Very-High Temperature (200 °C) and High-Speed Operation of Cascade GaN-Based Green Light-Emitting Diodes With an InGaN Insertion Layer

Jin-Wei Shi, H.-W. Huang, F.-M. Kuo, J.-K. Sheu, W.-C. Lai, and M. L. Lee

***Abstract*—We demonstrate a novel type of linear cascade green light-emitting diode (LED) arrays as a light source for in-car or harsh environment plastic optical fiber (POF) communications. To further enhance its dynamic and static performance, an InGaN layer is inserted between an n-type GaN cladding layer and InGaN–GaN multiple quantum wells as an efficient current spreading layer. Compared with the control device without that layer, our three-LED cascade array demonstrates a smaller turn-on voltage (9.3 versus 11 V at 20 mA) and a larger output power (25.5 versus 22.5 mW at 180 mA), corresponding to an enhancement of around 31% in wall-plug efficiency. Furthermore, under the constant voltage bias of an in-car battery (12 V), our three-LED array exhibits an electrical-to-optical 3-dB bandwidth (100 versus 40 MHz) performance superior to that of the control device. Even under high-temperature dynamic operation, we observe that the InGaN insertion layer gives strong enhancement of modulation speed with negligible degradation of the output power, unlike the red resonant-cavity LEDs conventionally used for POF. We achieve 200-Mb/s error-free transmission at 200 °C which is the highest operation temperature among all the reported high-speed LEDs.**

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

I. Introduction

RECENTLY, high-speed III–nitride-based green light-emitting diodes (LEDs) ($\sim$520 nm) have been used for applications in polymethylmethacrylate (PMMA)-based plastic optical fiber (POF) communication, which plays an important role in in-car data transmission and data-acquisition/control in power-generation systems (e.g., wind-farms) [1]. This has attracted a lot of attention because of the narrower optical bandwidth of the red operating window ($\sim$5 versus $\sim$20 nm) in the POF, and higher propagation loss (0.125 versus 0.09 dB/m) than that of another minimum PMMA loss window, which operates at a wavelength of around 500 or 550 nm [1], [2]–[4]. In addition, compared with the most commonly light source used for POF communication today (i.e., AlInGaP–GaAs-based red resonant-cavity light-emitting diodes (RCLEDs) [5], [6]), III–nitride-based green LEDs should be much more immune to variations in ambient temperature due to their larger bandgap. In previous reports [4], we demonstrated the invariability of high-speed performance of III–nitride-based green LEDs at ambient temperatures as high as over 150 °C. That device featured a linear cascade array structure, which gave a significant improvement in the differential quantum efficiency over that of a single LED without sacrificing the modulation speed. In this study, we demonstrate a novel cascade green LED with an additional InGaN bottom current spreading layer, which has been successfully applied to the GaN blue LEDs [7]. We report the temperature-dependent dynamic performance of such a device in more detail than in our previous work [8]. In comparison to the control device without such an insertion layer, the three-LED array exhibits a lower turn-on voltage, higher output power, and a higher modulation speed under the constant voltage bias from an in-car battery output (12 V). Furthermore, the demonstrated device exhibits strong modulation-speed enhancement, during operation from room-temperature (RT) to 200 °C, with negligible degradation in the output power.

II. Device Structure and Fabrication

The epi-layer structures were grown on a (0001) sapphire substrate. The thicknesses of the six-period $In_xGa_{1-x}N$–GaN green multiple quantum-well (MQW) region, bottom n-type GaN layer and topmost p-type GaN layer were about 100, 4000, and 210 nm, respectively. The n-type doping density in some of the GaN barrier layers near the n-type cladding layer was around 7×10^{17} cm^{-3}. The n-type doping was used to enhance the modulation speed and output power of the LEDs; see our previous work [3]. The major difference between our epi-layer structure and that of typical GaN-based green LEDs was the n-type $In_xGa_{1-x}N$ bottom current spreading layer. This layer had a mole fraction x ($x = 6 \sim 8\%$) much less than that of green MQW layers. This 100-nm-thick layer (with a doping density of 1×10^{18} cm^{-3}) was inserted between the bottom n-GaN layer and active MQW layers which benefited bottom current spreading in the fabricated LEDs due to its narrower bandgap, high doping density, and possible lower resistivity than that of the n-GaN layer. Two kinds of devices were fabricated and tested. Device A had an InGaN insertion layer and device B, which served as the control, did not have this insertion layer. The inset to Fig. 1 shows a top-view of the demonstrated three-LED array connected in a series. Each

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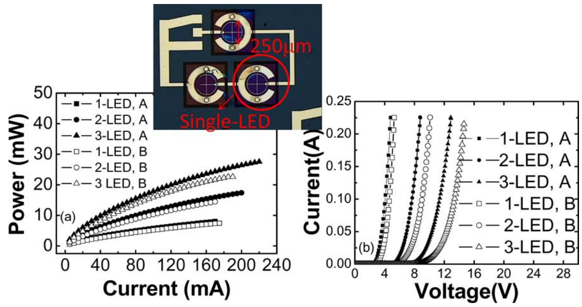

Fig. 1. (a) Total output optical power (P) versus bias current (I) of a single LED, two-LED array, and a three-LED array for devices A and B; (b) typical I–V curves of a single LED, two-LED array, and a three-LED array for devices A and B under forward bias. The inset shows a top-view of the demonstrated LED arrays and a single LED.

LED has an active diameter of around 250 μm. For details of the fabrication processes of the cascade LED array please refer to our previous work [4].

III. Measurement Results

The central wavelength of the measured electroluminescence (EL) spectra of both devices is the same, around 520 nm (under 20 mA), and both devices also show similar blue-shift behaviors under pulse and continuous-wave (CW) operation. Such a result implies that the inserted InGaN layer has no significant influence on the strain-induced piezoelectric field of the MQW layers. Fig. 1(a) shows the total output power (P) from devices A and B, with single LED, two-LED, and a three-LED arrays of the same structure, operated at RT, as measured by the integrating sphere, versus the bias current (I). We can clearly see that for both devices, the output power of the three-LED (or two-LED) array is proportional to the number of cascade units, which is consistent with our previous report for cascade light-emitters [4]. Furthermore, device A has a significantly higher output power than device B under the same bias current (25.5 versus 22.5 mW at 180 mA). Fig. 1(b) shows the measured current–voltage (I–V) curves for devices A and B. One can clearly see that the measured turn-on voltages under a 20-mA bias current increase linearly with the number of cascade units. In addition, device A exhibits a much better I–V performance (smaller turn-on voltage: 9.3 versus 11 V at 20 mA) than does device B. The superior I–V and P–I performance of device A to device B corresponds to an enhancement in wall-plug efficiency of around 31% under a bias current of around 180 mA.

Fig. 2 show the measured near-field distribution of devices A and B under a 50-mA bias current for the single LED structure. The inset shows the 1-D averaged near-field distribution measured within the marked rectangular region. As can be seen, the white area with a strong optical field (current) distribution in device A is larger than that in device B, which means that device A exhibits a more uniform current distribution. This clearly indicates that the inserted InGaN layer serves as an efficient bottom current spreading layer leading to the superior P–I and I–V performance of device A. Similar results have also been demonstrated for GaN-based blue LEDs with an InGaN insertion layer [7].

Fig. 3(a) and (b) shows the measured electrical-to-optical (E-O) frequency responses of devices A and B for the single LED and three-LED array structures, respectively. For this

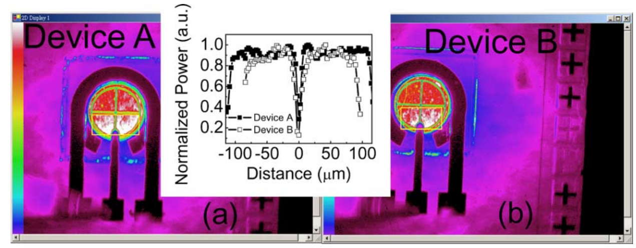

Fig. 2. (a), (b) Measured near-field distribution of devices A and B with a 250-μm active diameter under a 50-mA bias current. The white and purple colors represent the strongest and weakest optical field distribution, respectively. The inset shows the measured 1-D plot of optical near-field distribution of both devices.

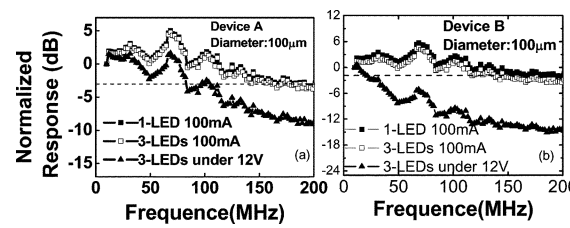

Fig. 3. Measured E-O frequency responses for (a) devicesA and (b) device B under different bias currents or a 12-V bias voltage for the single LED and three-LED array structures.

measurement, the active diameter of the single LED units is the same for devices A and B: 100 μm. During dynamic measurement, radio-frequency (RF) signal or digital signals were injected into the devices and the output modulated optical power was collected by the POF (NA: 0.3 with a 1-mm diameter). The modulated optical power was then fed into a Si-based photoreceiver (New Focus: 1801-FC) with a 125-MHz electrical bandwidth. The resonant peak in the measured E-O responses of both devices was around 70 MHz and can be attributed to impedance mismatch between the photoreceiver module and network analyzer. We can clearly see that under the same constant bias current, devices A and B exhibit the same E-O bandwidth, which implies the same spontaneous recombination time in their MQW regions. These results indicate that the enhanced static performance of device A, as discussed in Fig. 1, can mainly be attributed to the current spreading effect rather than improvement in quality (lifetime) of the MQWs with the bottom inserted InGaN layer. Furthermore, although the three-LED array had a much larger active area and higher differential efficiency than the single LED, the 3-dB E-O bandwidths of both devices A and B were exactly the same, as high as around 200 MHz. This is due to the reduction of the total junction capacitance due to serial connections [4]. On the other hand, for the three-LED array structure under a constant voltage bias (12 V), device A exhibited a much larger 3-dB E-O bandwidth (100 versus 40 MHz) than that of device B. This can be attributed to its better I–V characteristics, as shown in Fig. 1(b), and higher corresponding bias current, which should increase the carrier density in MQW layers and effectively reduce the spontaneous recombination time. Compared with our previous work on cascade III–nitride-based green LEDs [4], there is great improvement in both the demonstrated dynamic and static output power performance.

Fig. 4(a) and (b) shows the measured-log [bit-error rate (BER)] versus driving current of devices A and B, respectively, using the three-LED cascade structure. The active diameter

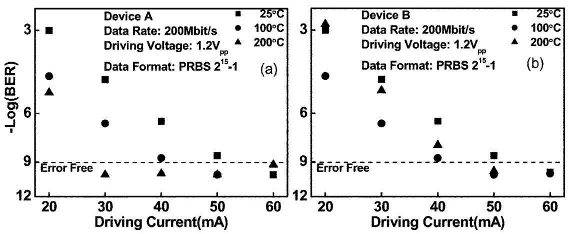

Fig. 4. Measured-log (BER) versus bias current of cascade LEDs under different temperatures for (a) device A and (b) device B.

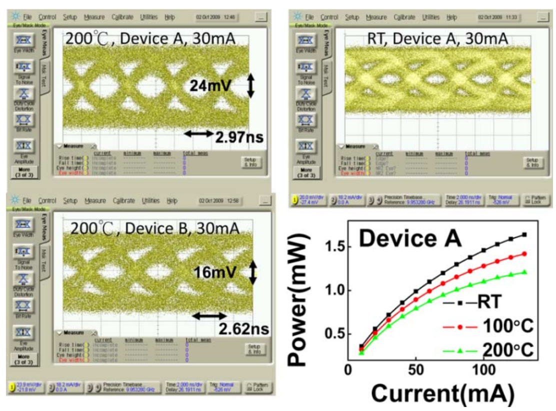

Fig. 5. Measured eye-diagrams for devices A and B. The inset shows the coupled optical power into POF versus the bias current (I) for a three-LED array under different ambient temperatures (RT to 200 °C).

is 100 μm and data rate is 200 Mb/s, which is limited by the 3-dB bandwidth of the Si-based photoreceiver circuit used (125 MHz). Fig. 5 shows eye-diagrams at 200 Mb/s (pseudo-random bit sequence, $2^{15}-1$) for devices A and B operated under a fixed 30-mA bias current, a fixed 1.2-V peak-to-peak RF driving voltage, and different ambient temperatures (200 °C and RT). As shown in Fig. 4(a), when the ambient temperature rises to 200 °C, device A can achieve error-free (BER $< 10^{-9}$) operation under a bias current over 30 mA. Such a result definitely indicates the capability of our cascade LED array to obtain 200-Mb/s data transmission under temperatures as high as 200 °C and at a constant 12-V voltage bias, which corresponds to a bias current of around 40 mA. Although the data rate achieved is lower than the record reported for red RCLEDs [5] (200 versus 622 Mb/s) with an operation temperature lower than 100 °C, to the best of our knowledge, our operation temperature (as high as 200 °C) holds the record among all the reported high-speed LEDs [4]–[6]. On the other hand, under a 30-mA bias current, the BER increases significantly when the ambient temperature is reduced, which is consistent with the measured RT E-O frequency responses, as shown in Fig. 3. Device B shows a very similar temperature-dependent speed performance behavior to that observed in Fig. 4(b). However, the reduction of BER with increase of temperature is much less for device B than for device A. The optimum operating condition seems to be around 100 °C and for error-free operation we need a bias current of over 50 mA. The optimum operation temperature of device B (compared with device A) may indicate that device B suffers from more serious device-heating due to its poorer I–V performance, which may impede the bandwidth enhancement effect and result in more serious thermal-induced noise. We thus expect that the problem of device-heating with device B under 200 °C may be too serious to obtain an improved eye-quality. The observed bandwidth enhancement effect for operation of device A under 200 °C can be directly verified by the measured temperature-dependent eye-patterns. As can be seen in Fig. 5, the rise/fall time of device A's eye-pattern shows a significant reduction with the increase of temperature (RT to 200 °C). On the other hand, under the same temperature (200 °C) and bias current (30 mA), device B's eye-pattern exhibits poorer eye-opening than those of device A. The reported red RCLEDs also usually exhibit a slight bandwidth enhancement ($\sim 20\%$) phenomenon when the ambient temperature increases; however, the increase in the nonradiative recombination rate leads to a serious degradation in its output power [5]. The inset to Fig. 5 shows the measured coupled power into the POF fiber versus bias current under different temperatures for device A. Both devices A and B exhibit the same and much smaller thermal dependence of coupling power, from RT to 200 °C, under a moderate bias current (~40 mA) than those reported for commercial red RCLEDs [6] or green III–nitride-based LEDs [2], [4] ($-0.1\%°C^{-1}$ versus $-0.64\%°C^{-1}$ [6] , $-0.15\%°C^{-1}$ [4] at RT). These measurement results clearly show strong bandwidth enhancement exhibited by our device A under high-T operation with negligible degradation of power.

IV. Conclusion

We have demonstrated a green cascade three-LED array with an InGaN insertion layer, which exhibits a bandwidth enhancement under high temperature operation with negligible degradation in the output power. Under an ambient temperature of 200 °C, our device can exhibit an error-free 200-Mb/s POF transmission.

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