Utilizing Metasurfaces for Directional Control of LED Emission

Hanbo Xu, Zhiwei Men

Jilin University, Jilin 130015, China

Abstract. This study provides a detailed modeling and analysis of four different three-dimensional GaN-based LED structures. The results reveal that incorporating DBRs effectively focuses light and enhances the light extraction efficiency (LEE). Additionally, the integration of Metasurface in the Micro-LED+DBRs+M structure allows for precise control of light emission direction and further radiation focusing. Furthermore, in the Micro-LED+DBRs+M2 structure with improved periodic nanocolumns, the light beam can be deflected simultaneously in multiple directions. These findings offer new possibilities for the advancement of LED technology.

Keywords: GaN-based LED, DBRs, LEE, Metasurface.

1. Introduction

Gallium Nitride (GaN) based LEDs are revolutionizing lighting and display technologies due to their energy efficiency, longevity, environmental friendliness, and versatile light quality. These LEDs are increasingly replacing conventional lighting in various settings, including general lighting, automotive, and displays, as highlighted in recent studies. [1-4]Notably, their small size and controlled light emission make them ideal for innovative applications like Virtual Reality (VR) and Augmented Reality (AR) technologies. Micro-LEDs, a subset of LEDs, stand out for their exceptional brightness and resolution, making them ideal for VR applications. Their unidirectional emission reduces optical crosstalk and improves image quality, essential for 3D displays and VR environments.[4-8]

However, the luminous efficiency of leds is still low, which seriously limits the application and development of these light sources. [9-11]When light reaches the interface between the semiconductor material and the ambient air, total internal reflection occurs due to the large refractive index difference, resulting in the light returning to be absorbed by the semiconductor or adopting the waveguide mode. Only light at smaller angles smaller than the critical reflection Angle can be released into the air. All these factors lead to a very low efficiency of LED, generally around 4% [12-14], which seriously hinders the development and application of LED.

The integration of metasurface structures with Micro-LEDs enhances their light extraction efficiency(LEE)and allows for controlled emission angles, crucial for directional emission in VR applications. For example, to improve LEE and enhance spectral narrowing, Ai, J. et al reported a combination of their selective overgrowth approach developed very recently and epitaxial lattice-matched distributed Bragg reflectors (DBRs) embedded to prepare ultra-small, ultra-compact and ultra-efficient InGaN microlight-emitting diodes(μLEDs) with narrow Spectral Line Width.[15]Huang, J. et al proved that reported GaN-based RC micro-LEDs have the potential to be used in the display panel for AR applications in a variety of scenarios, including AR glasses, and head up display for cars and airplanes.[16]This technology not only improves display brightness but also enables the realization of polarized Micro-LEDs, enhancing the 3D effect in VR eyewear.[4]

Thus, The integration of complex photonic crystal structures has been a crucial method to enhance LEE in GaN-based or Micro LEDs. Ge, D. et al designed a new complex periodic photonic crystal structure containing two kinds of hemispheres on the surface of the planar LED, and a finite-difference time-domain method was used to optimize the hemisphere materials (ZnO, GaN, and SiC) and the structural parameters of the complex photonic crystal (the size of the hemisphere radius and the lattice constant of complex structure),which have led to an 8.3-fold enhancement in LEE compared to planar LEDs, offering a significant boost in performance.[17]Besides, by Lee, J. et al, incorporating two-dimensional photonic crystal patterns and angled sidewall deflectors into LEDs has been shown to improve surface-normal emission, thereby increasing the total surface emission and enhancing the overall efficiency of these light sources.[18]

To further improve LEE, the Micro-LED-VR model I built is shown in Figure 1. From bottom to top, they are: (1)Metal Layer(2)GaN/InGaN Quantum Well (3) TiO2/SiO2 Distributed Bragg Reflector (DBR) (4) Metasurface. The metal layer is not only considered for industrial use, but its reflectivity can reflect the light transmitted to the metal layer to improve the LEE. The more divergent light is focused through the interwoven structure of the distributed Bragg reflector, and then through the asymmetric dielectric surface microstructure on the metasurface to realize the control of the light direction,as shown in Figure 2.Its excellent brightness and monochromatic light will contribute to VR.

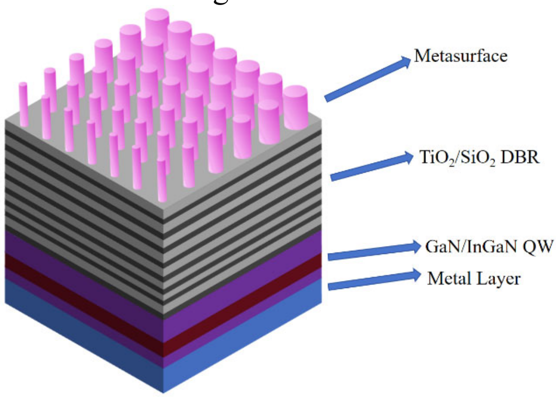

Figure 1. Micro-LED-VR model

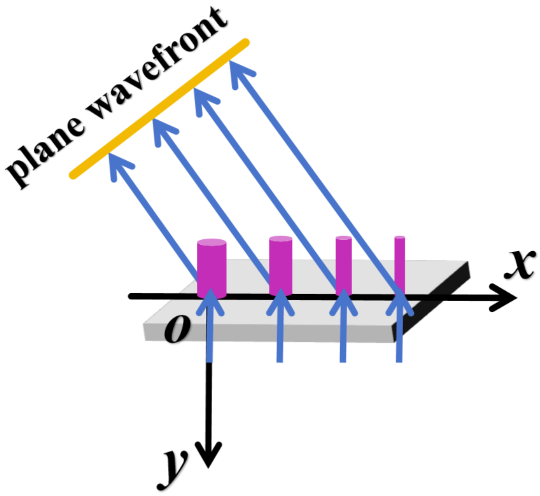

Figure 2. Control of light emitting direction on metasurface

2. Modeling and methodology

The three-dimensional (3D) GaN-based LED is illustrated in **Fig. 3.** The main structure of the LED with a radius of 1.5μm is depicted in **Fig. 3(A)**, composed from bottom to top of a 300nm-thick AL substrate (Metal Layer, refractive index of 1.0, for reflecting light emitted to the bottom to enhance light extraction), a 400nm-long FP emitting cavity (containing GaN/InGaN multiple quantum wells, with a refractive index of approximately 2.4). The GaN/InGaN multiple quantum wells include GaN/InGaN sub-quantum well arrays and GaN/InGaN top-quantum well arrays. The GaN/InGaN sub-quantum well array consists of 10 periods of GaN and InGaN overlapping with a thickness of 0.003μm each, totaling 0.06μm in thickness. The GaN/InGaN top-quantum well array consists of 5 periods of GaN with a thickness of 0.01μm and InGaN with a thickness of 0.005μm, totaling 0.075μm in thickness. The rest of the FP emitting cavity is composed entirely of GaN. The light source is a modulated sinusoidal excitation dipole light source with a wavelength of 445 nm, placed at the center of the bottom plane of the GaN/InGaN top-quantum well array. Perfectly matched layers (PML) are placed around the model boundaries to absorb external waves and avoid non-electromagnetic reflections, thereby enhancing the accuracy of the simulation results. This structure is denoted as "Micro-LED".

As shown in **Fig. 3(B)**, on top of the main structure, to transform the divergent light emitted from the main body into sharp, focused light, a staggered structure of Bragg reflection (DBRs) is constructed on the FP cavity. It consists of 9 periods of TiO2 and SiO2 overlapping with a thickness of 0.059μm and 0.085μm, respectively, totaling 1.296μm in thickness. This structure is denoted as "Micro-LED+DBRs".

As shown in **Fig. 3(C)**, aiming to achieve directional control of LED emission while maintaining light concentration, an asymmetric dielectric surface microstructure (Metasurface - Periodic Surface Crystal) is constructed to deflect or adjust the emitted light beam. On top of the DBRs, horizontally aligned rows of nanocolumns with a refractive index of 1.0, initially with a height of 445nm and starting radius of 75nm, decreasing by 5nm from right to left with a spacing of 250nm, are arranged vertically with a periodic interval of 250nm. (**Fig. 3(C)** is schematic and not to scale.) This structure is denoted as "Micro-LED+DBRs+M".

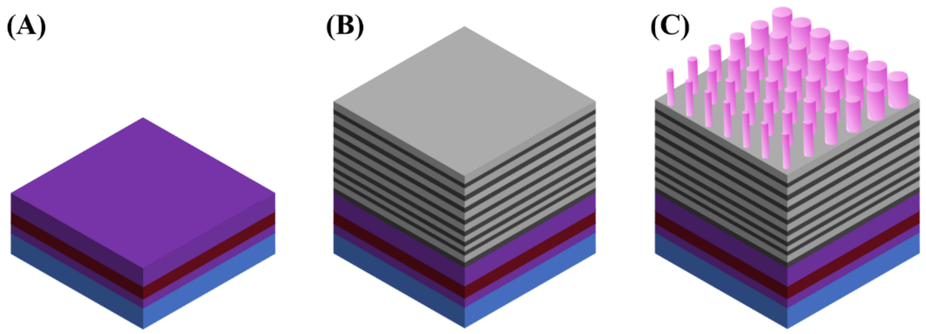

Figure 3. Basic information about device

The common feature among the three-dimensional modeling structures is readily discernible: they exhibit periodic symmetry along the vertical axis. To streamline computational demands, horizontal cross-sectional analyses were performed on the three-dimensional structures, focusing on the light emission characteristics of a two-dimensional cross-section. This approach effectively captures the overall light emission behavior of the entire three-dimensional LED model. Utilizing the device depicted in **Fig. 3(C)** as a case study, a horizontal cross-sectional representation for two-dimensional modeling is presented in **Fig. 4.**

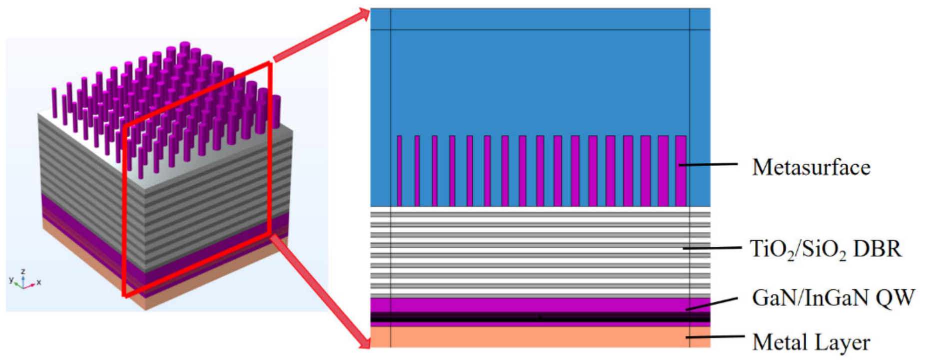

Figure 4. The process of two-dimensional modeling

Constructing from bottom to top, the structure includes a 300nm-thick AL substrate (Metal Layer), a 400nm-long FP emitting cavity (containing a total thickness of 135nm GaN/InGaN multiple quantum wells, with a modulated sinusoidal excitation dipole light source distributed at the center of the bottom plane of the GaN/InGaN top-quantum well array), DBRs with a total thickness of 1.296μm, and a Metasurface. Additionally, perfectly matched layers (PML) are constructed around the model to absorb external waves and prevent non-electromagnetic reflections. Simulations were conducted to compare the electric field and radiation direction of three LED structures: "Micro-LED," "Micro-LED+DBRs," and "Micro-LED+DBRs+M." This is illustrated in **Fig.5 ,Fig. 6 and Fig.7.**

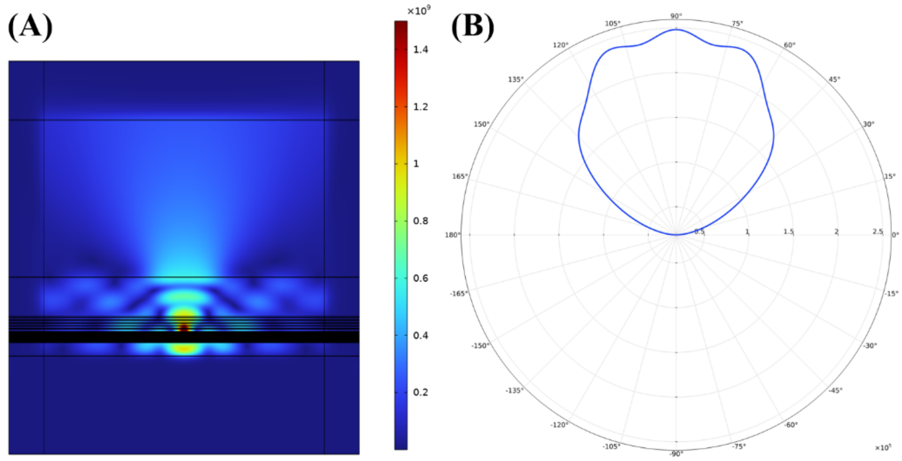

Figure 5. Simulation Results of Electric Field and Radiation Direction for "Micro-LED"

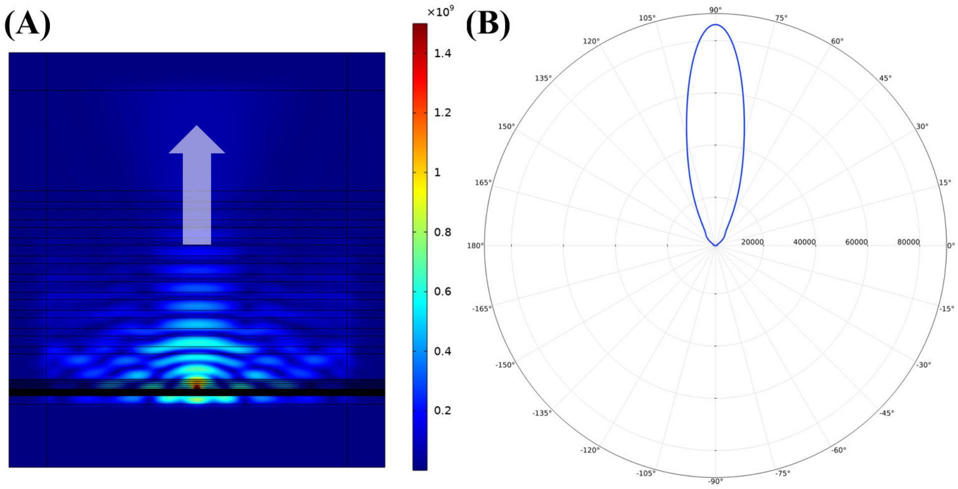

Figure 6. Simulation Results of Electric Field and Radiation Direction for "Micro-LED+DBRs"

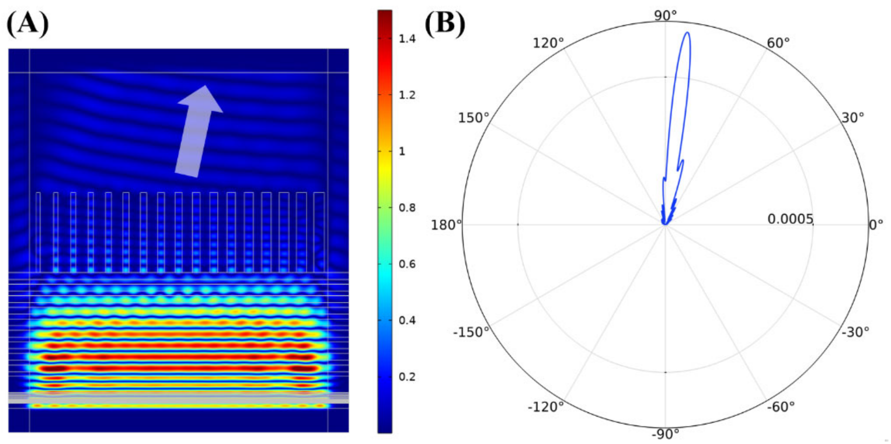

Figure 7. Simulation Results of Electric Field and Radiation Direction for "Micro-LED+DBRs+M."

To further control the light emission direction and deflect the light beam simultaneously towards multiple directions, a new Metasurface was constructed, denoted as "Micro-LED+DBRs+M2". As shown in **Fig.8**,it consists of nanocolumns with a small middle radius (35nm) and increasing radii towards both sides (increasing by 5nm each step), with a refractive index of 1.0. These nanocolumns are horizontally aligned in rows and vertically arranged with a periodic interval of 250nm.

Similarly, due to the periodic symmetry along the vertical axis, horizontal cross-sectional analyses were conducted on the three-dimensional structure to study the light emission characteristics of a two-dimensional cross-section, reflecting the entire three-dimensional structure. The process of constructing the two-dimensional COMSOL structure is as described earlier. Following construction, simulations were conducted to compute the electric field and radiation direction, as depicted in **Figure 9.**

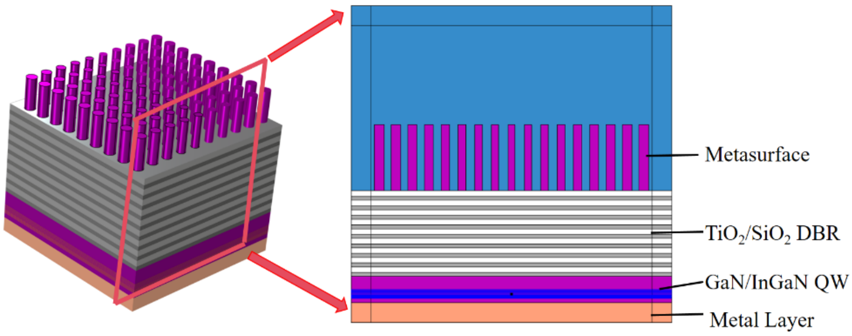

Figure 8. The Two-Dimensional Modeling Process of "Micro-LED+DBRs+M2"

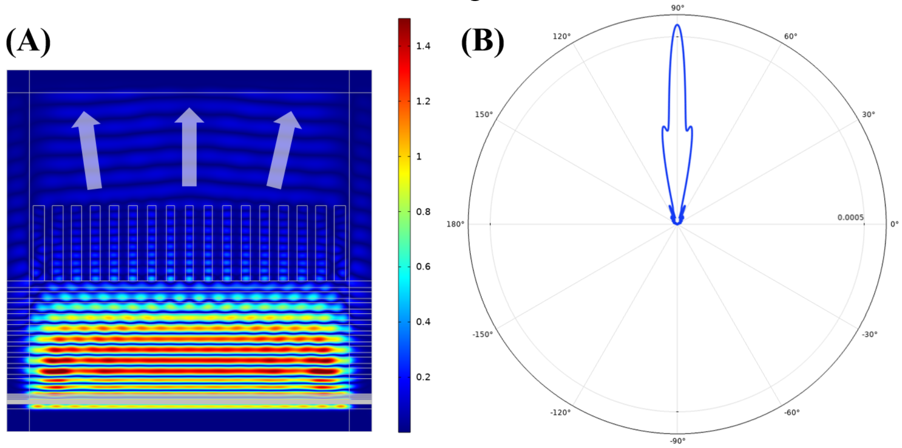

Figure 9. Simulation Results of Electric Field and Radiation Direction for "Micro-LED+DBRs+M2"

3. Result and Discussion

By comparing the electric field maps of "Micro-LED" , "Micro-LED+DBRs" , and "Micro-LED+DBRs+M" in **Fig.5(A), Fig6(A) and Fig.7(A)**, several observations can be made: The electric field of the Micro-LED, comprising only the AL substrate and the FP cavity, exhibits a divergent and undirected pattern (as indicated by the outlined divergent region in the figure). Despite reflection by the AL substrate, the emitted light continues to diverge in air, with an uneven distribution and relatively weak intensity. The introduction of DBRs significantly concentrates the emission direction of the Micro-LED, with the most concentrated emission occurring at an angle of 90° (as indicated in the figure). Following emission, the electric field distribution becomes more concentrated and exhibits higher intensity, indicating the successful concentration of divergent light by the DBRs and an enhancement in light extraction efficiency (LEE). Upon integration of the Metasurface, a noticeable deflection in the electric field direction can be observed after passing through the Metasurface (as indicated in the figure), with a sustained high intensity. This demonstrates the successful directional control achieved by the asymmetric Metasurface, as evidenced by its influence on the shape of the light beam, as depicted in the figure.

By analyzing the radiation direction of the Micro-LED **Fig.5(B), Fig6(B) Fig.7(B)andFig. 9(B)**, and subsequently plotting and measuring the angles, we obtained the angular ranges and the angles where radiation is most focused for the three structures:

Table 1. Radiation Angles of the Micro-LED

device	Angle（degree）
Micro-LED	3.5~173.4
Micro-LED+DBRs	42.2~134.8
Micro-LED+DBRs+M	58.1~106.8
Micro-LED+DBRs+M2	64.3~115.7

By comparing the first three structures, it is evident that the radiation of the Micro-LED containing only the AL substrate and FP cavity diverges without a specific direction. However, with the addition of DBRs, the radiation of the Micro-LED becomes significantly concentrated, with the most focused radiation occurring at an angle of 90°. Furthermore, upon integration of the Metasurface, it is evident that the radiation direction is deflected and further focused after passing through the Metasurface, with the most focused radiation occurring at an angle of 84°. This demonstrates the successful control of the emission direction. These findings not only validate the conclusions drawn from the electric field simulations but also suggest that the constructed periodic photonic crystal can further focus radiation.

With the improved periodic nanocolumns in "Micro-LED+DBRs+M2," as observed in **Figure 9(A)**, it can be seen that the electric field has three directions after passing through the Metasurface, successfully achieving simultaneous deflection of the light beam towards multiple directions. Combining Figure **9(B)** and Table 1 reveals the main lobe (90°) and side lobes (80°, 100°), with the energy still concentrated in the main lobe (90°). The schematic representation of the results is depicted in **Figure 10**.

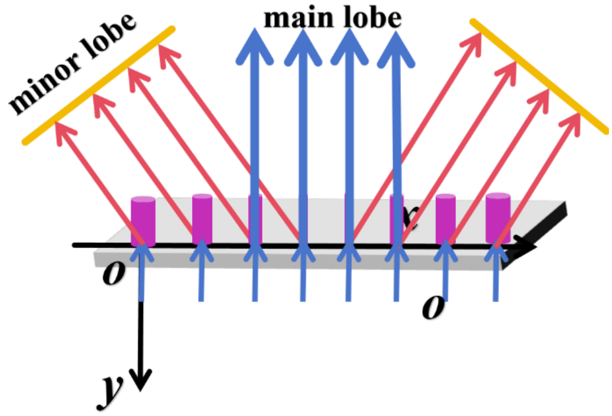

Figure 10. Illustration of Electric Field and Radiation Direction Simulation Results for "Micro-LED+DBRs+M2"

4. Conclusion

The main structure of the Micro-LED exhibits a relatively divergent and weak electric field distribution; however, in the Micro-LED+DBRs structure, the DBRs successfully focus the divergent light, concentrating the electric field distribution and significantly enhancing the light extraction efficiency (LEE). Incorporating the Metasurface into the Micro-LED+DBRs+M structure maintains a strong electric field intensity while effectively controlling the emission direction through its asymmetric dielectric surface microstructure, as well as further focusing the radiation. Following the improvement of the periodic nanocolumns, the Micro-LED+DBRs+M2 achieves simultaneous deflection of the light beam towards multiple directions.

These results demonstrate the potential of DBRs and Metasurface in optical manipulation. In subsequent studies, increasing the size difference between the nanocolumns on both sides can concentrate the energy on the side lobes to achieve complete deflection of the beam towards multiple directions.

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ORCID ID

Hanbo Xu, the first author,undergraduate student at Jilin University, majoring in Physics (Sino-foreign cooperative education), E-mail: 17686793889@163.com.

Zhiwei Men,corresponding author,Key Laboratory of Physics and Technology for Advanced Batteries, College of Physics, Jilin University, Changchun 130012, E-mail:zwmen@jlu.edu.cn.

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