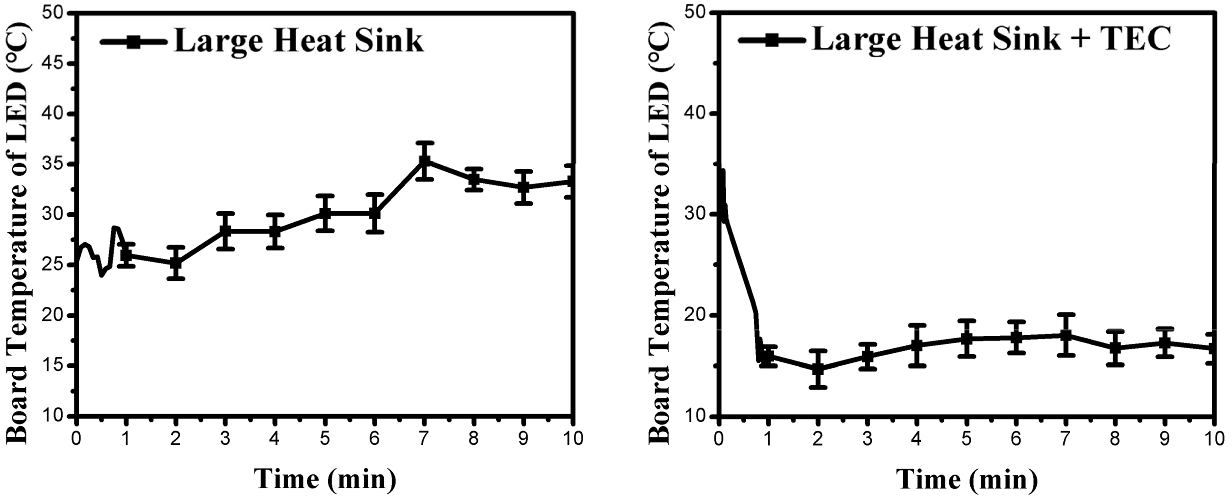
FIGURE 8. Comparison of LED board temperature.

Considering that different chips have different luminous decay characteristics, the peak wavelength of the



(a) Small Heat Sink

(b) Small Heat Sink + TEC



(c) Large Heat Sink

(d) Large Heat Sink + TEC

FIGURE 9. Relationship between transient temperature and timing points.

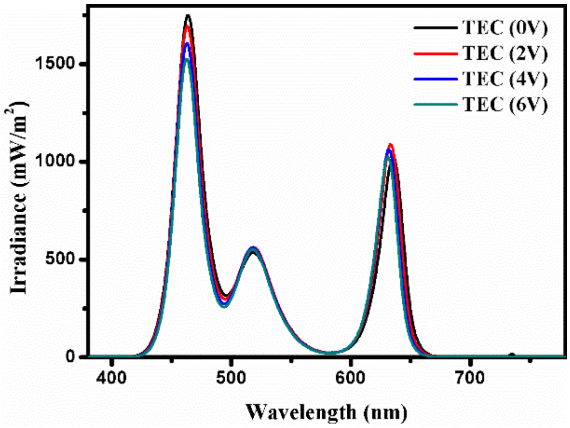


FIGURE 10. Spectrogram of the LED of the RBG channel.

three-primary light shifts differently when the chips work and heat up. As shown in Table 4, the red light is most obvious in the process of lowering the board temperature. For a voltage of 2 V, the TEC starts working for active cooling, providing an effective cooling for LEDs, so the wavelength of the red LED is restored to 3 nm. When the voltage is increased to 4 V or even to 6 V, the TEC reduces the temperature of the LED chip to near room temperature. The passive heat dissipation of the environment is greatly reduced, which means that the

TABLE 4. Change in LED wavelength for an RGB channel with TEC cooling.

TEC Voltage (V)	0	2	4	6
Wave Peak of Red Light (nm)	636	633	632	631
Wave Peak of Green Light (nm)	518	518	518	518
Wave Peak of Blue Light (nm)	464	463	463	463

TABLE 5. Changes in optical performance of white LEDs during TEC cooling.

TEC Voltage (V)	CCT (±1) (K)	CRI (±0.001)	Illuminance (±0.1) (Lux)	Peak Amplitude (±0.1) (mW/m^2)	CIE1931	
					X (±0.0001)	Y (±0.0001)
0	3995	71.8178	26768.93	547.39	0.37856	0.369216
2	3999	71.9104	43579.88	912.52	0.377905	0.367374
4	3990	71.9278	64814.68	1357.43	0.378261	0.367426
6	3992	71.9326	82962.79	1737.51	0.378323	0.367498

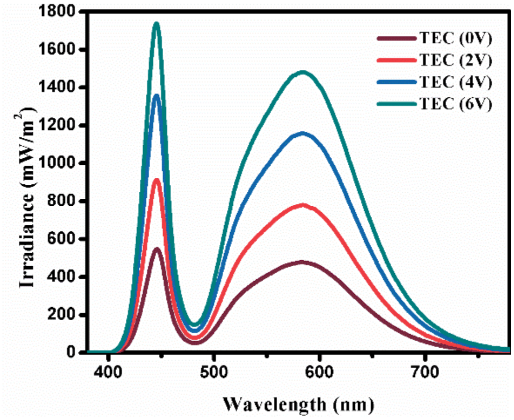


FIGURE 11. Spectrogram of white LED.

working load of the TEC is larger, so the change in the wavelength recovery is not obvious. The peak wavelength is restored by 5 nm in the direction of shorter wavelengths in the range of 0 V to 6 V. This illustrates that excessive board temperature obviously causes the red light to redshift. power. Since the power of the white LED is small, a small-sized heat sink and a TEC are used in our experiment. Then, its optical characteristics are measured by a spectrometer.

Similarly, the white LED chip is also turned on at the rated It can be clearly seen from Fig. 9 that the irradiance of each band becomes significantly stronger as the input power of the TEC increases. The peak amplitude with a power of 6 V TEC is 3 times that for a power of 0 V. When the voltage of the TEC is 6 V, the power consumption of the TEC reaches 14.4 W. This results in a clear increase in irradiance with a 6 V TEC; as the voltage increases, the power doubles. As the temperature decreases, the band gap and electron mobility are increased while the concentration of electrons and holes is decreased. In addition, the probability of recombination of electrons and holes in the potential well increases, thereby increasing the internal quantum efficiency of the LED. As shown in Table 5, the changes in the various parameters can be seen in detail. As the temperature decreases, a slight improvement in CRI indicates that the decrease in the board temperature is advantageous for improving the ability of the light source to reproduce color. The irradiance improves 3 times with increasing TEC cooling power. This signifies that the light characteristics of the LED are improved and that the luminous flux is also increased due to the decrease in board temperature.

From the above experiments, the board temperature of the LED is effectively controlled by the TEC cooling, and the package size of the LED heat dissipation system can be reduced by a reasonable combination of the TEC and heat sink. When the board temperature is effectively controlled by the TEC, the optical performance of the LED is significantly improved. In the case of using a TEC and small heat sinks for white LED cooling, the illuminance is increased by 3 times from 26,768.93 Lux to 82,962.79 Lux with the TEC power increasing from 0 W to 14.4 W. Although the CRI changes very weakly, the CRI continues to increase when the TEC voltage increases continuously. The CCT is stable between 3990 K and 4000 K, but it does not change with the change in the TEC, so it is an irrelevant parameter in this experiment. The offset of x-y chromaticity values is also very small due to the small temperature change.

VI. CONCLUSION

LED chip cooling by a TEC through experimental methods is studied in this paper, and the optical characteristics of the RBGW LEDs such as spectrum, irradiance, CRI and other optical characteristics are measured and analyzed. Compared to the passive heat dissipation method in which only a heat sink is involved, a TEC exhibits a good heat dissipation effect. When the LED is cooled by a TEC and large-sized heat sink, the working board temperature of the LED is only 17 °C. By the regulation of optical parameters, the optical characteristics of the LEDs are obviously improved under the condition of a TEC participating in heat dissipation. In addition, the wavelength of a red LED is restored by 5 nm for RGB LEDs dissipated by a TEC and large-scale heat sink. In the case of using a TEC and small-sized heat sinks for white LED cooling, the illuminance increased from 26,768.93 Lux to 82,962.79 Lux. As a good cooling device, a TEC can provide a reliable and controllable working environment for an LED.

REFERENCES

[1] Y. S. Liu, J. T. Hsu, and J. Y. Chi, "Progress of solid state lighting technology in Taiwan," in *Proc. SPIE*, San Diego, CA, USA, Aug. 2003, pp. 199–206.

[2] E. F. Schubert, "Solid-state light sources getting smart," *Science*, vol. 308, no. 5726, pp. 1274–1278, May 2005.

[3] J. Y. Tsao, "Solid-state lighting: Lamps, chips, and materials for tomorrow," *IEEE Circuits Devices Mag.*, vol. 20, no. 3, pp. 28–37, Jun. 2004.

[4] S. W. Brown, S. Carlos, and G. P. Eppeldaue, "Development of a tunable LED-based colorimetric source," *J. Res. NIST*, vol. 107, no. 4, pp. 363–371, Jul. 2002.

[5] S. K. John, D. John, N. Bijoy, R. Chathanathodi, and A. A. Anappara, "Magnesium diboride: An effective light-to-heat conversion material in solid-state," *Appl. Phys. Lett.*, vol. 111, no. 3, Jul. 2017, Art. no. 125802.

[6] K. C. Yung, H. Liem, H. S. Choy, and Z. X. Cai, "Thermal investigation of a high brightness LED array package assembly for various placement algorithms," *Appl. Thermal Eng.*, vol. 63, no. 1, pp. 105–118, Feb. 2014.

[7] H. Shen, T. Duong, J. Peng, D. Jacobs, N. Wu, J. Gong, Y. Wu, S. K. Karuturi, X. Fu, K. Weber, X. Xiao, T. P. White, and K. Catchpole, "Mechanically-stacked perovskite/CIGS tandem solar cells with efficiency of 23.9% and reduced oxygen sensitivity," *Energy Environ. Sci.*, vol. 11, no. 2, pp. 394–406, 2018.

[8] R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon, R. A. Sherif, and N. H. Karam, "40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells," *Appl. Phys. Lett.*, vol. 90, no. 18, Apr. 2007, Art. no. 183516.

[9] Y. Ma, R. Hu, X. Yu, W. Shu, and X. Luo, "A modified bidirectional thermal resistance model for junction and phosphor temperature estimation in phosphor-converted light-emitting diodes," *Int. J. Heat Mass Transf.*, vol. 106, pp. 1–6, Mar. 2017.

[10] B. Sun, X. Fan, H. Ye, J. Fan, C. Qian, W. van Driel, and G. Zhang, "A novel lifetime prediction for integrated LED lamps by electronic-thermal simulation," *Rel. Eng. Syst. Saf.*, vol. 163, pp. 14–21, Jul. 2017.

[11] B. Vandevelde, A. Griffoni, F. Zanon, and G. Willems, "Methodology for solder-joint lifetime prediction of LED-based PCB assemblies," *IEEE Trans. Device Mater. Rel.*, vol. 18, no. 3, pp. 377–382, Sep. 2018.

[12] B. Damilano, N. Grandjean, and J. Massies, "InGaN/GaN quantum wells grown by molecular beam epitaxy emitting at 300 k in the whole visible spectrum," *Mater. Sci. Eng. B*, vol. 82, nos. 1–3, pp. 224–226, May 2001.

[13] A. Žukauskas, R. Vaicekauskas, F. Ivanauskas, R. Gaska, and M. S. Shur, "Optimization of white polychromatic semiconductor lamps," *Appl. Phys. Lett.*, vol. 80, no. 2, p. 234, Jan. 2002.

[14] S. Chhajed, Y. Xi, Y. L. Li, T. Gessmann, and E. F. Schubert, "Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light-emitting diodes," *J. Appl. Phys.*, vol. 97, no. 5, p. 10, Mar. 2005.

[15] X. Luo and S. Liu, "A microjet array cooling system for thermal management of high-brightness LEDs," *IEEE Trans. Adv. Packag.*, vol. 30, no. 3, pp. 475–484, Aug. 2007.

[16] M. Ha and S. Graham, "Development of a thermal resistance model for chip-on-board packaging of high power LED arrays," *Microelectron. Rel.*, vol. 52, no. 5, pp. 836–844, May 2012.

[17] T. Acikalin, S. V. Garimella, J. Petroski, and A. Raman, "Optimal design of miniature piezoelectric fans for cooling light emitting diodes," in *Proc. 9th Intersociety Conf. Thermal Thermomechanical Phenomena Electron. Syst.*, Las Vegas, NV, USA, Jun. 2004, pp. 663–671.

[18] N. Wang, H.-W. Li, C. Ding, L.-Y. Shi, H.-Z. Jia, Z.-D. Ren, and Z.-Y. Zhao, "A Double-Voltage-Controlled effective thermal conductivity model of graphene for thermoelectric cooling," *IEEE Trans. Electron Devices*, vol. 65, no. 3, pp. 1185–1191, Mar. 2018.

[19] M. Redmond, K. Manickaraj, O. Sullivan, S. Mukhopadhyay, and S. Kumar, "Hotspot cooling in stacked chips using thermoelectric coolers," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 5, pp. 759–767, May 2013.

[20] S. Lineykin and S. Ben-Yaakov, "Modeling and analysis of thermoelectric modules," *IEEE Trans. Ind. Appl.*, vol. 43, no. 2, pp. 505–512, Apr. 2007.

[21] J. Li, B. Ma, R. Wang, and L. Han, "Study on a cooling system based on thermoelectric cooler for thermal management of high-power LEDs," *Microelectron. Rel.*, vol. 51, no. 12, pp. 2210–2215, Dec. 2011.

[22] D. Zhong, H. Qin, C. Wang, and Z. Xiao, "Thermal performance of heatsink and thermoelectric cooler packaging designs in LED," in *Proc. 11th Int. Conf. Electron. Packag. Technol. High Density Packag.*, Xi'an, China, Aug. 2010, pp. 1377–1381.

[23] H. Qin, D. L. Zhong, and C. H. Wang, "Thermal performance evaluation and economic analysis of LED integrated with thermoelectric cooler package," *Adv. Mater. Res.*, vol. 216, pp. 106–110, Mar. 2011.

[24] J. Li, X. Zhang, C. Zhou, J. Zheng, D. Ge, and W. Zhu, "New applications of an automated system for high-power LEDs," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 2, pp. 1035–1042, Apr. 2016.

[25] V. Semenyuk and R. Dekhtiaruk, "Novel thermoelectric modules for cooling powerful LEDs: Experimental results," *J. Electron. Mater.*, vol. 42, no. 7, pp. 2227–2232, Jul. 2013.

[26] N. Wang, J. Chen, K. Zhang, M. Chen, and H. Jia, "Equivalent model optimization with cyclic correction approximation method considering parasitic effect for thermoelectric coolers," *Sci. Rep.*, vol. 7, no. 1, Dec. 2017.

[27] N. Wang, X.-C. Li, and J.-F. Mao, "Improvement of thermal environment by thermoelectric coolers and numerical optimization of thermal performance," *IEEE Trans. Electron Devices*, vol. 62, no. 8, pp. 2579–2586, Aug. 2015.

GUORONG SUI (Member, IEEE) was born in 1974. He received the Ph.D. degree in optical engineering from the University of Shanghai for Science and Technology, Shanghai, China, in 2008. Since 2008, he has been a Faculty Member with the University of Shanghai for Science and Technology, where he is currently an Associate Professor. His current research interests include high-speed semiconductor device, integrated optics device, and optical-electrical detection.

JIAJUN CHEN was born in 1994. He received the master's degree in optical engineering from the University of Shanghai for Science and Technology, Shanghai, China, in 2019. Since 2016, he has been committed to research on thermoelectric cooling. Has He published an article about equivalent model optimization for thermoelectric coolers by the second author (the first author is supervisor N. Wang). His current research interests include thermoelectric cooling and microelectronic.

HAO NI was born in 1999. She is currently pursuing the degree in electronic information with the University of Shanghai for Science and Technology, Shanghai, in 2018. She is also committed to learning and researching on the thermoelectric cooling.

YANYING MA was born in 1994. She is currently pursuing the degree in photoelectric information science and engineering with the University of Shanghai for Science and Technology, Shanghai, in 2016. Her current research interest includes pulse broadening in Terahertz and electromagnetic wave technology.

XIUMIN GAO was born in 1978. He received the Ph.D. degree from the Shanghai Institute of Optics and Fine Mechanics (SIOM), in 2006. He joined the University of Shanghai for Science and Technology (USST), in 2017. He is currently a Leader of several research programs, including the National Natural Science Foundation of China National Key Research and Development Plan. He has published more than 60 articles in journals, such as *Nature Communications*, *Scientific Reports*, and *Applied Optics*. He obtained more than 50 patents, and his several research achievements have been industrialized. His current research includes instruments and meters, smart sensing technology, optical engineering, and precision measurement.

NING WANG was born in 1984. He received the M.S. and Ph.D. degrees in microelectronic from Xidian University, Xi'an, China, in 2009 and 2012, respectively. Since 2012, he has been with the China North Industries Group Corporation General Electronics Group, Suzhou, China, as a Research and Development Engineer and a Project Leader. From 2013 to 2015, he was a Postdoctoral Researcher with Shanghai Jiao Tong University, Shanghai. Since 2015, he has also been a Faculty Member with the University of Shanghai for Science and Technology, Shanghai, where he is currently an Associate Professor. His current research interests include high-speed interconnect technology, thermoelectric energy conversion, and harvesting.