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High-Power GaN-Based Vertical-Cavity Surface-Emitting Lasers with AlInN/GaN Distributed Bragg Reflectors

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Received: 17 December 2018; Accepted: 20 January 2019; Published: 26 January 2019

Abstract: High-efficiency and high-power operation have been demonstrated for blue GaN-based vertical-cavity surface-emitting lasers (VCSELs) with AlInN/GaN distributed Bragg reflectors. The high-efficiency performance was achieved by introducing a novel SiO₂-buried lateral index guide and adjusting the front mirror reflectivity. Lateral optical confinement has been shown to greatly lower the otherwise significant loss of transverse radiation exhibited by typical VCSELs based on GaN. Employing a long (10λ) cavity can also enhance the output power, by lowering the thermal resistance of the VCSEL and increasing the operating current associated with thermal rollover. This modification, in conjunction with optimized front mirror reflectivity and a buried SiO₂ lateral index guide, results in a blue VCSEL (in the continuous wave mode with an 8 μm aperture at 20 °C) having a superior differential quantum efficiency value of 31% and an enhanced 15.7 mW output power. This unit also exhibits a relatively high output power of 2.7 mW at temperatures as high as 110 °C. Finally, a 5.5 μm aperture VCSEL was found to generate a narrow divergence (5.1°) single-lobe far field pattern when operating at an output power of approximately 5 mW.

Keywords: GaN-based VCSEL; AlInN/GaN DBR; lateral optical guide; internal loss; differential quantum efficiency; thermal resistance; small divergence angle

1. Introduction

GaN-based vertical-cavity surface-emitting lasers (VCSELs) are important in numerous applications, including adaptive laser headlamps [1–3], retinal scanning displays and visible light communication systems. VCSELs have numerous advantages, including the avoidance of catastrophic optical damage (COD), ready integration with two-dimensional arrays, minimal temperature dependence and circular output beams with limited divergence. It is especially important to avoid COD in automotive headlamp laser diodes to ensure safety, and it is also helpful if the lasing wavelength is not affected by temperature so that a stable beam color is obtained. Based on these requirements, a combination of blue VCSELs and phosphors are the most attractive light source for next-generation laser headlamps. Recently, some research groups have achieved continuous-wave (CW) operation of GaN-based VCSELs [3–11] and reported output power values of approximately 1 mW [7,10,12–14] and 4.2 mW [15]. However, further improvements in GaN-based VCSELs are required for applications such as laser headlamps. Figure 1 shows the relationship between light output powers (LOPs) and external

differential quantum efficiencies (η_d^F) reported to date for GaN-based VCSELs [7,8,12,13,15–21]. Improving the output power of such devices evidently requires that the η_d^F value be increased. Our own group has recently reported an enhanced output power of 6 mW, as a result of increasing η_d^F [20]. We have also demonstrated improvements in the thermal resistance of these units [21] in conjunction with CW operation, leading to an increased output power of 15.7 mW. Section 2 of this paper discusses the process by which lowering both the front cavity mirror reflectivity and the internal loss results in a superior η_d^F value [20]. The high-temperature functioning of a blue VCSEL based on GaN and having a long cavity, in conjunction with a significant output power and minimal beam divergence, is demonstrated in Section 3 [21]. This paper summarizes prior publications by our group in *Applied Physics Letters* [20] and *Applied Physics Express* [21].

Figure 1. Light output power as a function of differential quantum efficiency for reported GaN-based VCSELs [7,8,12,13,15–21]. The open and closed circles indicate pulsed operation and CW operation, respectively.

2. Enhancement of Differential Quantum Efficiency

The η_d^F value obtained from the front side mirror for a VCSEL can be expressed as:

$$\eta_d^F = \eta_i \times \frac{\alpha_m^F}{\alpha_i + \alpha_m^F + \alpha_m^R} \quad (1)$$

where α_i is the internal loss, η_i is the internal quantum efficiency, and α_m^F and α_m^R are the front and rear mirror losses, respectively [22]. Reducing the internal loss is important for enhancing η_d^F . One potential reason for a low η_d^F is a high internal loss in the cavity. Most VCSELs based on GaN that have been reported in the literature thus far have achieved homogeneous current injection and current confinement by employing SiO₂ apertures and intra-cavity contacts made of indium tin oxide (ITO), despite the anti-guiding that can result from such features [23]. Hashemi et al. [23] performed a theoretical analysis of the transverse radiation loss caused by a lateral anti-guiding structure and determined that the total internal loss could range from 50 to 70 cm^{−1} in a GaN-based VCSEL with a simple SiO₂ aperture. They proposed several lateral optical confinement (LOC) structures to reduce the internal loss. Equation (1) shows that a low η_d^F can also result from the cavity mirror design. Thus, the mirror reflectivity should be adjusted in accordance with variations of the optical gain and loss parameters. Reducing α_i allows more range in the mirror design and reduces the front mirror reflectivity. The present section describes a blue VCSEL based on GaN exhibiting greatly improved differential quantum efficiency, as a result of lowering the cavity mirror reflectivity and incorporating a SiO₂-buried LOC structure.

Figure 2 presents diagrams of a SiO₂-buried VCSEL and a conventional SiO₂ aperture, both of which were fabricated using metalorganic vapor phase epitaxy in conjunction with GaN substrates. Each unit comprised a 10.5-pair SiO₂/Nb₂O₅ distributed Bragg reflector (DBR), a 4.5λ cavity and a 46-pair AlInN/GaN DBR. A 75 nm p-GaN layer, 20 nm p-Al_{0.15}Ga_{0.85}N electron blocking layer, 3 nm 5-pair GaInN/4 nm GaN multiple quantum well and 570 nm n-GaN layer were situated between the DBRs. In Figure 2a, the thickness of the SiO₂ layer was 100 nm with an aperture diameter of 8 μm. A 20 nm ITO contact layer was deposited following fabrication of the conventional SiO₂ aperture, following which a 10.5-pair SiO₂/Nb₂O₅ DBR and a 38 nm Nb₂O₅ spacer layer were applied to the ITO such that a VCSEL cavity was obtained [11]. Assuming that a local shift of the resonance wavelength produces a corresponding change in the effective index [24], a calculation of the resonance wavelength difference gave a normalized effective index difference ($\Delta n_{eff}/n$) of -0.025 for this structure, thus showing anti-guiding. Figure 2b shows a buried SiO₂ structure that was fabricated from an 8 μm diameter region of the p-GaN layer by reactive ion etching to a depth of 20 nm. Following this, magnetron sputtering was employed to deposit a thin (20 nm) SiO₂ film that was subsequently lifted off in a self-aligned manner. A 20 nm ITO contact layer was applied to the buried SiO₂ and central current injection regions, followed by the deposition of a 38 nm Nb₂O₅ spacer layer and a 10.5-pair SiO₂/Nb₂O₅ DBR. The $\Delta n_{eff}/n$ value for this device was determined to be 2.6×10^{-3} , confirming lateral optical guiding. Both n- and p-electrodes were fabricated in each structure, followed by polishing of the GaN substrate and coating of the substrate's back surface with an anti-reflection coating comprising four layers of a SiO₂/Nb₂O₅ dielectric. Note that the substrate side is defined herein as the front of the device (see Figure 2). The reflectivity values for the 46-pair AlInN/GaN and 10.5-pair SiO₂/Nb₂O₅ DBRs at 445 nm were determined to be 99.8% and 99.98%, respectively. By way of comparison, a previous study produced a VCSEL having a 40-pair AlInN/GaN DBR and a 410 nm band that showed 99.7% reflectivity [11]. To obtain the same level of reflectivity in a VCSEL with a 445-nm band, the number of AlInN/GaN pairs must be increased, because the refractive index difference between AlInN and GaN is relatively small at longer wavelengths. In this work, the number of AlInN/GaN DBR pairs was also varied, over the range from 42 to 46, so as to tune the reflectivity. The characteristics of the structures in Figure 2a,b were compared.

Figure 2. Schematics of the fabricated blue VCSELs with (a) simple SiO₂ aperture and (b) SiO₂-buried lateral optical confinement structures.

The AlInN/GaN DBR reflectivity value was calculated based on the front slope efficiency ratioed to the rear slope efficiency, in conjunction with pulsed operation [25]. A reflectivity of 99.98% was determined for the 10.5-pair SiO₂/Nb₂O₅ DBR. The slope efficiency ratio can be expressed as:

$$\frac{\eta_s^F}{\eta_s^R} = \frac{(1 - R_f)\sqrt{R_r}}{(1 - R_r)\sqrt{R_f}}, \quad (2)$$

where η_s^F and η_s^R are the front and rear slope efficiencies, and R_f and R_r are the front and rear reflectivity, respectively. In order to prevent thermal effects on the slope efficiency, these data were acquired with a pulse width of 300 ns and a 0.5% duty ratio. The time-resolved waveform of the current signal was obtained using a sampling oscilloscope (LeCroy 9374TM 1 GHz bandwidth) and by measuring the average light output power with an optical power meter (ADCMT 8230). Figure 3a,b show the reflectivity and slope efficiency from the front side as functions of the number of AlInN/GaN DBR pairs. These VCSELs exhibited the lasing wavelength ranged from 440 nm to 443 nm. From Figure 3a, it is evident that the reflectivity decreases as the number of DBR pairs decreases from 46 to 42, corresponding to a change in the reflectivity from 99.8% to 99.5%. The slight difference in reflectivity between the VCSELs with and without the LOC structure may be due to the In-plane distribution. This drop in reflectivity from 99.8% to 99.5% approximately doubles α_m^F and therefore, based on Equation (1), gives a higher slope efficiency. Compared to the efficiency of a 46-pair AlInN/GaN DBR VCSEL with a conventional SiO₂ aperture (0.13 W/A), the efficiency increased by a factor of 4.7 (to 0.61 W/A) upon introducing the LOC structure, and was further improved, to a total factor of 6.7 (to 0.87 W/A), by additionally tuning the front cavity mirror. This represents the highest slope efficiency yet reported for a GaN-based VCSEL.

Figure 3. (a) Reflectivity of front mirror as a function of the number of AlInN/GaN DBR pairs. (b) Slope efficiency under pulsed conditions as a function of the number of AlInN/GaN DBR pairs. The open and closed symbols indicate the results obtained from VCSELs with a conventional SiO₂ aperture and a SiO₂-buried lateral optical confinement structure, respectively.

To evaluate the impact of reducing the internal loss by introducing the LOC structure, we analyzed the relationship between the mirror loss and the total external differential quantum efficiency

(η_d^{total}) [26,27]. η_d^{total} was calculated by determining both the front and rear side slope efficiencies. The mirror loss in a VCSEL, α_m , can be expressed as:

$$\alpha_m = \frac{1}{2L_{eff}} \ln \left(\frac{1}{R_f R_r} \right), \quad (3)$$

where L_{eff} is the total effective cavity length (equal to the physical length of the device plus the penetration depths into the front and rear mirrors). In this study, L_{eff} was calculated to be 1002 nm for our device, based on coupled-mode theory [25,28]. We used the calculated reflectivity value of 99.98% for the 10.5-pair $\text{SiO}_2/\text{Nb}_2\text{O}_5$ DBR as R_r and the measured reflectivity of the front cavity mirror as R_f . Figure 4 shows the inverse of η_d^{total} as a function of the inverse of the mirror loss. The inverse of the internal quantum efficiency can be obtained from this plot as the intercept of a linear fit to the data, while the internal loss can be obtained from the slope of the line. From these data, the standard GaN-based VCSEL was determined to have an internal quantum efficiency of 0.5 together with an internal loss of 73 cm^{-1} in the absence of an LOC structure. As anticipated based on theoretical studies, the internal loss associated with this device was exceptionally high, at 73 cm^{-1} [23]. In contrast, the internal loss of the VCSEL incorporating the LOC structure was significantly reduced, to 23 cm^{-1} . Thus, it was experimentally found that the impact on the transverse radiation loss was extremely high, namely a reduction of 50 cm^{-1} , more than 2/3 of the whole internal loss in the conventional VCSELs. In addition, a maximum η_d^{total} of 32% was obtained from the SiO_2 -buried VCSEL with a 42-pair AlInN/GaN DBR under pulsed operation. This is also the highest efficiency ever reported for a GaN-based VCSEL. From Figure 4, the internal quantum efficiency of the VCSEL with the LOC structure was found to be 0.6. This value was also improved compared to that of the conventional VCSEL structure possibly due to the lower losses and threshold current densities. However, there is still room to improve the internal quantum efficiency as well as the internal loss value of blue GaN-based VCSELs.

Figure 4. Inverse of external differential quantum efficiency as a function of the inverse of the mirror loss. The open and closed circles indicate the results obtained from VCSELs having a conventional SiO_2 aperture and a SiO_2 -buried lateral optical confinement structure, respectively.

In subsequent trials, VCSEL chips having LOC structures and $8 \mu\text{m}$ apertures were assessed during CW operation after being placed on heat sinks made of Cu with their p-sides facing downwards (equivalent to flip-chip bonding). The front side light output power and voltage during room temperature CW operation are plotted against the injection current in Figure 5a. The threshold current, threshold current density and threshold voltage for the VCSEL with 42-pair AlInN/GaN DBR were determined to be 3 mA, $6.0 \text{ kA}/\text{cm}^2$ and 4.7 V, respectively. Although this device had the highest mirror loss among the fabricated VCSELs in this study, the threshold current and current density were relatively low owing to the low internal loss of 23 cm^{-1} . A maximum output power of

6 mW was obtained. In the figure, it can be seen that the L-I curve exhibits kinks due to multimode lasing. The 8- μm aperture was relatively large and hence higher-order modes were possible even with an extremely low $\Delta n_{\text{eff}}/n$ value of 2.6×10^{-3} [14]. Multimode spectra were also acquired at a lasing wavelength of 441 nm using an optical spectrum analyzer (ANDO AQ-6315B), as shown in Figure 5b. The slope efficiency and the external differential efficiency for the front side were 0.64 W/A and 23% in the vicinity of the threshold current under CW operation. Comparing these values to the results obtained under pulsed operation, the efficiencies were decreased due to thermal effects. From Figure 5a, the maximum power under CW operation when the number of DBR pairs was reduced. This is because the enhancement of the slope efficiency, rather than the threshold current increase, makes a large contribution to the maximum power value. Therefore, a combination of internal loss reduction and cavity mirror control is an effective approach for developing high power GaN-based VCSELs.

Figure 5. I-L/I-V characteristics (a) and emission spectrum (b) of the fabricated GaN-based VCSELs with 42 (solid line), 44 (dashed line), and 46 (dotted line) AlInN/GaN DBR pairs during CW operation at room temperature.

3. High-Power and Narrow Divergent Beam Performance Using a Long Cavity Structure

The data in Figure 5a demonstrate that thermal rollover limited the maximum output power, meaning that it is vital to lower the thermal resistance (R_{th}) to increase output power. Figure 2b shows the structure having a 10.5-pair SiO₂/Nb₂O₅ DBR, 4.5 λ cavity and 42-pair AlInN/GaN DBR, which was found to generate the highest output power. Because the DBR materials in this device, such as AlInN, have comparatively low thermal conductivities [29,30], while GaN (the primary cavity material) possesses significant thermal conductivity [31,32], R_{th} is expected to be reduced as a result of implementing a long-cavity structure [33–35]. A previous theoretical study by Mei et al. [35] assessed the effect of cavity length on R_{th} in the case of a VCSEL based on GaN and having an AlInN/GaN DBR. This prior work employed a cylindrical model and estimated that a longer cavity would result in a 43% decrease in R_{th} . Similarly, the present section demonstrates that incorporating a long cavity (of 10 λ) results in the fabrication of a blue VCSEL based on GaN that exhibits a greater output power of 15.7 mW. A 5 λ -cavity VCSEL was also fabricated so as to compare the I-L data from the two different devices at various thermal resistance values and temperatures. The far field pattern (FFP) narrow divergent angle was also assessed to evaluate the effect of adding the long cavity.

The 5 λ - and 10 λ -cavity devices comprised a 10.5-pair SiO₂/Nb₂O₅ DBR, 5 λ or 10 λ cavity and 42 or 41-pair AlInN/GaN DBR. As discussed in Section 2, the AlInN/GaN DBR mirror reflectivity in the 10 λ -cavity VCSEL was lowered to offset any reduction in the slope efficiency stemming from the

long cavity configuration. It should also be noted that, between the DBRs, the epitaxial structure was essentially identical to that shown in Figure 2b, and that the thicknesses of the n-GaN layers in the 5 λ - and 10 λ -cavity VCSELs were 660 and 1570 nm, respectively. A 20 nm thick SiO₂-buried structure was also incorporated into each device as a means of lowering the internal loss (see Figure 4). As described above (in Equation (2)), the AlInN/GaN DBR reflectivity values were calculated as the ratio of the front slope efficiency to the rear slope efficiency. The 41-pair and 42-pair AlInN/GaN DBRs were found to have reflectivities of 99.1% and 99.3%, respectively. Prior to testing, each 8 μ m aperture VCSEL was bonded to a heat sink made of Cu with its p-side facing downwards (equivalent to flip-chip bonding) and tests were performed in conjunction with CW conditions.

The I-L/I-V data obtained from a 5 λ -cavity VCSEL between heat-sink temperatures of 20 and 100 °C are presented in Figure 6a. The VCSEL showed high temperature lasing to a temperature of 100 °C, in conjunction with a threshold voltage, threshold current density and threshold current (I_{th}) at 20 °C of 5.1 V, 8.4 kA/cm² and 4.2 mA, respectively. This I_{th} is somewhat greater than the value in Figure 5a as a result of the increased front mirror loss that, in turn, stemmed from the decreased front mirror reflectivity. A combination of high efficiency and enhanced output power was obtained by lowering the front mirror reflectivity, although it should be noted that this raised the threshold current. A maximum output power of 8.2 mW at 20 °C and a 20 mA operating current are seen in Figure 6a, and these results are attributed to the differential quantum efficiency (η_d) of 25.4% and the significant slope efficiency (η_s) of 0.71 W/A. Thermal rollover limited the maximum output power obtainable from the VCSEL, while the maximum output power and rollover operating current were both decreased as the heat sink temperature was increased. Therefore, it was anticipated that reducing the thermal resistance would result in a relatively high rollover current and thus provide an enhanced output power over a significant range of temperatures.

Figure 6. (a) I-L/I-V characteristics of the VCSEL having a 5- λ cavity structure over a temperature range from 20 to 100 °C. (b) I-L/I-V characteristics of the VCSEL having a 10- λ cavity structure over the temperature range from 20 to 110 °C.

The I-L/I-V data acquired from the 10- λ cavity VCSEL from 20 to 110 °C are summarized in Figure 6b. These data demonstrate that the rollover operating current and maximum output power were both greatly increased as a result of this structure. An η_s value of 0.87 W/A together with an increased η_d of 31% and an elevated output power of 15.7 mW were observed at 20 °C. The threshold voltage, threshold current density and threshold current at 20 °C were 5.1 V, 9.0 kA/cm² and 4.5 mA, respectively. Relative to the 5 λ -cavity analogue, a much higher rollover operating current was obtained (20 vs. 29 mA at 20 °C). This result can likely be ascribed to a lowering of the thermal resistance, together with a higher slope efficiency stemming from the reduced front mirror reflectivity [20].

Consequently, the light output power was close to double the original value at 20 °C. The 10- λ cavity device showed a maximum wall-plug efficiency of 8.9% at 20 °C together with an elevated lasing temperature of 110 °C at an output power of 2.7 mW (see Figure 6b). This operating temperature together with a differential quantum efficiency of 31% and output power of 15.7 mW are, to our knowledge, the best results yet obtained from a GaN-based VCSEL in the CW mode.

The emission spectra acquired at current injection levels of $0.9I_{th}$, $0.95I_{th}$, I_{th} and $1.05I_{th}$ from the VCSELs with both cavity structures are presented in Figure 7a,b. A significant increase in the peak intensities once a threshold value is exceeded is apparent in both figures. During CW operation at 20 °C, the 5- λ and 10- λ cavity structures generated narrow 0.08 nm lasing linewidths at 443.5 and 440.1 nm, respectively.

Figure 7. (a) Emission spectra of the VCSEL with a 5 λ -cavity structure at different injection currents. A narrow peak wavelength at 443.5 nm was observed above the threshold. (b) Emission spectra of the VCSEL with a 10- λ cavity structure at different injection currents. A narrow peak wavelength at 440.1 nm was observed above the threshold.

Incorporating a long cavity structure lowered the thermal resistance, and this effect was assessed by monitoring the thermal resistance (R_{th}) values. These values were obtained from experimental data via the equation:

$$R_{th} = \frac{\Delta T}{\Delta P_{diss}} = \frac{\frac{\Delta \lambda}{\Delta P_{diss}}}{\frac{\Delta \lambda}{\Delta T_{hs}}}, \quad (4)$$

where $\Delta \lambda / \Delta P_{diss}$ is the wavelength shift over the power dissipation value and $\Delta \lambda / \Delta T_{hs}$ is the wavelength shift over the variation in the heat sink temperature [34–37]. $\Delta \lambda / \Delta T_{hs}$ values from 0.012 to 0.0185 nm/K have been previously reported for these types of devices [34,35,37,38]. Herein, thermal effects were negated by obtaining the $\Delta \lambda / \Delta T_{hs}$ data in conjunction with pulsed operation, and the 5 λ - and 10 λ -cavity devices were determined to have values of 0.0142 and 0.0146 nm/K, respectively, which are in agreement with previously reported data. These same two VCSELs were found to have $\Delta \lambda / \Delta P_{diss}$ values of 0.015 and 0.0103 nm/mW, respectively, and R_{th} values of 1100 and 710 K/W were calculated based on Equation (4). The apparent increase of 65% in this value suggests an approximately 1.5 fold increase in the operating current at rollover, as seen in Figure 6a,b. This effect can be demonstrated by considering the 1.45 fold increase in the rollover operating current at 20 °C (from 20 to 29 mA). It is therefore evident that lowering R_{th} increases the output power. Based on the theoretical evaluation of R_{th} in Ref. 35, this effect of lowering R_{th} in the present work is not

unexpected, so it is apparent that increasing the n-GaN layer thickness enhances thermal dissipation within the VCSEL.

Using the power dissipation and R_{th} , values of 159 and 161 °C were estimated for the internal temperature at rollover ($T_i^{rollover}$) of the devices having 5λ- and 10λ-cavity structures. The fact that these temperatures are quite close to one another demonstrates that a lower R_{th} value explains the increased output power of the 10λ-cavity unit. Therefore, obtaining the maximum possible lasing temperature (T_{hs}^{max}) requires optimization of both R_{th} and $T_i^{rollover}$. During lasing, the value of this parameter can be written as:

$$T_{hs}^{max} < T_i^{rollover} - R_{th} \times P_{diss}^{threshold} \approx T_i^{rollover} - R_{th} \times I_{th} \times V_{th}. \quad (5)$$

where, $P_{diss}^{threshold}$ is the threshold power dissipation while I_{th} and V_{th} are the threshold current and voltage. Therefore, the effect of temperature on I_{th} is a primary factor with regard to the magnitude of T_{hs}^{max} . The threshold currents are plotted as functions of temperature in Figure 8. It is evident from these data that the effect of temperature on I_{th} was small from 293 to 333 K, and that the 10λ-cavity VCSEL showed a comparatively elevated characteristic temperature ($T_0 = 316$ K). Conversely, the I_{th} value was increased rapidly as the temperature was increased above 330 K. This trend greatly increased the internal temperature of the VCSEL at high temperatures but below the threshold, such that the device exhibited a maximum lasing temperature of 110 °C. The VCSEL threshold current is determined by the degree of mismatch between the peak gain and the cavity mode wavelength. Thus, the optimal extent of lasing mode detuning as a result of temperature changes is required for each specific application [39].

Figure 8. Temperature dependence of the threshold current under CW operation.

The long-cavity structure strongly affects not only the thermal resistance but also the transverse mode in VCSELs because the normalized effective index difference ($\Delta n_{eff}/n$) decreases even for SiO₂-buried layers of the same thickness in Figure 2b, and the diffraction loss of higher-order-modes increases, compared to the short-cavity structure. Furthermore, the thermal lens effect in the long-cavity structure must fade off at the same dissipated power because of the change in the thermal resistance. In general, low divergent output beams are preferred for many applications because they allow for the use of simple optics and exhibit high brightness. Yeh et al. have demonstrated a small full width at half maximum (FWHM) divergence angle of approximately 5° in a GaN-based VCSEL with a 3-μm aperture Si-diffusion-defined confinement structure [40]. The FFP and I-L characteristics at low power of small aperture VCSELs were also assessed so as to examine variations in the mode patterns beam divergence between the 10λ- and 5λ-cavity VCSELs. The I-L plots obtained from both types of device having 5.5 μm apertures during CW operation at 20 °C are presented in Figure 9a.

These data demonstrate that the 5 λ -cavity VCSEL exhibited a maximum power, threshold current density and threshold current of 6.6 mW, 9.7 kA/cm² and 2.3 mA, respectively. The smaller aperture size gives a lower threshold current and maximum power due to the volume effect, compared to the 8- μ m aperture VCSEL in Figure 6a. This tendency is the same for the 10- λ cavity VCSEL. From Figure 9a, the threshold current, threshold current density and maximum power of the 10- λ cavity VCSEL were 2.8 mA, 11.7 kA/cm² and 12.5 mW, respectively. These data also indicate that the high power performance of the 10- λ cavity VCSEL is superior to that of the 5 λ -cavity VCSEL with a small aperture due to the improvement in the thermal resistance.

Figure 9. (a) I-L characteristics of the 5 λ - and 10 λ -cavity VCSELs with 5.5- μ m aperture under CW operation at 20 °C. (b) Full width at half maximum (FWHM) of far field pattern (FFP) of the 5 λ - and 10- λ cavity VCSELs with 5.5- μ m aperture as a function of light output power. The insets show the FFP images at around 1 mW and 5 mW.

Figure 9b shows the FWHM divergence angle of the 5 λ - and 10 λ -cavity VCSELs with 5.5- μ m aperture as a function of their LOP. The insets show the FFP images at around 1 mW and 5 mW. An extremely small divergence angle of 4.2° was observed for the 10 λ -cavity VCSEL with around 1 mW. Furthermore, a narrow beam of 5.1° in FFP angle was observed even at a relatively high LOP of 5 mW, as shown in Figure 9b. The FFP image of the 5 λ -cavity VCSEL at 5 mW, on the other hand, was clearly different and shows a doublet multi-mode shape, although a small divergence angle of 4° was observed at around 1 mW. In this case, the divergence angle gradually spread out with an increase in LOP, indicating that the component of the higher-order-mode became dominant due to spatial refractive index changes, such as spatial hole burning and thermal lens effects. The improvement of thermal resistance and the large asymmetry of the mirror design possibly suppressed the spatial refractive index change in the 10 λ -cavity VCSEL. It is very interesting that such high power technologies established by edge emitting lasers are also effective in GaN-based VCSELs.

4. Conclusions

In conclusion, we have demonstrated a blue GaN-based VCSEL featuring a SiO₂-buried LOC structure, in which the reflectivity can be tuned by varying the AlInN/GaN DBR. Without the LOC structure, a conventional GaN-based VCSEL exhibits an extremely high transverse radiation loss, shown by internal loss measurements. The internal loss was significantly reduced by introducing the SiO₂-buried LOC configuration. This decrease in the internal loss, combined with an adjustment of the

cavity mirror reflectivity, resulted in the highest slope efficiency value so far recorded of 0.87 W/A and the highest η_d^{total} of 32% under pulsed operation, in addition to a maximum output power of 6 mW under CW operation. It is evident that controlling the cavity mirror and lowering the internal loss are both important with regard to increasing external differential quantum efficiency, slope efficiency and output power. On this basis, the present study obtained output power values of 15.7 and 2.7 mW at 20 and 110 °C, respectively. These represent the highest power values reported to date for a blue VCSEL based on GaN, and were achieved by reducing the reflectivity of the front cavity mirror to 99.1% while incorporating a long (10 λ) structure. The thermal resistance of the device relative to that of a 5 λ analogue was lowered from 1100 to 710 K/W, and these VCSELs were found to exhibit an elevated internal temperature of 434 K at their rollover point. Tuning the front mirror reflectivity in conjunction with these other modifications improved the device performance, giving an 8.9% wall-plug efficiency, 31% differential efficiency and an output power of 15.7 mW at 20 °C. In transverse mode control, the 10 λ -cavity VCSEL with a 5.5- μ m aperture exhibited a very narrow divergence beam of around 5° even at around 5 mW output power. These technologies and their superior performances may open the door to the practical use of VCSEL eyewear display. In a future study, we will investigate a W-class high-power VCSEL array in the blue wavelength range, with potential use in highly functional automotive headlamps.

Author Contributions: Conceptualization and device design, M.K.; epitaxial growth, T.A. and K.T. (Kazufumi Tanaka); fabrication process, S.K. and K.T. (Komei Tazawa); measurement and evaluation, M.K. and K.T. (Komei Tazawa); project administration, T.S.; supervision, T.T.; writing and original draft preparation, M.K.; writing, review and editing, T.T. and M.K.

Funding: This research received no external funding.

Acknowledgments: The authors thank Y. Kawakami, S. Tanaka, Y. Yokobayashi, S. Kubo, K. Takashima, K. Nakata and K. Kiyohara for their support during fabrication of the device and for helpful discussions. We also thank T. Tanabe and J. Sonoda for their encouragement during this work.

Conflicts of Interest: The authors declare no conflict of interest.

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