Azimuthally isotropic irradiance of GaN-based light-emitting diodes with GaN microlens arrays

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Abstract: In this paper, the irradiance-modifying concept is proposed by introducing a microlens array on the p-GaN layer of GaN-based light-emitting diode (LED). Every microlens can locally modulate photons emitting from a micro-scaled active region of multiple quantum wells (MQWs) just beneath the microlens. The azimuthally isotropic irradiance from the GaN-based LED with microlens arrays is demonstrated numerically and experimentally. To realize such a novel LED, one-dimensional GaN microlens array with a period of 1.6 μm and a filling factor of 0.64 are fabricated by using dry etching. According to experimental results, the azimuthally isotropic light emission of proposed LED is observed. By using the angular-resolved photoluminescence, its intensity variation corresponding to the azimuth angles is as low as 10% within the angle region of ±50°.

OCIS codes: (230.3990) Micro-optical devices; (230.3670) Light-emitting diodes.

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1. Introduction

GaN-based light-emitting diodes (LEDs) are becoming more and more appealing in various applications from indicator lights to solid-state lighting due to their superior performances of energy efficiency, high reliability, and versatile colors. However, as considering LED lighting a replacement for fluorescent lighting, several characteristics such as brightness, color uniformity, and uniform irradiance should be taken into account. The brightness of LED lighting strongly related to output efficiency of LED chips is the first priority among these characteristics. Several approaches have been proposed and demonstrated to improve the output efficiency of GaN-based LED chips, such as surface texturing [1-3], photonic crystals (PhCs) [4, 5], micrometer-scale LEDs [6, 7], proper substrate shaping [8], thin GaN structures [9], and flip-chip packaging [10]. A better color uniformity can be obtained in LED lamps or lighting modules by arranging the LED chips in certain sequences and patterns [11] or altering the form factor of phosphor-coating design [12, 13].

Various LED array configurations designed to achieve the uniform illumination on a target plane by optimizing LED-to-LED spacing [14] and arranging the LED array on a spherical surface [15] have been proposed. As considering compact lighting systems, directly modulating the emitting light pattern of a LED chip by adjusting its geometric parameters is important in applications such as projection TV light engines and direct flat panel display illumination. Several light-pattern modulation schemes have been reported, including theoretical demonstrations of etching photonic crystals [16] and photonic quasi-crystals [17] into the top emitting surfaces of LEDs or the experimental demonstration of monolithically integrated microlenses into sapphire substrates of LEDs [18]. Among these approaches, the ordered surface patterning of photonic (quasi-)crystals can be applied to design various azimuthally anisotropic irradiances from LEDs [16, 17]. The GaN micro-LEDs with monolithically integrated microlenses on the sapphire rear face can improve the directionality of the light emitted [18]. Unfortunately, the scheme of tailoring geometric parameters of LED chips to demonstrate azimuthally isotropic irradiances is not yet realized.

In this paper, the local modulation of photons within a micro-scaled region of MOWs just beneath the GaN microlens is proposed. We present the first experimental demonstration of the azimuthally isotropic irradiance from GaN-based LEDs. The azimuthally isotropic light emission with an intensity variation less than 10% is observed within the emitting angles of ±50° by using the angular-resolved photoluminescence.

2. Numerical simulation of GaN-based LEDs with microlens arrays

The proposed structure of LED grown on a sapphire substrate, as illustrated in Fig. 1, includes an n-GaN layer, multiple quantum wells (MQWs), and a p-GaN layer with microlens arrays. The microlenses fabricated on the p-GaN layer plays a role to modulate the emitting photons just beneath the microlenses. As illustrated in this figure, the structure parameters given in the numerical analysis include period of microlens array $\Lambda = 1.6$ μm, filling factor of microlens F $= 0 - 1$, p-GaN layer thickness $h_{pGaN} = 0.3$ μm, MQWs thickness $h_{MQWS} = 0.01$ μm, n-GaN layer thickness $h_{nGaN} = 4$ μm, p-GaN reflective index $n_{pGaN} = 2.5$, MQWs reflective index

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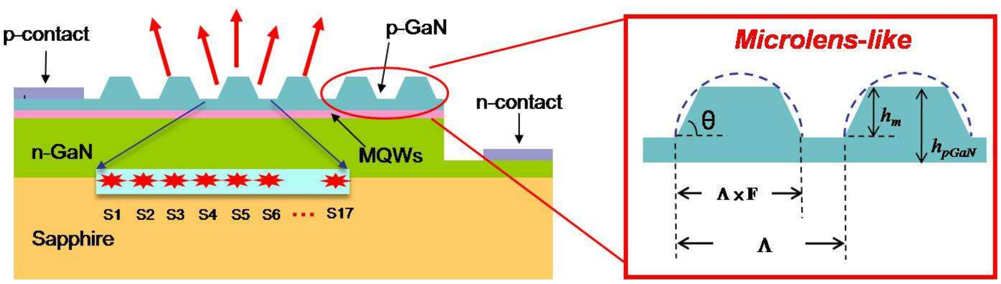

Fig. 1. Schematic diagram of the proposed GaN-based LED. The microlens patterns are employed on the top surface of the p-GaN layer.

n_{MQWS} = 2.4, n-GaN reflective index n_{nGaN} = 2.5, microstructure etching depth h_m = 0.185 μm, and microstructure slanted angle θ = 27.4°. The finite-difference time-domain (FDTD) analysis is used to study the irradiance behaviour of the proposed LED with microlens arrays. In order to describe the random propagation of unpolarized photons trapped within or escaping from LEDs, multiple TE and TM-polarized point sources with the wavelength of 460 nm are arranged within the MQWs region with an interval of 100 nm. In one identical period of the microlens, the average number of point sources is 16. As shown in Fig. 1, there are 17 points (S1 – S17) uniformly located in the MQWs region underneath one identical period of microlens array. Two outer point sources are shared with neighboring microlenses. To facilitate the numerical simulation, the computation window of 160 × 80 μm^2 with a spatial discretization of 20 nm is employed under the limitation of computer memory. Figure 2 shows the simulated angular radiation patterns emitting from the proposed LEDs with microlens arrays of various filling factors, including F = 0, 0.4, 0.64, and 1. The four emission patterns are normalized to unity intensity at their maximum values. Among these four cases, the filling factor of 1 is the planar type with the p-GaN layer thickness of 0.3 μm. The filling factor of 0 means the p-GaN layer of the planar type is etched down to 0.115 μm. Two different filling factors F = 0.4 and 0.64 are applied to demonstrate the modulation effect of microlens with different sizes. As shown in this figure, a Lambertian light pattern emitting from the planar LED is agreed with the theoretical prediction. The angular radiation patterns are varied with the filling factors of microlenses. As indicated in this figure, the azimuthally isotropic light emission with an intensity variation less than 10% is observed within the emitting angles of ±50° for the case of F = 0.64.

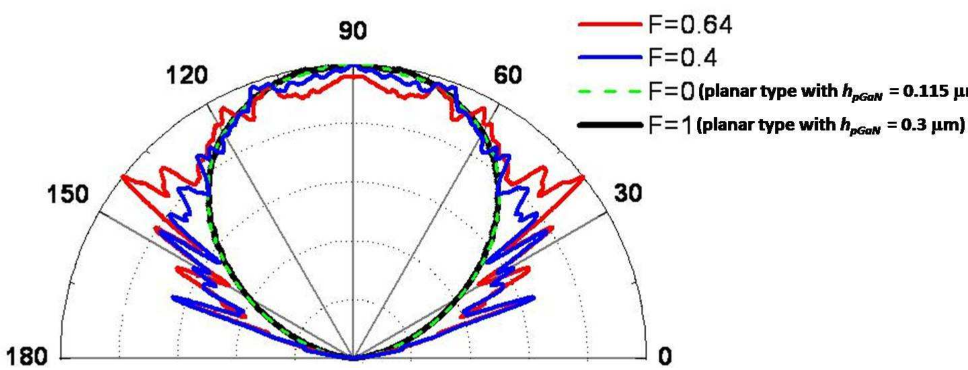

Fig. 2. Angular radiation patterns emitting from the proposed LEDs with microlens arrays of filling factors F = 0, 0.4, 0.64, and 1.

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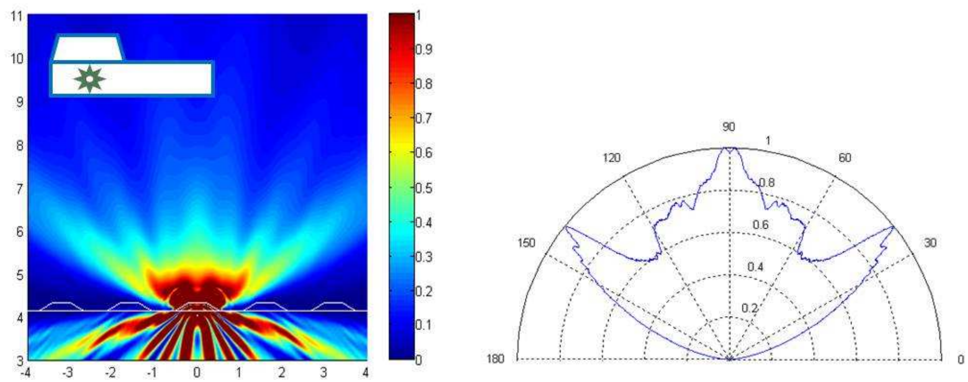
3. Light extraction of single point-source under modulation of microlens

In order to understand the azimuthally isotropic irradiance of the proposed GaN-based LED with a filling factor of 0.64 for the microlens array, the spatial modulation due to a microlens on a single point source is demonstrated by using the FDTD method. The single point source is chosen for providing a good resolution for clearly observing the spatial modulation caused by the microlens. According to specific positions of single point sources arranged in the MQWs beneath one identical period of the microlens array, the spatial modulation of microlens can be classified into three categories including the case A of full modulation, the case B of partial modulation, and the case C of non-modulation.

Figure 3(a) demonstrates light emits from the proposed LED of the case A with the single point-source arranged in the MQWs just beneath the central part of microlens. As shown in this figure, most of photons escape from two slanted surface due to their larger light-escape cones. It is notable that the radiation pattern as shown in Fig. 3(b) possesses three peak intensities at θ = 0° and ±50°. It means that the two-lobe near-field radiation pattern of the case A gradually converts into the three-peak far-field pattern. The total intensity integration of angular radiation pattern of the case A is 58.74.



(a) (b)

Fig. 3. The case A of full modulation. (a) Poynting intensity distribution of the proposed LED with the single point-source arranged in the MQWs beneath the central part of microlens. (b) Radiation pattern.

Figure 4(a) demonstrates light emits from the proposed LED of the case B with the single point-source arranged in the MQWs just beneath the right corner of microlens. In this figure, most of photons escape from the right slanted surface and form a single-lobe radiation pattern as illustrated in Fig. 4(b). The total intensity integration of angular radiation pattern of the case B is 12.58. It means that the laterally shift of a point-source corresponding to the central position of microlens would degrade the coupling effect of microlens.

Figure 5(a) demonstrates light emits from the proposed LED of the case C with the single point-source arranged in the MQWs just beneath the planar p-GaN layer between two microlenses. In this figure, photons directly escape from the planar p-GaN surface and form a bat-wing radiation pattern as illustrated in Fig. 5(b). The total intensity integration of angular radiation pattern of the case C is 27.47. As compared with the case A, it is almost 2-fold reduction in the light extraction from the planar p-GaN surface. Moreover, the bat-wing radiation pattern reveals that the microlenses still modulate the emitting light pattern into that with two peak intensities at θ = ±30° although almost photons penetrate into the air from the planar interface.

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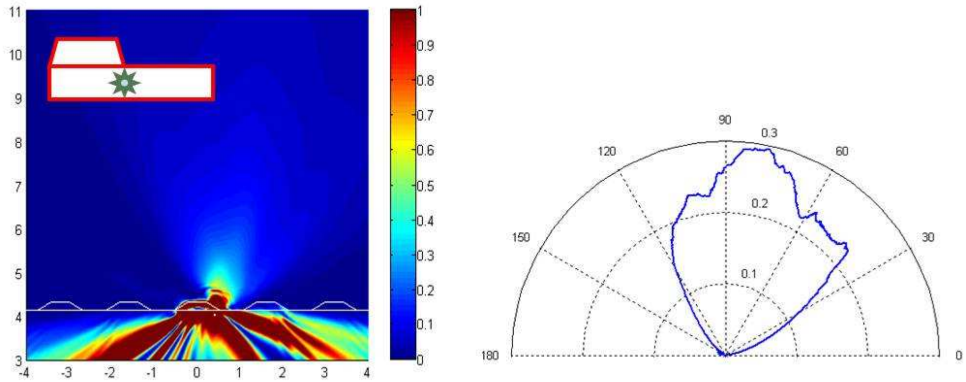
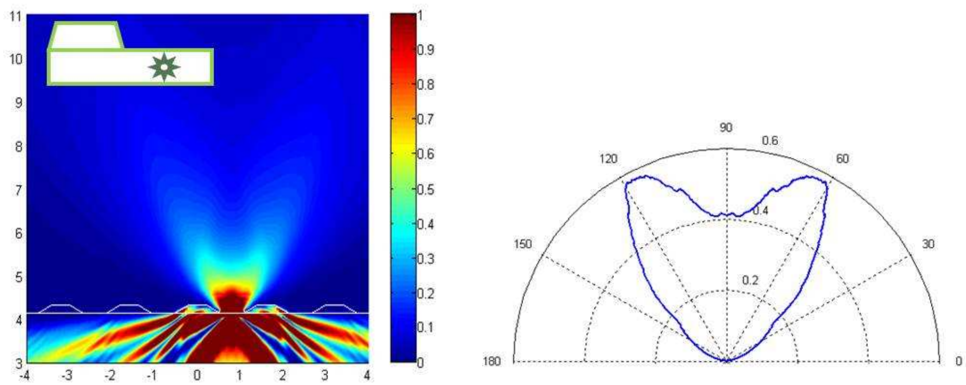


(a) (b)

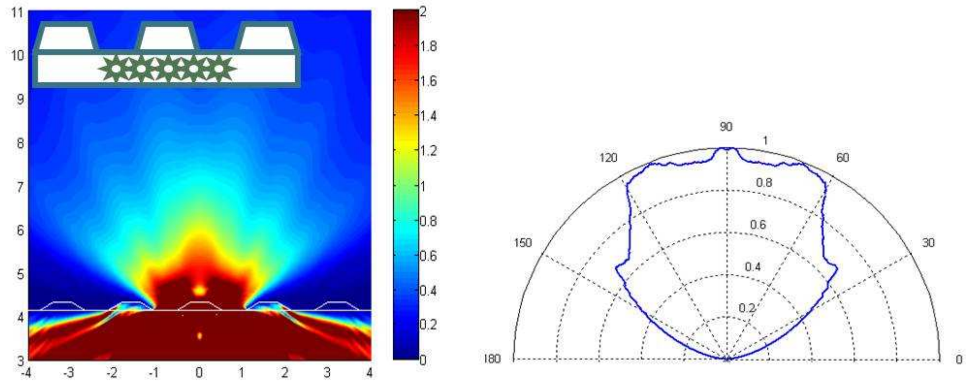
Fig. 4. The case B of partial modulation. (a) Poynting intensity distribution of the proposed LED with the single point-source arranged in the MQWs beneath the right corner of microlens. (b) Radiation pattern.



(a) (b)

Fig. 5. The case C of non-modulation. (a) Poynting intensity distribution of the proposed LED with the single point-source arranged in the MQWs beneath the planar p-GaN layer between two microlenses. (b) Radiation pattern.

In order to combined the coupling effects of cases A, B, and C on the irradiance feature of proposed LED, a FDTD numerical model with five point sources in one identical period is established as shown in the inlet of Fig. 6(a), which demonstrates light emits from the proposed LED with five point sources arranged in the MQWs just beneath one identical period of the microlens. In this figure, most of photons escape from two slanted surface as illustrated in Fig. 3(a). It means the coupling effect of case A would be a dominant factor for light extraction. However, the combination of three coupling effects of cases A, B, and C forms a uniform light pattern within ±30° as shown in Fig. 6(b). Moreover, if the FDTD numerical model with five point sources in one identical period is extended to be the one with seventeen point-source, the light emits from the proposed LED and its related light pattern are shown in Figs. 7(a) and 7(b). With a dense point-source arrangement, the modulation effect of the proposed structure would be evident that the uniform emitting light pattern spreads from ±30° to ±50°. For completely appearing the light pattern modulation of microlens, the pitch of point-source should be reduced to 100 nm as the case demonstrated in Fig. 7. In the proposed numerical simulation, the pitch of point-source is set as 100 nm to satisfy the calculation accuracy.



(a) (b)

Fig. 6. The combinations of case A, B, and C. (a) Poynting intensity distribution of the proposed LED with five point sources arranged in the MQWs beneath one identical period of the microlens. (b) Radiation pattern.

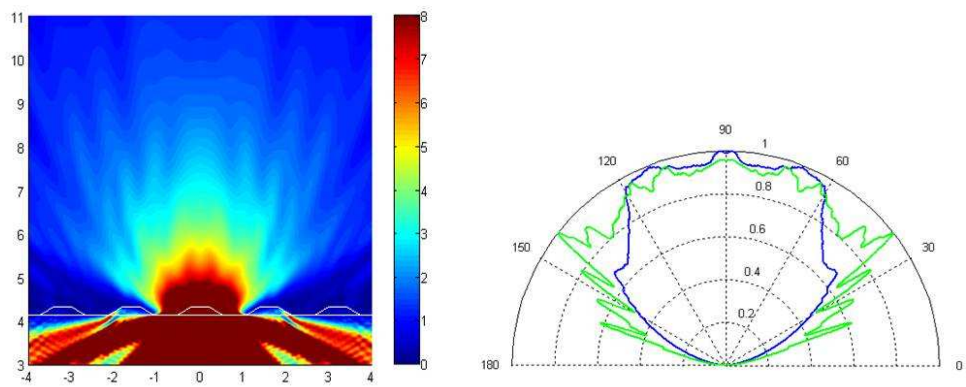


Fig. 7. Combinations of case A, B, and C with dense point-source. (a) Poynting intensity distribution of the proposed LED with seventeen point-source arranged in the MQWs beneath one identical period of the microlens. (b) Radiation pattern of seventeen point-sources (green line).

4. Experimental results

The microlens array is constructed on the p-GaN layer to investigate the feasibility of modulating the emitting light patterns of LEDs. Initially, intended microlens profile with a period of 1.6 μm is defined in PMMA by e-beam lithography. Then, the patterned PMMA on the p-GaN surface is developed in a solution of methylisobutyl ketone and isopropyl alcohol. Finally, a following inductive-coupled plasma (ICP) dry etching process is used to transfer the patterned structure to the p-GaN layer. Figures 8(a) and 8(b) show pictures of fabricated microlens array observed by scanning electron microscope (SEM) and atomic force microscope (AFM), respectively. The microlens is observed with an average period close to 1.6 μm. The filling factor F corresponding to the average period is around 0.64. The lateral size of the area of fabricated microlens is over 1 mm × 1 mm.

In order to confirm the modulation in azimuthally isotropic irradiance of one-dimensional GaN microlens, the irradiance measurement of proposed LED is carried out by using an angular-resolved photoluminescence (PL) configuration. It is not an electroluminescencen (active operation) of a LED. As illustrated in Fig. 9, the measurement setup consists of He-Cd laser of 325 nm, a monochromator, a photomultiplier tube, a lock-in amplifier, a laser-line

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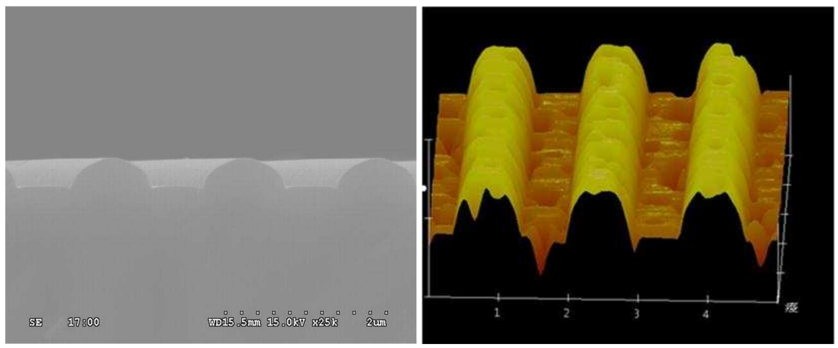
bandpass filter, a long-pass filter, an object lens of 20X magnification, and a fiber with a collimator. For showing the modulation of proposed structures clearly, the measured irradiance plane is perpendicular to the direction of one-dimensional microslens. With inserting a laser-line bandpass filter in the optical path of measurement system, the GaN-based LED can be pumped by using He-Cd laser of 325 nm only. The focusing beam of He-Cd laser with a diameter smaller than 1 mm is obliquely incident to the fabricated microlens region on the p-GaN surface. The most part of emitting light radiated from the inner of chip would couple into the air through the proposed structure surface. The fiber with a collimator in an angular-resolved irradiance measurement is adopted to collect the spatial emitting light. Under geometric arrangement of these optical components as shown in Fig. 9, an angular resolution of 4.4° can be obtained in the system. This angular-resolved irradiance measurement system is convenient to get the emitting light pattern of LEDs for photoluminescence configuration.



(a) **(b)**

Fig. 8. Images of fabricated microlens array by (a) SEM and (b) AFM.

Figure 10 shows the measured angular radiation patterns emitting from the proposed LED and the planar LED. For comparison, the simulated angular radiation patterns emitting from microlens LEDs is illustrated in this figure. As shown in this figure, the theoretical model can be used to precisely predict the irradiance of both LEDs. An azimuthally isotropic light emission with an intensity variation less than 10% within the emitting angles of ±50° is observed. It also means that a great amount of photons with higher spatial frequencies emit from the proposed LED as compared with the planar one. With the assistance of the microlens array, more photons induced in GaN-based LED can be effectively coupled into the air.

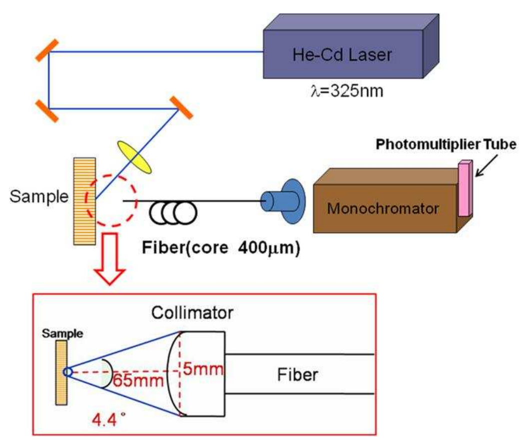


Fig. 9. Angular-resolved photoluminescence measurement setup.

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The deviation between the experimental and simulated results may result from the spatial resolution of angular PL system. However, the main feature of the uniform light pattern still agrees with the results obtained in the simulation. Moreover, it is referred that the surface roughness of microlens, as shown in Fig. 8(b), also induce the inevitable scattering that would degrade the uniformity of irradiance in certain degree. However, such surface roughness of microlens would enhance the light extraction efficiency. As compared with the planar one, the improvement of light extraction from proposed LEDs is about 250%.

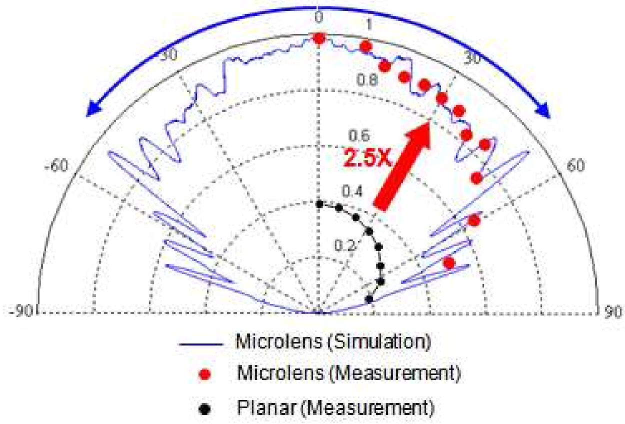

Fig. 10. Measured angular radiation patterns of microlens and planar LEDs.

5. Conclusion

The microlens array has been applied to a p-GaN surface of LED for purpose of modulating the light pattern uniformly within a cone of 100°. Through the simulation of FDTD and the measurement of PL angular-resolved, the proposed structure reveals the strong modulation effect in uniformity light pattern of LED light source. As a concluding remark, the proposed microlens-like structure provides modulation for LEDs as a spatial intensity uniformity device integrated with GaN-LEDs structure. The further work would be in designing the functional radiation pattern to increase the applications of LEDs light source. And we expect that further optimization of the angular-resolved irradiance measurement system such as the angular resolution and co-plane stability will promise high accuracy radiation pattern of LEDs.

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