Very-High Temperature (200℃) Operation of GaN-Based Cascade Green Light Emitting Diode for Plastic Optical Fiber Communication

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Abstract: We demonstrate cascade green light-emitting-diodes, which greatly release trade-off between output-power and speed and exhibits strong modulation-speed enhancement with negligible output-power degradation from room-temperature to 200℃ operation. 200Mbit/sec error-free transmission at 200℃ can be achieved.

OCIS codes: **(230.3670) Light-emitting diodes, (060.2330) Fiber optics communications**

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 (~650nm) is narrower, and the propagation loss is higher (0.125dB/m vs. 0.09dB/m) than that of a minimum PMMA loss window, which operates at a wavelength of around 500nm [1,4]. This makes high-speed III-nitride-based green LEDs a more promising choice for such applications [4,5]. 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 (EMI) 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]. In this paper, we demonstrate an III-nitride based linear cascade high-speed green LEDs array with optimized epi-layer structure for high-speed and high-temperature operation. The demonstrated three-LED cascade array exhibits a three-times larger output power (active area) than that of a single LED and the same 3-dB electrical-to-optical (E-O) bandwidth under the same bias current. Furthermore, the demonstrated device exhibits strong modulation-speed enhancement from room-temperature (RT) to 200℃ operation with negligible degradation of output power. By use of such device, we can achieve 200Mbit/sec error-free operation under a low bias current (30mA) and record high operation temperature as high as 200℃ among all the reported high-speed light-emitters.

II. Device Structure

The epi-layer structures were grown by metal-organic-chemical-vapor-deposition (MOCVD) on a sapphire substrate. The thicknesses of the $In_xGa_{1-x}N$/GaN multiple quantum well (MQW) region, bottom n-type GaN layer, and topmost p-type GaN layer were about 90nm, 4000nm, and 400nm, 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 ($7\times10^{17}cm^{-3}$). There are two major differences between our epi-layer structure and typical GaN based green LED. One is that we have reduced the number of MQW layers to increase the injected current (carrier) density in the active layers, which greatly improves the modulation-speed [3]. The second is that we adopted a novel bottom current spreading layer with $In_xGa_{1-x}N$/GaN super-lattice (SL) structure, inserted between bottom n-GaN layer and active MQW layers. Compared with control device without such layer, this insertion layer can not only improve the current spreading, which is verified by the near-field measurement result, but also greatly improve the high-temperature dynamic performance. Figure 1 shows a top-view of the demonstrated three-LED array connected in a series. Each LED has an active diameter of around 100μm. For details of the fabrication processes please refer to our previous work [5].

III. Measurement Results

Figure 2 (a) shows the output power (P) versus the bias current (I) of a single LED, a two-LED array, and a three-LED array, which was measured by use of an integrating sphere. Each LED has an active diameter of around 250μm. We can clearly see that the output power of three-LED array is around three times larger as compared to a single LED under the same bias current. Significant improvement in differential quantum efficiency can be attributed to the fact that the bias current is led from one emitter to the next in the cascade arrays and the total output power can thus be increased along with increase in number of cascade units under the same bias current at the expense of increasing turn-on voltage. The measured ratio (three) of improved optical power is thus similar to the ideal values (3 times). In addition, the output power (6mW) of our array under 20mA bias current is much higher than that of high-speed red LED under the same bias current (1mW) [6]. Figure 2(b) shows the measured current-voltage (I-V) curves of a single LED, a two-LED array, and a three-LED array. One can clearly see that the measured turn-on voltage (3V and 9V) under a 20mA bias current increase linearly with the number of cascade units. During AC (modulation-speed) and data transmission measurement, we injected the RF or data signal into devices and the output modulated optical power was collected by a typical PMMA POF (1mm in diameter and with a 0.3 numerical aperture), and then fed into a low noise Si based photo-receiver with a 125MHz electrical bandwidth. By measuring the difference in collected optical power, obtained using an integrating sphere and a POF, we can obtain the coupling efficiency, which is around 8%. Figure 3 shows the measured electrical-to-optical (E-O) frequency responses of single LED and cascade three-LED array under (100mA) bias currents, respectively. For such measurement, each LED has an active diameter of around 100μm. We can clearly see that compared with a single LED, even the three LED array has a much larger active area and three-times higher output power; it can have a exactly same 3-dB E-O bandwidth (200MHz). Good speed performance of arrays can be attributed to their low differential resistance as well as the reduction of total junction capacitance due to serial connection [5]. For the application to in-car data communication, we expect that our arrays can be operated directly under the DC output voltage of in-car battery (12V) without using the expensive constant current power supply [7]. Figure 3 also shows the measured frequency response of 3 LEDs array under 12V bias, which shows a 3-dB bandwidth around 100MHz. Figure 4 (a) shows the measured -log (Bit-error-rate) vs. driving current of cascade LED with a 100μm active diameter at 200Mbit/sec data rate, which is limited by the 3-dB bandwidth of used Si-based photo-receiver circuit (125MHz, New Focus: 1801-FC) instead of LED itself. Figure 4 (b) shows eye-diagram at 200Mbit/sec (pseudo random bit sequence, 2^{15}-1) of 3 LED-array under a fixed 30mA bias current, a fixed 1.2V peak-to-peak RF driving voltage, and different ambient temperatures (200℃ and RT). As shown in Figure 4(a), when the ambient temperature rises up to 200℃, error-free (BER$<10^{-9}$) operation under a bias current over 30mA can be achieved. Such result definitely indicates the capability of our cascade LED array for 200Mbit/sec data transmission under temperature as high as 200℃ and constant 12V voltage bias, which corresponds to around 40mA bias current. However, under 30mA bias current, when the temperature reduces the BER incases significantly, which is consistent with the measured E-O frequency responses. As shown in Figure 3, under a 30mA bias current at RT, the 3-dB E-O bandwidth is below 100MHz. The observed bandwidth enhancement effect under 200℃ operation can be directly verified by the measured temperature dependent eye-patterns. As can be seen in Figure 4(b), the rise/fall time of eye-pattern reduces significantly with the increase of temperature (RT to 200℃). The dynamic temperature-dependent performance of red RCLEDs usually exhibits a slight bandwidth enhancement (~20%) phenomenon when the ambient temperature increases; however, the increase in the non-radiative recombination rate leads to a serious degradation of its output power [3]. The inset to Figure 4(b) shows the measured coupled power into POF fiber versus bias current under different temperature of our cascade green LED with a 100μm active diameter. Our device exhibits a much smaller thermal dependence of coupling power from RT to 200℃ under a moderate bias current (~40mA), which corresponds to 12V constant voltage bias, than those reported for the commercial red RCLEDs [6] or green III-nitride based LEDs [4,5] used in POF communication (-0.1%℃$^{-1}$ vs. -0.64%℃$^{-1}$ [6], -0.15%℃$^{-1}$ [5], and -0.28%℃$^{-1}$ [4] at RT). These static and dynamic measurement results clearly show that our device exhibits distinct and strong bandwidth enhancement phenomenon under high temperature operation with negligible degradation of output optical power. To the best of author's knowledge, this (200℃) is the highest operation temperature ever reported for high-speed LEDs [4-6].

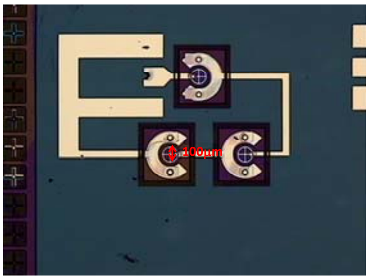

Fig. 1. A top-view of the demonstrated LED array with three light-emitting units, which were connected in series.

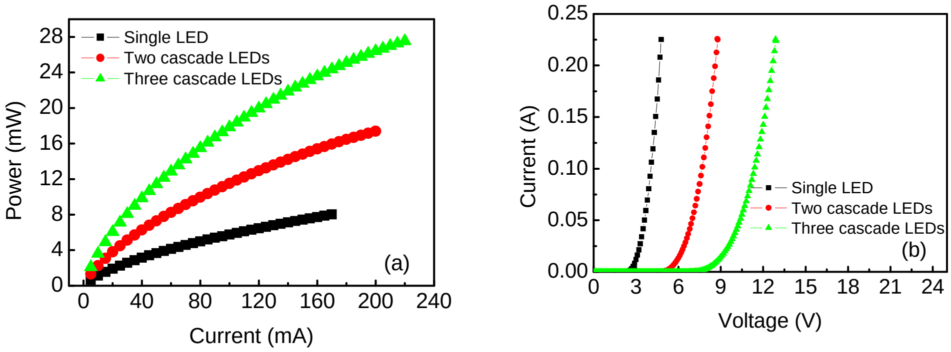

Fig. 2 (a) The measured output optical power (P) vs. the bias current (I) of a single LED, two LED, and three LED arrays. (b) The measured current (I)-voltage (V) curves of a single LED, two LED, and three LED arrays under forward bias. The active diameter of each LED is 250μm.

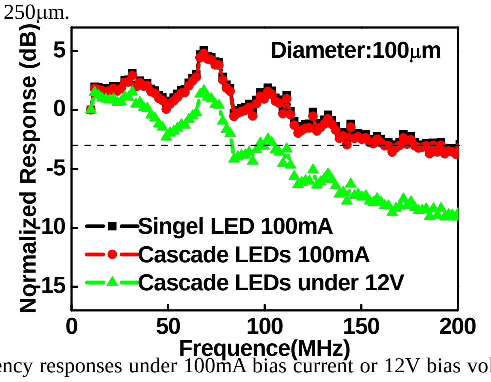

Fig. 3. The measured E-O frequency responses under 100mA bias current or 12V bias voltage (43mA current) of a single LED and three LEDs array. The active diameter of each LED is 100μm.

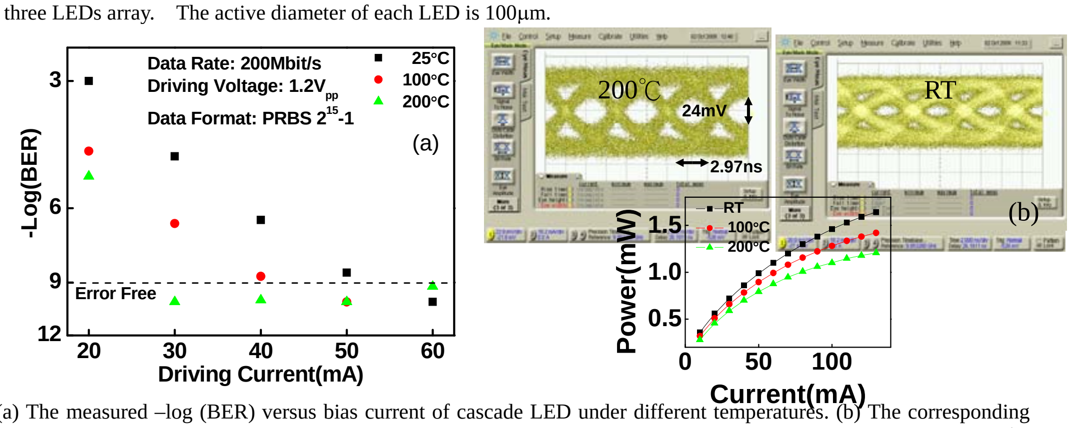

Fig. 4. (a) The measured –log (BER) versus bias current of cascade LED under different temperatures. (b) The corresponding eye-diagram measured under a fixed bias current (30mA), a fixed RF driving voltage (1.2V), and different temperatures (200℃ and RT). The inset to (b) shows the coupled optical power into POF vs. the bias current (I) of a three-LED array under different ambient temperatures (RT to 200℃)

IV. Conclusion

We demonstrate a novel cascade III-nitride based green three-LED array, which not only greatly release trade-off between speed and output power but exhibit distinct bandwidth enhancement effect under high temperature (200℃) operation with negligible degradation in output power. Even under a low bias current (30mA) and a very-high operation temperature (200℃), our device can exhibit a error-free POF transmission at 200Mbit/sec data rate limited by the speed of receiver.

V. Reference

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