Characteristics of GaN-Based Photonic Crystal Micro-Vertical Light-Emitting Diodes for étendue-Limited Applications

Chun-Feng Lai

Department of Photonics, Feng Chia University, No. 100, Wenhwa Road, Seatwen, Taichung 40724, Taiwan

Email address
chunflai@fcu.edu.tw

Citation

Abstract
This study experimentally and theoretically demonstrated the emission aperture area characteristics of GaN photonic crystal (PhC) micro-vertical light-emitting diodes (µVLEDs) for étendue-limited applications. A highly collimated far-field profile of the GaN PhC µVLEDs was achieved using a 5-µm emission aperture and was attributed mainly to the Bragg diffraction of the PhCs. The GaN PhC µVLEDs within the standard full-stop/0.7 projection lens enhanced the light-collection power efficiency by approximately 85%, and the étendue value was 33 µm²-steradian. These results are valuable to the design of GaN µLED arrays for pico projector light sources.

1. Introduction

The unique properties of light-emitting diodes (LEDs) render them suitable for applications in indicator lights, optical communication systems, displays, and general lighting [1-2]. Recently, full LED arrays have been used in televisions for backlighting. Similarly, GaN micro LED (µLED) arrays have been applied in micro displays, transparent head-mounted display (HMD), and augmented reality devices [3-6] and are becoming increasingly attractive for pico projector development. Pico projector engines based on µLED arrays must feature constraints on the angular extents of the collimated far-field profile in their engine. Unfortunately, the étendue limit of a pico projector is primarily caused by the small emission size and numerical aperture (NA) limited [7]. The µLED array is compact because of its self-emissive property; thus, the number of optical components is reduced. The next generation of pico projector light engines must feature the higher directionality intensity for extracted light to reduce optical crosstalk and enhance the light-collection efficiency. In highly directional far-field profiles, photonic crystal (PhC) nanostructures fabricated on GaN thin-film vertical LEDs (VLEDs) have been demonstrated to enable high light-extraction efficiency and the modulation of emitted far-field distributions [8-9]. In our previous studies, we have revealed the guided mode extraction characteristics of GaN PhC µVLEDs that are limited by the finite extraction length of PhCs [10]. The emission aperture was fabricated on GaN PhC µVLEDs, which served as a gradual guided mode filter that obtained highly directional far-field profiles [10-11]. In addition, the extraction length of the fundamental mode in double-embedded PhCs (DPhCs) used for extracting the guided mode in LEDs, that decreased to 21-39 µm [12-13]. Therefore, the guided mode extraction characteristics of GaN PhC µVLEDs can be optimized using DPhCs, and pico projector
light engines can incorporate GaN PhC µVLED arrays as a light source in the future. Thus, this study experimentally and theoretically examined the characteristics of étendue limited for various emission aperture areas of GaN PhC µVLEDs to efficiently couple the light emitted for pico projection applications.

2. Materials and Methods

The GaN-based PhC µVLED samples used in this study were the same as those mentioned in [10]. Figure 1(a) shows a cross-sectional view of the individual GaN PhC µVLED structures, in which various emission aperture diameters of 5, 30, and 50 µm were fabricated. The lattice constant $a$ and hole diameters $d$ of the square lattice were approximately 420 and 180 nm, respectively, and the etch depth was 150 nm (Figs. 1(b) and 1(c)).

Three-dimensional (3D) emitted far-field profile images were captured by imaging spheres (Radiant imaging, IS-LI) under the same 20 mA current conditions as used for the far-field profile comparison, and were thereafter normalized using peak intensity (Fig. 2). The emitted far-field angles ($\theta_{\text{far}}$) at half intensity for the 50, 30 and 5 µm GaN PhC µVLEDs were 94.7° (93.0°), 96.8° (92.9°) and 68.4° (65.3°), respectively, in the ΓX (ΓM) orientation. These results were based on the guided-mode extraction behavior of the GaN PhC µVLEDs [10]. Figures 2(a) and 2(b) show the circular beam output of the 50-µm GaN PhC µVLEDs; the solid angle $\Omega$ can be approximately expressed as

$$\Omega = \pi \sin^2 \alpha$$

(1)

where $\alpha (=\theta_{\text{far}}/2)$ is the half-light cone angle of far-field distribution. Figures 2(c) shows the half-light cone angle for three PhC emission aperture sizes of 47° (50 µm), 48° (30 µm), and 34° (5 µm) in the ΓX plane.

3. Results and Discussions

To determine how the half-light cone angle $\alpha$ of the emitted far-field distribution affects the light-collection power efficiency of the pico projector light engines, the light-collection power efficiency was defined as the ratio of the light output power of the half-light cone angle $\alpha$ divided by the total light output power and was estimated using the measured data shown in Fig. 2. The light output power was integrated from ±0° to plotted the angle, ensuring that the total power until ±90° was achieved. The light-collection power efficiency of the GaN PhC µVLEDs with varying f-numbers (f/#) was plotted (Fig. 3). The general f/# formula is expressed in (2) and can be approximated using a focus length (f) with a lens diameter (D) as follows:

$$f/# = f/D = 1/(2\sin \alpha)$$

(2)

where f/# defined the limited half-light cone that was accepted at angle $\alpha$. The minimum f/# for an aberration-corrected projection lens was 0.5. The light-collection power efficiency was the percentage of light emitted from the GaN PhC µVLEDs within the light source, and the f/# was established.
according to the projection optics. The f/# of the projection optics and the emission area of the GaN PhC µVLEDs established to match the étendue of the pico projector light engine. Therefore, 100% efficiency indicated that all of the light was transmitted within the étendue limited. In this ideal condition, the device preserved étendue.

Maximal light-collection power efficiency was achieved when the source étendue was smaller than the étendue limited of the subsequent optical system [16]. For pico projectors, the étendue is frequently limited spatially by the emission area of the light source and angularly by the NA of the projection lens. A larger étendue increases problems in the design of projection systems, such as increased size and weight. Therefore, an analysis of the étendue compared with the emission aperture area in various f/# can enable determining the appropriate étendue for a projection system. According to Eq.(3), the étendue of the GaN PhC µVLEDs with varying emission aperture sizes was calculated using individual emission aperture areas to compare the experimental étendue values. Figure 4 shows the plot of the experimental (□, ○, and Ð points) and theoretical (various dashed lines) étendue values as a function of the emission aperture area for a radius of 0 to 50 µm. The PhC emission aperture sizes of 5, 30, and 50 µm produced étendue values of 32.7, 2728.5, and 10138.9 µm²-steradian, respectively. Figure 4 shows that the étendue increased substantially with an increased emission aperture area. In addition, the standard full-stop f/2.0 projection lens had a smaller étendue value than did the others; this value was more conducive to designing a high cutoff emitted radiation shape. Thus, light sources must have a small étendue value for applications in pico projector light engines. For example, in this study, the pico projector volume was assumed to be 1 cm³ and the standard full-stop projection lens was f/2.0. Therefore, the projection lens diameter was 8.5 mm, enabling the half-light cone angle α of the GaN PhC µVLEDs to be within 30° and the light-collecting power efficiency to be approximately 46% (Fig. 3(b)). According to the experimental and theoretical results, further optimization of the light-enhanced far-field distribution of GaN PhC µVLEDs can be achieved using DPhC structures [12]. In addition, enhanced light extraction efficiencies and a highly directional far-field distribution can be obtained for applications in the GaN µLED arrays of pico projector light sources.

\[ E = \int [\cos \alpha \sin \theta d\theta] = \pi A_n \alpha = \pi A/[4(f/#)^2] \]  

To better elucidate the trends involved with the various angles α of the emitted far-field distribution, this study defined the highly directional far-field profile of a cos²(θ) (obtained α = 15°) and cos⁴(θ) (obtained α = 30°), where θ ranges from -90° to 90° (Fig. 3(a)). Figure 3(b) shows that the light-collecting power efficiency in the collection cone angles (f/#) strongly depended on the emitted far-field distribution of the GaN PhC µVLEDs. In this study, the directional far-field distribution of 5-µm GaN PhC µVLEDs involved adding the appropriate standard full-stop f/0.7 projection lens and enhancing the light-collecting power efficiency by more than 85% (Fig. 3(b)), compared with conventional nonimaging concentrators [14-15], thereby yielding compact and highly efficient components. In addition, Fig. 3 shows that a smaller half-light cone angle of the emitted far-field distribution can more light-collection efficiency in a pico projector light engine. For the collimated far-field distribution, the light-collection power efficiency increased with the reduced collection angle. The nearly Lambertian radiation distribution of 50-µm GaN PhC µVLEDs revealed poor light-collecting power efficiency. Therefore, the high collimated far-field distribution contributed to a stronger directional light enhancement in the pico projector light engine. In addition, optimizing the emitted radiation shape of GaN PhC µVLEDs was crucial for enhancing the uniformity of short focus lengths [7].

This study further examined the effects of f/# and the emission aperture area on the étendue, which was used a critical parameter that matches the light source with the pico projection system and embodies the relationship between the far-field profile divergence and cross-sectional area of the far-field profile. Consider that the surface of an emission aperture area A immersed in a medium of air (air refractive, n_air = 1.0) is crossed by emitted light that is confined to a half light-cone angle α. The formal definition of étendue (E) for the light crossing A is expressed in (3) and can be approximated for a flat plane with a uniform emission profile [7]:

\[ E = \int [\cos \alpha \sin \theta d\theta] = \pi A_n \alpha = \pi A/[4(f/#)^2] \]
4. Conclusions

In conclusion, this study measured and addressed the theoretical aspects of the étendue limited for various emission aperture areas of GaN PhC µVLEDs for pico projector light engine applications. The light-colllecting power efficiency of 5-µm GaN PhC µVLEDs within the standard full-stop \( f/0.7 \) projection lens was approximately 85%, and the étendue value was 33 µm\(^2\)-steradian. These results can facilitate developing of GaN µLED arrays for pico projector light engines that have high luminance outputs under the étendue limited conditions.

Acknowledgment

This work is supported by the National Science Council, and Ministry of Science and Technology in Taiwan, under contract numbers NSC100-2218-E-035-004, NSC101-2221-E-035-022, NSC102-2221-E-035-046, NSC102-2622-E-035-030-CC2, MOST102-2632-E-035-001-MY3, MOST103-2221-E-035-029, and MOST103-2622-E-035-007-CC2. The authors appreciate the Precision Instrument Support Center of Feng Chia University in providing the fabrication and measurement facilities.

References


