Linear Cascade GaN-Based Green Light-Emitting Diodes With Invariant High-Speed/Power Performance Under High-Temperature Operation

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***Abstract*—We demonstrate the performance of linear cascade green light-emitting diode (LED) arrays suited for use in plastic optical fiber (POF) communications in automobiles or harsh environments. With this three-LED array, driven by the constant voltage bias of an in-car battery output (12 V) we obtain high-speed (∼100-Mb/s eye-opening), high-coupling power (0.9 mW), and a very small variation of coupled power versus temperature [$-0.12\%^{\circ}C^{-1}$ at room temperature (RT)] for the whole measured temperature range (i.e., RT to 120 °C). Even under high bias current (100 mA) operation, our device can sustain a clear 150-Mb/s eye-opening from RT to 120 °C. The static and dynamic measurement results indicate that the speed and power performance of this device are less sensitive to variations in ambient temperature than are those of the red resonant-cavity LEDs utilized for POF communication.**

***Index Terms*—Cascade, GaN, light-emitting diodes (LEDs).**

I. Introduction

PLASTIC optical fiber (POF) communication has attracted a lot of attention in recent years because of its numerous applications, such as in in-car data transmission [1] and data-acquisition/control in power-generation systems (e.g., wind farms) [2]. Up to now, the most popular light source for the commercially used polymethylmethacrylate (PMMA)-based POF has been the red resonant-cavity light-emitting diodes (RCLEDs) [3]. However, the optical bandwidth of the red operating window (∼650 nm) is narrower, and the propagation loss is higher (0.125 versus 0.09 dB/m) than that of a minimum PMMA loss window, which operates at a wavelength of around 500 nm [1], [4]. This makes high-speed III–nitride-based green light-emitting diodes (LEDs) a more promising choice for such applications [4]–[7]. As compared to the AlInGaP–GaAs-based red RCLED, the speed and power performance of III–nitride-based green RCLEDs should have much more immunity to variations in ambient temperature and electromagnetic interference due to its larger bandgap. These are important issues for the application of POF in harsh environments, such as in weaponry or in power generation systems [2]. However the lattice-mismatch problem of nitride-based materials makes the growth of high-quality distributed-Bragg-reflector (DBR) mirrors on a GaN substrate, such as is needed for the RCLED structure, a considerable challenge. In this letter, we demonstrate an alternative structure for high-speed green LEDs for which it is not necessary to use III–nitride-based DBRs but can achieve comparable performance with red RCLEDs: the linear cascade green LED array [5], which can achieve a significant improvement in the differential quantum efficiency without sacrificing the modulation speed, over that of a single LED [5]. In this current work, we in detail study its temperature dependent performance and change the number of cascade units to 3 (compare this to our previous work [5]). This brings the turn-on voltage of the array (∼9 V) close to the output of an in-car battery (12 V) so we do not have to use a constant current bias, which should incorporate an additional resistor in the bias circuit and induce excess power consumption [8]. Under a 12-V bias, the three-LED array exhibits a coupling power (∼0.9 mW) to POF (NA : 0.3) and a speed (∼100-Mb/s eye opening) comparable to those of typical high-speed red RCLEDs [9] under around 20-mA bias current for the range of temperature measured (room temperature (RT) to 120 °C). Furthermore, our demonstrated device has a much smaller variation of coupled power versus temperature ($-0.12\%^{\circ}C^{-1}$ versus $-0.64\%^{\circ}C^{-1}$[9] at RT) than that reported for red RCLEDs [9]. Even under a high bias current (100 mA), our device can sustain a clear 150-Mb/s eye-opening at an ambient temperatures of 120 °C.

II. Device Structure and Fabrication

The epi-layer structures were grown by metal–organic chemical vapor deposition on a sapphire substrate. The thicknesses of the six-period $In_xGa_{1-x}N$–GaN multiple quantum well (MQW) region, bottom n-type GaN layer, and topmost p-type GaN layer were about 100, 4000, and 400 nm, respectively. Each period in the MQW active region was made of a 2.5-nm-thick $In_xGa_{1-x}N$ well layer and a 15.5-nm-thick GaN barrier layer with an n-type doping density of around (7×10^{17} cm^{-3}). This brings about such a great improvement in the output power and modulation speed performance of green LEDs [6]. Fig. 1 shows a top-view of the demonstrated three-LED array connected in a series. Each LED has an active diameter of around 250 μm. In order to enhance the light-extraction efficiency and output power performance of our device, we fabricated a Si_3N_4 film based microstructure with a

Manuscript received June 18, 2008; revised August 11, 2008. First published September 3, 2008; current version published November 12, 2008. This work was sponsored by the National Science Council of Taiwan under Grant NSC-96-2221-E-008-106-MY3.

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Digital Object Identifier 10.1109/LPT.2008.2005037

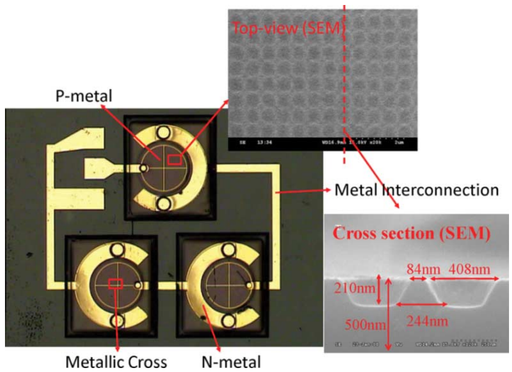

Fig. 1. Top view of the demonstrated LED arrays. Not the three light-emitting units connected in a series. The inset shows the top view and cross-sectional view of the microstructure. The electrical configuration, which includes contact metal and metal interconnection of the LED arrays, and the geometric size of the microstructure, are all specified.

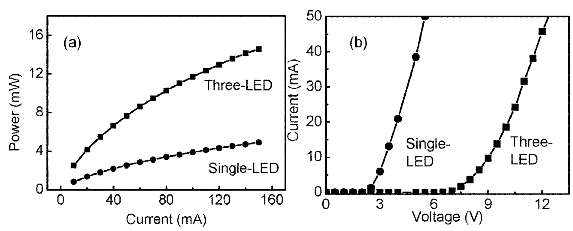

Fig. 2. (a) Total output optical power (P) versus the bias current (I) of a single LED and a three-LED array; (b) this diagram shows the typical I–V curves of a single LED and a three-LED array under forward bias.

thickness of around 500 nm on the topside of the device [10]. The insets show scanning electron microscopic pictures of the top and cross-sectional views of this microstructure located on the topside of the device. Details of the width and depth are also specified on these insets. There is an approximately 17% improvement in output power (under the same constant 12-V bias) for the entire range of temperature measured (RT to 120 °C) over that of the control device, which had the same geometric size and epi-layer structure but without the microstructure as those of the demonstrated device. For details of the fabrication processes please refer to our previous work [5].

III. Measurement Results

Fig. 2(a) shows the total output power (P) from the device operated at RT, as measured by the integrating sphere method, versus the bias current (I) of a single LED, and a three-LED array. We can clearly see that the output power (differential quantum efficiency) of the three-LED array is around three times greater than that of a single LED (under the same bias current). The significant improvement in the differential quantum efficiency can be attributed to the fact that the bias current flows from one emitter to the next in the cascade arrays. The ratio of improved optical power is thus close to the ideal values (three times) reported for cascade light-emitters [5], [11]. Fig. 2(b) shows the measured current–voltage (I–V) curves of a single LED and a three-LED array. One can clearly see that the measured turn-on voltage (3 and 9 V) and differential resistance (∼28 and ∼86 Ω) under a 20-mA bias current increase linearly with the number of cascade units. This behavior is similar to the results reported for cascade light-emitters [5], [11]. Fig. 3(a)

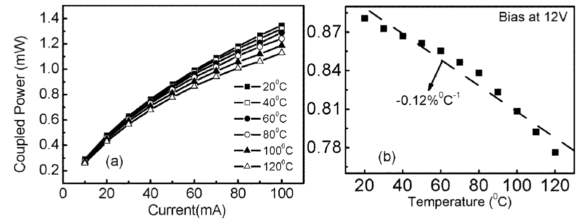

Fig. 3. (a) Coupled optical power into POF versus the bias current (I) of a three-LED array under different ambient temperatures (RT to 120 °C); (b) the figure shows the coupling power under a fixed 12-V bias voltage, which corresponds to a bias current of around 50 mA, in relation to the variation in the ambient temperature.

shows the coupling power to the POF (NA : 0.3) versus bias current under different ambient temperatures ranging from RT to 120 °C. The difference between the total power and coupled power, shown in Figs. 2 and 3, respectively, gives us the coupling efficiency, around 11.4%. These results are close to the value reported for high-speed green LEDs [4] and could be further improved by optimizing the geometric size of the microstructure so as to narrow down the divergence angle of far-field pattern [12]. As can be seen, the coupling power degrades as the temperature increases, becoming more significant when the bias current reaches 100 mA. This can be attributed to the fact that the increase in ambient temperature impedes the heat dissipation efficiency, which leads to more serious degradation of the output power when the device's junction temperature (bias current) becomes higher. Fig. 3(b) shows the coupling power under a fixed 12-V bias voltage, corresponding to a bias current of around 50 mA, in relation to the variation in the ambient temperature. We can clearly see that for this moderate bias current, there is a drop in coupling power over the whole temperature range of around 10%. The thermal dependency of the coupling power is $-0.12\%°C^{-1}$ at RT. Our device exhibits a much smaller thermal dependence of coupling power ($-0.12\%°C^{-1}$ versus $-0.64\%°C^{-1}$[9] and $-0.28\%°C^{-1}$[4] at RT) than that reported for the commercial red RCLEDs [9] or green III–nitride-based LEDs [4] used in POF communication, measured under ambient temperatures ranging from −40 °C to around 80 °C. During dynamic measurements, we injected a radio-frequency (RF) signal or digital signals into the devices then collected the output modulated optical power by the same POF in the dc measurements. The modulated optical power was then fed into a low noise Si-based photoreceiver (New Focus: 1801-FC) with a 125-MHz electrical bandwidth, which was in turn connected to an RF spectrum analyzer or a sampling scope to measure the frequency response or eye-pattern, respectively. The measured frequency responses of the demonstrated devices, as shown in the inset to Fig. 4(a), indicate that, although the three-LED array has a much larger active area and a higher differential efficiency than a single LED, it still has a similar speed performance [5]. This is due to the reduction of the total junction capacitance due to serial connections [5]. As can be seen, under 100-mA bias current level, the 3-dB optical-to-electrical (OE) bandwidths of the single LED and the three-LED array are the same, up to around 90 MHz. On the other hand, under a 12-V constant voltage bias (52-mA bias current), the 3-dB bandwidth of the three-LED array is around 60 MHz, which is fast enough to meet the MOST (media-oriented systems transport) standard

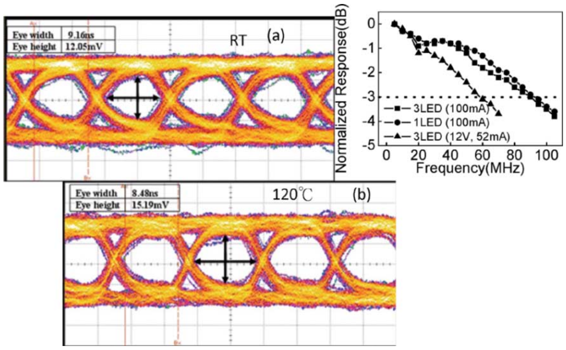

Fig. 4. Measured 90-Mb/s eye-patterns of our three-LED array under a fixed dc bias voltage 12 V at (a) RT and (b) at 120 °C. The inset to (a) shows the measured frequency responses of single LED and three-LED arrays under different bias currents at RT.

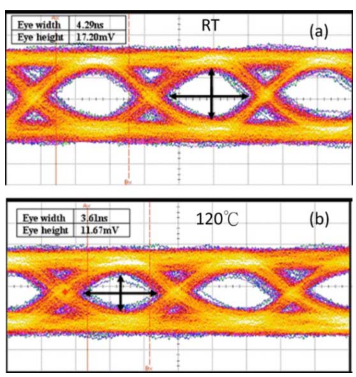

Fig. 5. Measured 150-Mb/s eye-patterns of our three-LED array under a fixed bias current 100 mA at (a) RT and (b) at 120 °C.

for in-car POF communication, which must run at a data rate of 22.5 Mb/s [1]. The higher speed performance of our device is made possible by the reduction in the active volume and the increase in its current density [6]. The dependency of the OE frequency response on the measured temperature (for single LEDs and our array) is invariant throughout the measured temperature range (RT to 120 °C). Fig. 4(a) and (b) shows the eye-patterns of the three-LED array (under a 12-V constant voltage bias) measured at RT and 120 °C, respectively. The input digital signal has a pseudorandom bit sequence of $2^{23}-1$, a bit rate of 90 Mb/s, and a 3-V peak-to-peak driving voltage. We can clearly see that the shape of the eye-pattern remains unchanged throughout this measured temperature range. As shown in Fig. 3, the degradation of the coupling power with the increase of temperature becomes more significant when the bias current reaches 100 mA. We boost the bias current of our array to 100 mA during dynamic measurement to investigate whether the speed performance degrades seriously at such a high ambient temperature (120 °C) and high bias current level. Fig. 5(a) and (b) show the eye-patterns of the three-LED array measured under a 100-mA bias current at RT and 120 °C, respectively. The input digital signal is the same as described in Fig. 4 except that the bit rate increased to 150 Mb/s. Clearly, even under this high bias current and high ambient temperature, our device can still sustain a clear eye-opening at 150 Mb/s. The dynamic temperature-dependent performance of red RCLEDs usually exhibits a bandwidth enhancement phenomenon when the ambient temperature increases; however, the increase in the nonradiative recombination rate leads to a serious degradation of output power [3]. Our static and dynamic measurement results show that both the speed and power performance of our green cascade LEDs have a much better immunity to variations in ambient temperature than do red RCLEDs [3], [9].

IV. Conclusion

We demonstrated a cascade green three-LED array, which can be driven by the constant voltage bias of an in-car battery output (12 V), but still offers high-speed and high-power performance under high ambient temperature (120 °C) operation. The large bandgap of III–nitride-based materials means that the coupling power and modulation speed of our device are much less thermally dependent than those of a typical high-speed red RCLED. Even under a high bias current (100 mA), our device can sustain a clear eye-opening at 150 Mb/s at 120 °C. We will perform bit-error-rate tests on our device in the future.

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