High-Performance InGaN-Based Green Resonant-Cavity Light-Emitting Diodes for Plastic Optical Fiber Applications

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***Abstract*—High-performance InGaN-based green resonant-cavity light-emitting diodes (RCLEDs) with a plating Cu substrate for plastic optical fiber communication applications are reported. Good stability of emission wavelength was obtained at 0.016 nm/mA. The RCLEDs presents low temperature dependence, showing only a 3% drop in light output power as the temperature increasing from 25 to 85 °C. The superior performance can be attributed to the decreased dynamic series resistance and the enhanced thermal dissipation of the heat sink substrate.**

***Index Terms*—InGaN, optical fiber, resonant-cavity light-emitting diode (RCLED).**

I. Introduction

THE enhancement brightness and extraction efficiencies of resonant-cavity light-emitting diodes (RCLEDs) have attracted significant interest because, compared to traditional light-emitting diodes (LEDs), RCLEDs have spectral purity, superior emission directionality, inherent temperature stability, and enhanced light extraction efficiency [1]–[4]. Furthermore, RCLEDs also provide the application of the plastic optical fiber (POF)-based local-area network for the in-home multimedia and automotive industries [5]–[7]. The transition windows of the POFs operate between 510 and 570 nm wavelength regions, which give a minimum attenuation loss of 0.07–0.13 dB/m [8]. Moreover, the transmission distance, operation speed, and temperature insensitivity of an optical signal source for the high-performance POFs are important, that is to say, the RCLEDs need to increase the light power, modulation speed, and temperature stability. RCLEDs with a large-sized light aperture can improve the optical performances, but it could decrease the modulation speed of RCLEDs. In contrast, the aperture size must be small in order to increase the modulation speed [9], [10]. In addition, the cavity detuning of RCLEDs can also modified to improve the light power, modulation speed, and temperature insensitivity [11], [12]. However, the full-width at half maximum (FWHM) of the spectra and forward operating voltage increased with decreasing n-GaN thickness [13], [14]. Based on these issues, the GaN-based green RCLED with high performance has been fabricated in this work. We report on the GaN-based green RCLEDs with a plating Cu substrate, which involves the use of a Fabry-Pérot cavity to redistribute the spontaneous emission pattern of quantum well emitters into the light extraction cone [15]. This structure can allow the RCLEDs to perform at high temperature, but not to affect the Fabry-Pérot mode, power efficiency, and modulation speed. The cause of temperature variations includes a change in the injected current level and/or a variation in the ambient temperature. Therefore, the characteristics as a function of the injected current level and ambient temperature of InGaN-based RCLEDs on Cu substrates will be presented.

II. Experiment

The InGaN/GaN RCLEDs structures were grown on 2-inch (0001)-oriented sapphire substrates by metal-organic chemical vapor deposition. The epitaxial structure has been reported previously [16]. In order to analyze the temperature dependence of the RCLEDs on various substrates, RCLEDs with Cu and sapphire substrates were fabricated. The planar electrodes were also applied to an RCLED/Cu device in order to maintain the consistence of process condition and emission light area with RCLED/sapphire. The process of the RCLED fabrication is as follows: The RCLED epilayers were mesa-etched into n-GaN layers having a 356×356 μm^2 area by an inductively coupled plasma dry ion etching system. A 200-nm thick indium-tin-oxide (ITO) film was evaporated onto the p-GaN as a current-spreading layer using an electron beam evaporator. Then, a SiO_2 insulation layer was deposited by plasma-enhanced chemical vapor deposition as a current confinement layer to define the mesa region. Electron beam evaporation of a Cr/Au bilayer formed as p- and n-contact pads, in which the p-pad makes contact with the p-GaN through the ITO layer, yielding a 40μm aperture for light output. $TiO_2/SiO_2/TiO_2$ multilayers were evaporated as the top mirrors using the electron beam evaporator. It presents $\sim 51\%$ reflectivity at 492-530 nm. Afterwards, the LED epiwafer was bonded to

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a temporary glass carrier using an adhesive layer, and a UV pulse laser was irradiated from the backside of the sapphire substrate to separate the sapphire from the RCLED sample. A diluted HCl solution was used to remove the residual Ga droplets on the exposed n-GaN surface. Subsequently, a Ti (30 Å)/Al (3000 Å) bilayer was evaporated on an exposed n-GaN surface as a bottom mirror. The bottom mirrors serve not only as a reflector, but also as a conduction layer. The bottom mirror presents $\sim 87\%$ reflectivity at 496-508 nm. The Pt film with 50 nm thickness was then deposited on the Ti/Al bilayer to serve as the seed layer for plating a Cu substrate. Then, a 130-μm thick Cu metal was electroplated as a permanent substrate for the RCLED/Cu device. Finally, a complete RCLED/Cu device was obtained after it was removed from the silica carrier. For comparison, a GaN-based epilayer with the Fabry-Pérot cavity structure was also fabricated for the RCLED/sapphire device. The RCLED/Cu and the RCLED/sapphire had the same epilayer and process structures, except for the substrates. The RCLED epilayers with a bottom reflector were also bonded to the sapphire substrate using the thermal pressure wafer bonding. These chips were mounted on the gold-coated TO-cans without epoxy.

III. Results and Discussion

The fiber-coupled light power as a function of an injection current for both types of RCLEDs into a plastic optical fiber of 1 mm diameter (N.A. $=0.5$) at room temperature is shown in Fig. 1(a). The fiber-coupled light power of RCLEDs with sapphire substrates first presents an increase, then saturation at $\sim$ 100 mA, and then decreases as the current increases. However, the light power of the RCLED/Cu increases with the forward driving current up to 200 mA. The fiber-coupled light powers of both types of RCLEDs are almost the same as the injection current at 20 mA. The phenomenon corresponding with the insets of Fig. 1(a) shows that both types of RCLEDs have similar light-emitting patterns at 20 mA injection. However, the thermal effect is not evident under a low current injection for these two types of RCLEDs. At the 100 mA current injection, the fiber-coupled light power of the RCLED/Cu displays an enhancement of 47% as compared with that of the RCLED/sapphire. The results are consistent with the insets of Fig. 1(a) indicating the RCLED/Cu at 200 mA. In contrast, the fiber-coupled light power of the RCLED/sapphire was saturated when the injection current reached 100 mA, which corresponds to the light-emitting pattern also shown in the inset of Fig. 1(a). Obviously, the RCLED/Cu has a superior fiber-coupled light power performance over the RCLED/sapphire at a high injection current. The improvement of the fiber-coupled light power for the RCLED/Cu was attributed to the Joule heating reduction due to a Cu substrate with a high thermal conductivity and the low dynamic resistance (R_s). The dynamic resistance and forward current-voltage (I-V) characteristics for both types of RCLEDs were also shown in Fig. 1(b). The forward voltage of the RCLED/sapphire is higher than that of the RCLED/Cu. It could be due to the additional lateral resistance except the resistances of the contact, p-type, and n-type layers in this device. As expected, the RCLED/Cu has a lower voltage than the RCLED/sapphire under the same current. It results in the

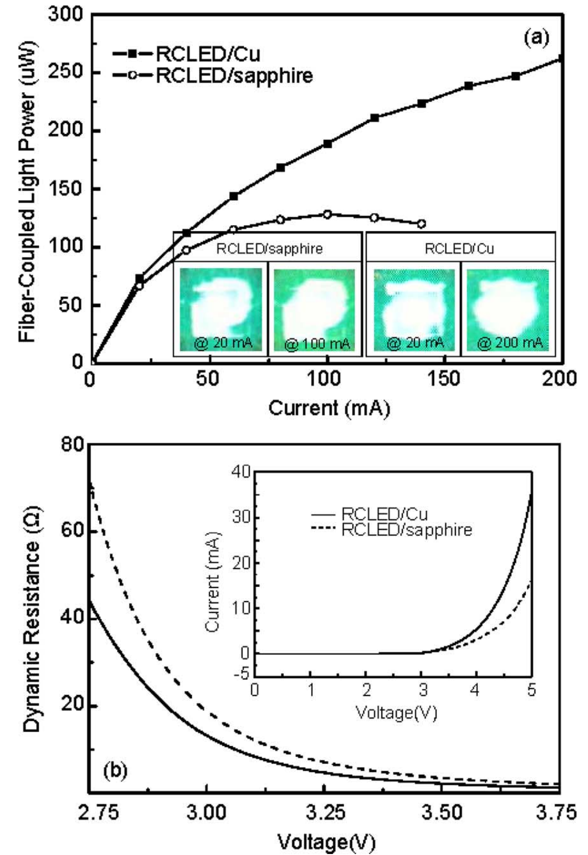

Fig. 1. (a) (Color online) Fiber-coupled light power of both types of RCLEDs as a function of injection current. The inset presents the light emission photographs of both types of RCLEDs at different injection currents. (b) Dynamic resistance and forward I-V characteristics for both types of RCLEDs.

RCLED/Cu presenting a superior dynamic resistance characteristic. The obtained results indicate that the R_s plays an essential role in obtaining the low forward voltage by the vertical conduction structures. The phenomenon is important for decreasing the Joule heating and increasing the quantum efficiency.

Fig. 2 and its inset show the electroluminescence (EL) spectra of both types of RCLEDs at the 50- and 100-mA current injections. The EL spectra of both types of RCLEDs were periodically modulated with several narrow resonant wavelength peaks. The phenomenon indicates that the interference is due to the multiple reflections between the top and down mirrors of the Fabry-Pérot cavity. The spectra of RCLED/Cu do not shift for the emission peak wavelength of 507 nm with the various injection currents of 50 and 100-mA, that is, the stable emission peak wavelength was obtained. The shapes of these emission spectra of RCLED/Cu are almost the same, even when the driving current is as high as 100-mA. Furthermore, the EL intensity of the RCLED/Cu apparently increases with a rise in the injection current, and the FWHM of the light emission is maintained around 43-nm under 100-mA. In contrast, the emission peak wavelength of the RCLED/sapphires revealed a large red shift from 508 to 519-nm when the injection current was injected from 50-mA increasing up to 100-mA. The EL intensity degraded and the FWHM of the light emission broadened from 43 nm to 50 nm with the increase in injection current. The discrepancy in these phenomena of both types of RCLEDs

was attributed to the temperature effects brought on by the increasing injection current, namely, the junction temperature (T_j) effects. The junction temperature versus a function of injection current for both types of RCLEDs was described in detail elsewhere [17]. All the phenomena above are discussed as follows: With the current increasing, the decrease of the EL intensity of RCLEDs/sapphire was caused by nonradiative recombination and ohmic contact heating by the dynamic resistance. The temperature dependence of the light output intensity can be described by the equation below [18], [19]

$$I = I_0 \exp^{-T/T_1} \tag{1}$$

where I_0 is a reference intensity and T_1 is the characteristic temperature. Likewise, the intrinsic emission wavelength (λ_{QW}) and the cavity resonance wavelength (λ_{cav}) shift toward longer wavelengths by the different rates also resulted from the decrease in emission intensity [20]. The λ_{QW} red-shift is due to a diminution in the energy gap of semiconductors with increasing temperature caused by an increasing injection current. The relationship between the temperature and energy gap can be given by [21]

$$E_g = E_g\,|_{T=0K} - \frac{\alpha T^2}{\beta + T} \tag{2}$$

where α and β are fitting parameters. The λ_{cav} red-shift is mainly the temperature dependence of the refractive index and the variation in optical thicknesses of the epilayer by thermal expansion. With the current increasing, the red-shift of the λ_{cav} is much smaller than that of the λ_{QW}. This results in a decreased overlap between the spectra of the cavity resonance and the intrinsic emission, as well as a decrease in the EL intensity [22]. In addition to all of the above, the decreasing EL intensity relative to the FWHM broadens the emission spectrum with the increasing current due to the high Joule heating. In comparison, the EL intensity, emission peak wavelength stability, and FWHM of RCLED/Cu are superior to that of the RCLED/sapphire, which is related to the junction temperature being quickly dissipated with the injection current. In a previous study, the rates of T_j are 0.48 $^\circ$C/mA and 1.07 $^\circ$C/mA for the RCLED/Cu and RCLED/sapphire, respectively. The current dependences of the RCLED/Cu and RCLED/sapphire emission energy were also obtained at a rate of $\sim$ 0.016 nm/mA and $\sim$ 0.15 nm/mA from Figs. 2 and 3 of the previous study [17], respectively. The result indicates that the emission peak wavelength of the RCLED/Cu is much steadier than that of the RCLED/sapphire. The emission peak wavelength stability of RCLEDs achieved in this study is comparable to that of RCLEDs controlled by modifying the cavity detuning in other similar studies [23].

Fig. 3 shows the shift in peak wavelength caused by increasing the mount temperatures for both types of RCLEDs at 20 mA. With increasing the mount temperature, the temperature-dependence of RCLED/Cu shifts to a long wavelength at a rate of 0.03 nm/$^\circ$C, which is lower than that of the RCLED/sapphire shift at a rate of 0.14 nm/$^\circ$C. The wavelength shift of the RCLED/Cu is approximately five times slower than that of the RCLED/sapphire. The peak wavelength shift is

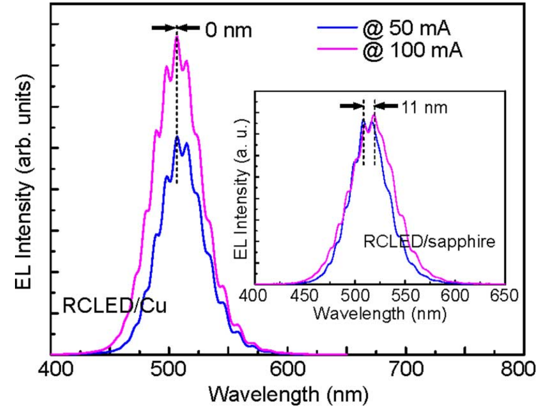

Fig. 2. (Color online) Electroluminescence spectra of both types of RCLEDs emitting at 507-nm under driving current 50 and 100 mA.

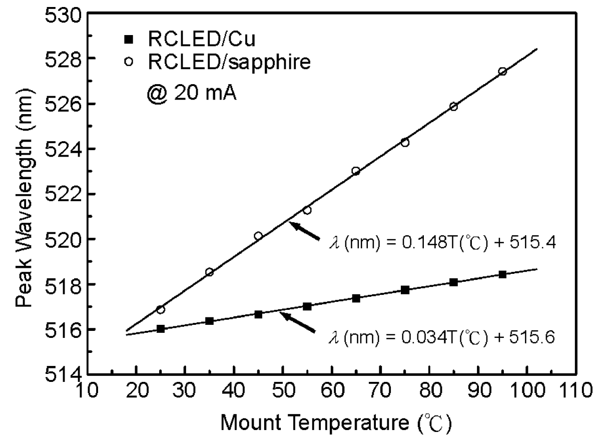

Fig. 3. Peak wavelength as a function of the mount temperatures for both types of RCLEDs at 20 mA.

principally determined by the InGaN energy gap and the optical thicknesses of the epilayer with temperature. The phenomenon corresponds to the result of Fig. 2. This result indicated that the RCLED/Cu emission wavelength stability is due to the superior thermal dissipation by a Cu substrate. The result is superior to the finding reported by Akhter *et al.* [24]. The thermal resistance (R_{th}) of both types of RCLEDs at different injection current is shown in Fig. 4. The T_j is related to the thermal resistance by [25]

$$R_{th} = \frac{T_j - T_a}{P} \tag{3}$$

where T_a is the ambient temperature and P is the drive power of the device. The R_{th} was calculated to be 145.42 $^\circ$C/W and 214.55 $^\circ$C/W at 20 mA for the RCLED/Cu and RCLED/sapphire, respectively. The result indicates that the R_{th} of the RCLED/Cu is lower than that of the RCLED/sapphire. It suggests that a decrease in the Joule heating leads to a corresponding increase in the thermal dissipation due to the T_j decreasing.

The surface temperature distribution along the diagonal for both types of RCLEDs at 100 mA current injection is shown in Fig. 5. The thermal energy emitted from the surface of devices by noncontact infrared thermal imaging systems. The surface temperature profile indicates that the RCLED/Cu is lower than

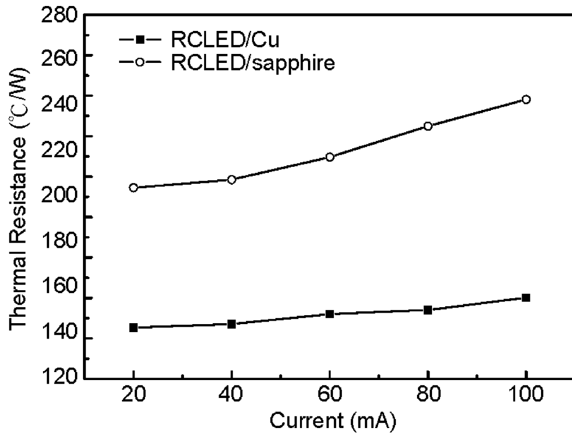

Fig. 4. Thermal resistances of both types of RCLEDs as a function of injection current.

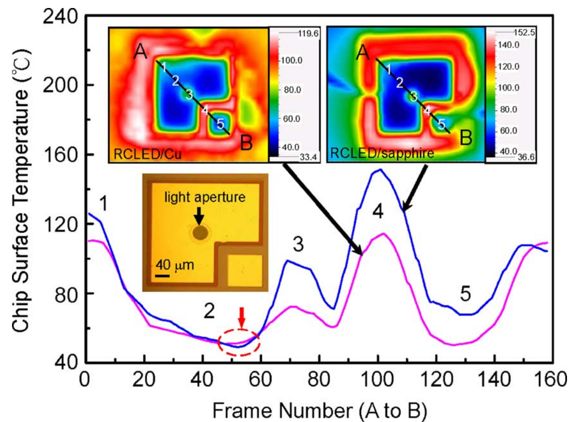

Fig. 5. (Color online) Surface temperature distribution along the diagonal for both types of RCLEDs at 100-mA current injection. Relative to the surface temperature distribution, the infrared thermal images of both types of RCLEDs are also shown in the inset. The symbol of each chip is added for clarity. The plane view of a chip is also shown in the inset.

that of the RCLED/sapphire. However, the red arrow point present is contrary to the result of the above. The phenomenon could be attributed to the lateral current path by a sapphire substrate result in the current crowding effect; therefore, the RCLED/sapphire has a lower temperature as compared with the RCLED/Cu in and around the red arrow point. Relative to the surface temperature distribution, the infrared thermal images of both types of RCLEDs were also shown in the inset of Fig. 5. The symbol of each chip is added for clarity. The infrared thermal image of the RCLED/sapphire surface presents the thermal dissipation around the chip. In contrast, the thermal dissipation of the RCLED/Cu was transferred to the TO-can heat sink by a Cu substrate. The result indicates that the conductive heat transfer of RCLED/Cu is superior to that of the RCLED/sapphire.

In determining the ambient temperature sensitivity of the RCLEDs, we studied the thermal responsive behavior of both types of RCLEDs under different ambient temperatures. The voltage versus ambient temperature for both types of RCLEDs under 20 mA injections current is shown in Fig. 6. It is found that the voltage of both types of RCLEDs shift towards a lower value with increasing ambient temperature. The phenomenon

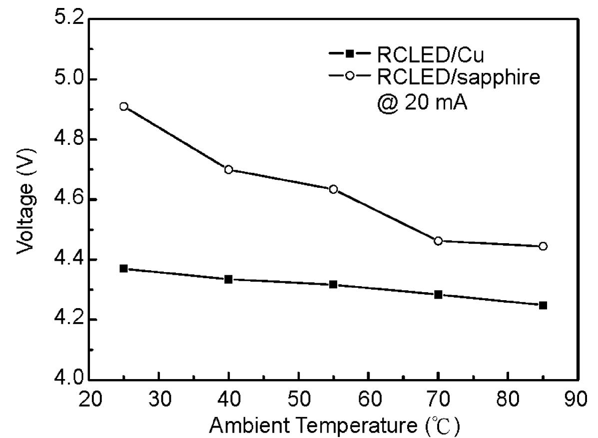

Fig. 6. Voltage as a function of ambient temperature for both types of RCLEDs at 20 mA.

is due to the changes in energy gap, which can be predicted by (2). As the temperature increases, the energy gap of a semiconductor decreases and results in the decreasing voltage of the device. The temperature dependence of the device voltage could be determined as follows [18]:

$$V(T) = \frac{kT}{e} \ln \frac{I}{I_s^*} + \frac{E_g(T)}{e} \tag{4}$$

where I_s^* is the saturation current. However, the voltage of RCLED/Cu is lower than that of the RCLED/sapphire at the same ambient temperature. The result could be attributed to the fact that RCLED/Cu provides the low contact heating through the lower Rs. On the other hand, the specific heat ($0.385 \mathrm{J/g}\ ^\circ\mathrm{C}$) of Cu is smaller than that ($0.942\ \mathrm{J/g}\ ^\circ\mathrm{C}$) of sapphire [26], [27]. Not only the Joule heat can be dissipated easily by Cu, but only the temperature of device is quickly up to thermal balance with ambient. These result that the temperature of device with Cu substrate is always lower than that with sapphire substrate. The result corresponding with Fig. 1(b) shows the low drive voltage for the RCLED/Cu.

The light output power as a function of ambient temperature for both types of RCLEDs at 20 mA is shown in Fig. 7. The light output power of both types of RCLEDs decreases with the increasing ambient temperature. The light output power of RCLED/Cu and RCLED/sapphire decayed by 3% and 9% under the ambient temperature from 25 to 85 °C, respectively. The RCLED/Cu has less degradation in the light output power than that of the RCLED/sapphire.

During modulation-speed measurement, the RF signal was injected into devices and a POF serve as the optical probe and collect the modulated optical power from the top of the chips without using lens and then fed into a low noise Si-based photoreceiver with a 125-MHz electrical bandwidth, which was connected with an RF spectrum analyzer. The frequency responses of both types of RCLEDs under different drive currents are shown in Fig. 8. The result indicates that the -3 dB bandwidth ($f_{-3\ \mathrm{dB}}$) of both types of RCLEDs rises with the increase in drive current. It could be a result from the fact that the recombination rate of carriers is proportional to the current injected into the multiquantum wells. It is worth noting

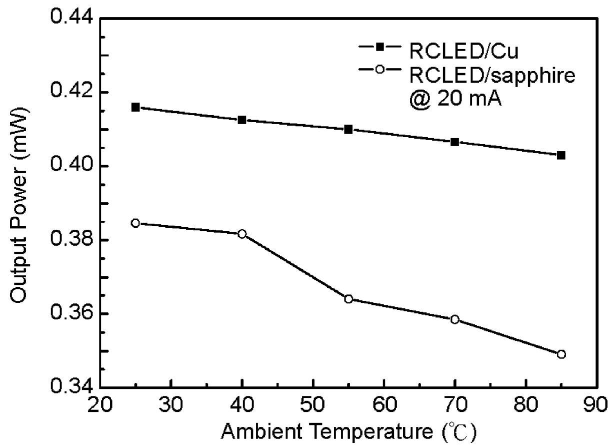

Fig. 7. Light output power as a function of ambient temperature for both types of RCLEDs at 20 mA.

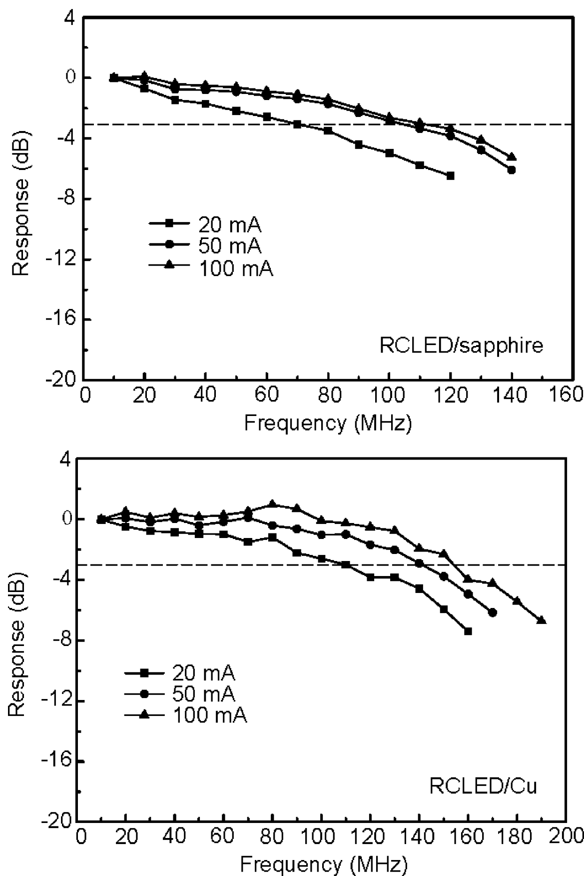

Fig. 8. Measured frequency responses of both types of RCLEDs under 20, 50, and 100 mA.

that the frequency responses of the RCLED/Cu ($\sim$ 110 MHz and $\sim$ 155 MHz) are superior to that of the RCLED/sapphire ($\sim$ 70 MHz and $\sim$ 110 MHz) under the drive currents of 20 mA and 100 mA, respectively. The RCLED/Cu exhibits a significant improvement in this frequency response under a high injected current as compared with the RCLED/sapphire. The improvement is due to an improved electrical injection associated with

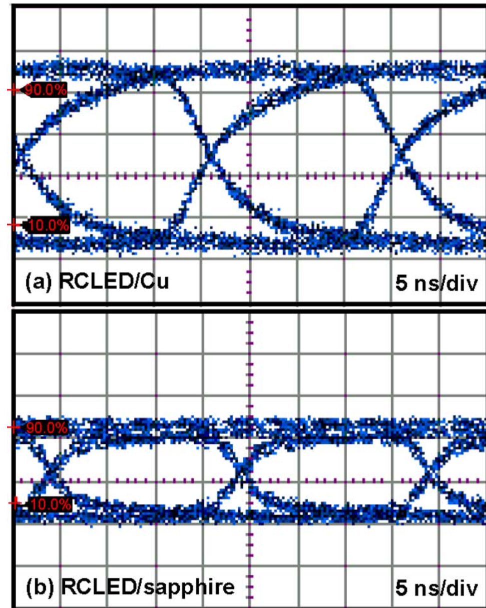

Fig. 9. (Color online) Eye diagram of both types of RCLEDs at a transmission rate of 100 MHz for a 100-m-long POF ($\mathrm{NA} = 0.5$), under a 100-mA driving current.

the vertical current path. The phenomenon can be evidenced from the following equation [28]:

$$f_{-3\ \mathrm{dB}} = \frac{1}{2\pi}\left(\frac{1}{\tau_{nr}} + \frac{1}{\tau_r}\right) \tag{5}$$

where τ_{nr} and τ_r are the nonradiation lifetime and radiation lifetime, respectively. Based on the above equation, the τ_{nr} decreasing results in the nonradiation recombination rate $(1/\tau_{nr})$ increasing and the high $f_{-3\ \mathrm{dB}}$ being obtained. The result demonstrated that the RCLED/Cu under a high current operation could be suitable for the 155 MHz application for fiber communication systems. This modulation speed is comparable to the data reported by Shi *et al.* [29]. Fig. 9 shows the eye diagram for both types of RCLEDs at a transmission rate of 100 MHz for a 100-m long POF ($\mathrm{NA} = 0.5$) under a 100 mA driving current. The eye diagram indicates that the amplitude of RCLED/Cu is larger than that of the RCLED/sapphire. The result shows that the light source of the POF using the RCLED/Cu can tolerate more noise amount than the RCLED/sapphire.

IV. Conclusion

We demonstrate the high-performance of InGaN-based RCLEDs with a Cu substrate at a green wavelength region. The improvement demonstrates that the temperature dependent on the rate of peak emission wavelength is only 0.03 nm/°C under the high mount temperature. The light output decayed by 3% under the ambient temperature from 25 up to 85 °C. In addition, the superior frequency responses was achieved a 155 MHz under the drive current of 100 mA. The eye diagrams have a clear and good open eye pattern. These results confirm that RCLEDs/Cu excellently perform for applications in POF-based multimedia networks.

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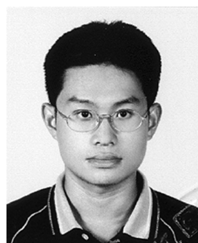

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