Mechanisms of the Asymmetric Light Output Enhancements in *a*-Plane GaN Light-Emitting Diodes With Photonic Crystals

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***Abstract*— The unique properties of nonpolar GaN light-emitting diodes (LEDs) have the advantages of generating polarized light emission. The employment of asymmetric 2-D photonic crystals (PhCs) can further enhance the light polarization ratio. In addition, it was generally recognized that the Purcell effect can increase the internal quantum efficiency of the LEDs with PhCs. In this paper, we study the properties of optical modes from different crystal planes. The Purcell effect is analyzed based on the PhCs and material crystal orientations. With different transition probability of the polarized photons in valence bands, the corresponding Purcell effect enhancement on the quantum efficiency varies.**

***Index Terms*— Light-emitting diodes, non-polar GaN, photonic crystal, purcell effect.**

I. INTRODUCTION

LIGHT-EMITTING DIODES (LEDs) have found their wide applications in general lighting and backlight for flat panel displays. Despite their penetration to our daily life, the tremendous demand has driven people in the industry and academia to continue improving LED performance. For conventional LEDs, because the material growth direction is along polar *c*-axis, the energy band structures of the quantum wells (QWs) are tilted due to the induced piezoelectric polarizations and spontaneous polarization. The tilted bands separate electron and hole wavefunctions [1] and degrade the internal quantum efficiency. The effect is called quantum-confined Stark effect (QCSE). To reduce the internal polarization, an effective way is to fabricate LEDs with non-polar or semi-polar GaN crystalline orientations [2]. Due to the absence of the polarization-related electric field along the growth direction, non-polar GaN is nearly QCSE free, which ensures the enhancement of radiative recombination by the strong overlap of electron and hole wavefunctions [3], [4]. In addition to the performance improvement, non-polar epi-material has the advantage of generating polarized light. Because the biaxial stress in the QWs splits the valence bands into the several states, linearly polarized emission was observed in non-polar GaN LEDs [5]–[7]. Non-polar GaN light sources have the opportunity to be applied to the backlight of flat panel displays [8], which has the advantage of removing one polarization film. The degree of polarization depends on several material factors such as the crystalline orientations, the indium compositions and growth temperatures of the GaN LEDs [9], [10]. Moreover, the polarized light emission can be improved by photonic crystals (PhCs) [11]–[13]. The PhC structure offers both the advantages of better light extraction and higher degree of light polarization.

Furthermore, it was previously demonstrated that Purcell effect in the MQWs is strengthened by the resonance in LEDs with PhCs [14], [15]. The anisotropic biaxial stress in non-polar/semi-polar GaN LEDs raises an interesting question on the corresponding Purcell effect of photons from various valance band states and light polarization. In this work, we designed asymmetric two-dimensional PhCs on *a*-plane GaN LEDs. We established a model to study Purcell effect on polar and non-polar GaN LEDs. Since the transition probability of the polarized photons in different valence bands is different, Purcell effect depends not only on the PhC structures but also on the material crystalline orientations.

II. EXPERIMENTS

To enhance the polarized emission, PhCs were designed and fabricated on the surface of *a*-plane GaN LEDs. The detailed process steps were described elsewhere in [16]. For *a*-plane GaN crystal structure, as shown in Fig. 1, the *a*-axis is the growth direction while the *m*- and *c*-axis are in the lateral direction. The PhCs have the period of 260 nm along the *m*-axis and 470 nm along *c*-axis. The idea of having asymmetric PhCs is to enhance light polarization of the device. The scanning electron microscopic (SEM) image of the PhCs is shown in Fig. 1(a). The current spreading layer, mesa definition and metal contacts were fabricated subsequently in the process. The device structure of the *a*-plane GaN PhC LED is illustrated in Fig. 1(b).

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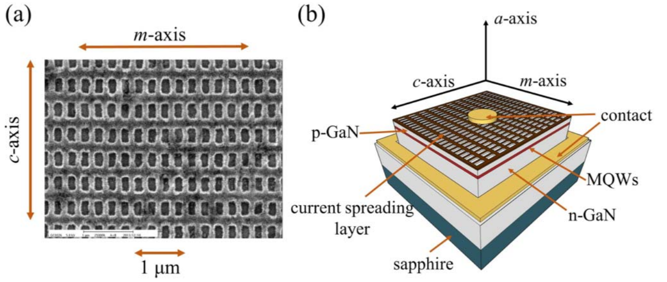

Fig. 1. (a) SEM image of the PhCs along the *m*- and the *c*-axis. (b) Illustration of the PhCs on the *a*-plane GaN LED. The PhCs were fabricated on top of the p-type GaN.

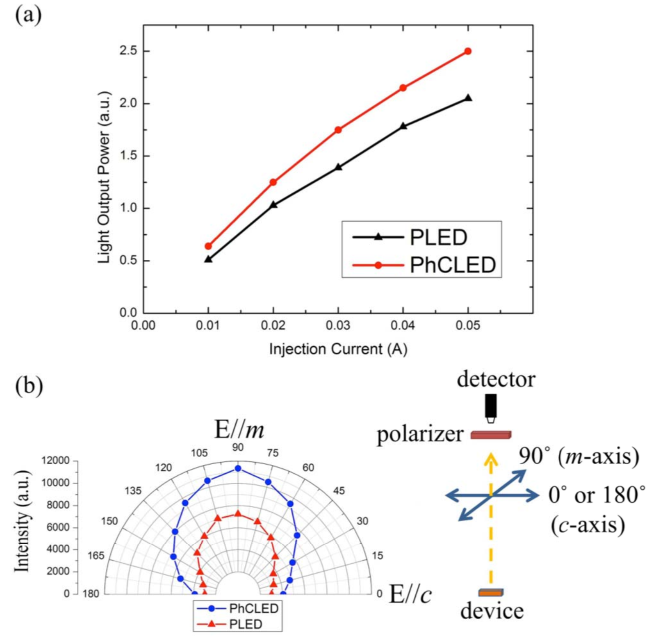

Fig. 2. (a) Total light output powers of PLED and PhCLED at different injection currents. (b) Light intensities of PhCLED and PLED at different polar angles in the vertical direction. The measurement was conducted by placing the detector on top of the chip with the insertion of the polarizer. The polar angle is adjusted by rotating the polarizer. The E//*m* modes are obtained by rotating the polarizer to 90° (parallel to m-axis), while E//*c* modes are at 0°.

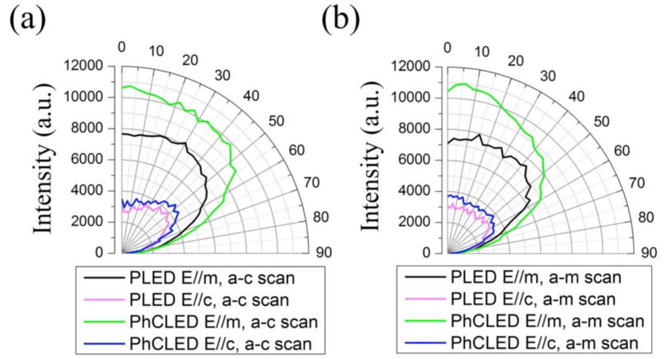

Fig. 3. Radiation profiles of E//*m* modes and E//*c* modes along (a) *a*-*c* plane and (b) *a*-*m* plane in PLED and PhCLED.

III. RESULTS AND DISCUSSION

A. Characterizations of Light Outputs

Optical properties of the photonic crystal LED (PhCLED) and the planar LED (PLED, the device without any PhC patterns) were first characterized. As shown in Fig. 2(a), at the injection current of 20 mA, light output of PhCLED is 21.4% higher than that of PLED, which is mainly attributed to the diffraction of the PhC structure. The contribution of E//m and E//c modes to light output in the vertical direction (surface normal) was then analyzed. The polarizer was placed in between the detector and device. And the detector for such a measurement was located right on top of the sample. The emission profiles of PhCLED and PLED are shown in Fig. 2(b). The degree in Fig. 2(b) is obtained by rotating the polarizer while the photo detector is still placed on top. For both devices, at 90° (the direction of linearly polarized light along the *m*-axis), E//*m* modes can be readily extracted because the direction of light polarization is parallel to the *m*-axis. Likewise, E//*c* modes are measured at 0° or 180°, at which the direction of light polarization is along the *c*-axis. The higher E//*m* mode light output is understood from the band split of non-polar *a*-plane material. For QWs grown on *a*-plane GaN orientation, the anisotropic biaxial strain results in the energy band separations. The valence bands split into the sub-bands of the $|\mathrm{Y}>$, $|\mathrm{Z}>$, and $|\mathrm{X}>$ states [13]. According to Fermi's golden rule, the transition in each state can be described by the corresponding electric dipoles which determine the direction of electric fields [11], [17]. Because of the valence band separations, the electric field of most polarized photons oscillates along the *m*-axis, while only a small portion of photons has the electric fields polarized along the *c*-axis. The enhanced polarized emission is observed in PhCLED, which further increases the intensity of E//*m* modes. The enhancement of light output by the PhC structure depends on the diffraction modes. More E//*m* photons are detected from PhCLED than those from PLED. The total light output of E//*m* and E//*c* modes are asymmetric with the presence of PhCs.

The above results indicate that the radiative characteristics of non-polar GaN LEDs are dependent on non-polar crystalline properties as well as the designated periodic arrangement of the PhCs. For PhCs with a small period, photons congregate within the small angular ranges due to the large lattice reciprocal vector [13]. The lattice reciprocal vector G ($G = 2\pi/a$, where a is the period of the PhCs) can change the out-coupled modes of in-plane k-vector $k'_{||}$, based on the diffraction condition ($k'_{||} = k_{g,||} + pG$, $k_{g,||}$ is the in-plane k-vector and p is an integer). With the smaller period, the lattice reciprocal vector G becomes large, and the guided modes tend to radiate towards the smaller angular scopes. In our experiment, the radiation profiles were measured on *a*-*c* and *a*-*m* planes, which E//*m* and E//*c* photons are collected, respectively. In Figs. 3(a) and 3(b), as compared with PLED, light output enhancements of PhCLED for both E//*m* modes and E//*c* modes are observed. It is worth mentioning that the PhCs in Fig. 1(a) is imperfect. It is mainly due to the interference during e-beam exposure. The effect will cause bandwidth broadening in the PhC energy bands

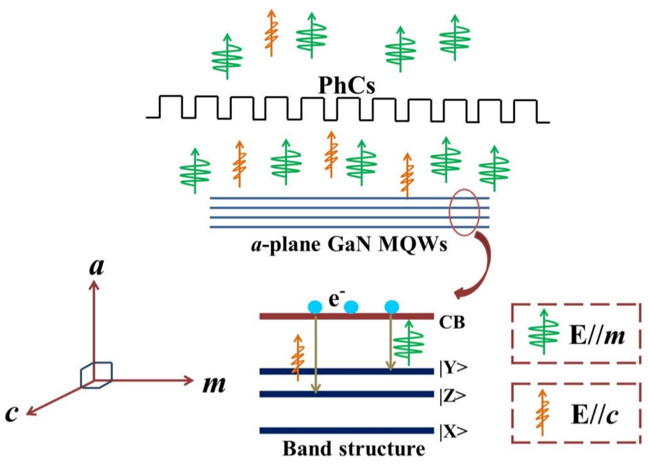

Fig. 4. Illustration of the photon (E//*m* and E//*c* modes) transmission in *a*-plane PhCLED. E//*m* and E//*c* photons are generated from CB-|Y> and CB-|Z> transitions, respectively. And both photons are diffracted by the PhC structure.

so that side lobes in the radiation patterns of Fig. 3 broaden accordingly. And the light extraction of E//*m* modes along both *a*-*c* and *a*-*m* planes is higher than that of E//*c* modes. In Fig. 3(a), the integrated intensities over all of the angles of E//*m* and E//*c* modes in PhCLED are increased by 29.4% and 12% on *a*-*c* plane, respectively. In Fig. 3(b), in a-m plane, E//*m* modes are increased by 29.4% while E//*c* modes are only enhanced with 12.6%. As to the measurement in the vertical direction, the light intensities of E//*m* and E//*c* modes are increased by 47.1% and 20.4% in PhCLED, respectively. The above results agree with our original design to achieve asymmetric light enhancements.

As to the light output polarization of the devices, the degree of polarization is enhanced by the PhC structure. When the angular profile was scanned along *a*-*c* plane, the degree of polarization is increased from 36.5% in PLED to 42.6% in PhCLED. Also in *a*-*m* scan, the degree of polarization is enhanced from 36.3% in PLED to 42.2% in PhCLED. Moreover, in the vertical direction, the degree of polarization increases from 39.7% in PLED to 47.8% in PhCLED. The above results indicate a strong diffraction for E//*m* modes by the asymmetric two-dimensional PhCs.

B. Model for Extracting Purcell Effect in the Device

Before we numerically compare the optical properties of the devices to understand Purcell effect, we first study light extraction paths of photons in *a*-plane PhCLED. As illustrated in Fig. 4, photons are detected after photon generation in the MQWs and followed by the diffraction of PhCs. In the band structure of *a*-plane GaN QWs, the injected electrons in the conduction band (CB) tend to recombine with holes in the ground |Y> state. A large number of E//*m* photons are thus generated in QWs. On the other hand, less E//*c* photons are generated because the probability of transition in the |Z> state is lower. In the corresponding crystal orientations, non-polar *a*-plane GaN is grown on the *a*-axis direction, and the generated E//*m* and E//*c* photons possess electric fields oscillating, respectively, along the *m*- and *c*-axis. E//*m* and E//*c* photons then interact with the PhC structure and are radiated to the air. The PhC periodic structure determines the photonic band profiles and light extraction efficiency of E//*m* and E//*c* modes.

There are two main mechanisms to improve LED efficiency by photonic crystals [14], [18]. First, the periodic surface patterns allow photons in the semiconductor to escape to the air by Bragg scattering so that the extraction efficiency of LED is improved. In our case, E//*m* modes have a higher extraction efficiency than E//*c* modes due to the design of two-dimensional PhCs. Second, the artificial PhC structure changes the spontaneous emission rate and enhances the internal quantum efficiency by Purcell effect ($F_p \equiv \Gamma_{lm}/\Gamma_{fr}$, where Γ_{lm} and Γ_{fr} are the spontaneous emission rates in the photonic environment and free space, respectively) [15], [19]. In *a*-plane PhC structure, Purcell effect modifies the emission rates of CB-|Y> and CB-|Z> recombination. Therefore, in addition to the extraction by the PhCs, Purcell effect affects the internal quantum efficiency and has the asymmetric enhancement of E//*m* and E//*c* modes.

Next, we study Purcell effect in the PhC structure based on the internal and external light extraction of the LEDs. The measured LED intensities are expressed by the following equation:

$$I_a^{\mathrm{PhC}} = \eta_{\mathrm{ext(a)}}^{\mathrm{PhC}} \cdot \eta_{\mathrm{int(a)}}^{\mathrm{PhC}} \cdot I_{\mathrm{injection}} \tag{1}$$

where $\eta_{\mathrm{ext(a)}}^{\mathrm{PhC}}$ and $\eta_{\mathrm{int(a)}}^{\mathrm{PhC}}$ are the extraction efficiency and internal quantum efficiency of PhCLED, respectively. $I_{\mathrm{injection}}$ is the injection carrier intensity at the injection current of 20 mA. The subscript parameter a describes the specific polarized modes. In our case, parameter a indicates E//*m* modes and E//*c* modes. Based on Eq. (1), the optical intensities of PhCLED and PLED in both vertical and integrated (over the whole angular domain) cases are compared for both E//*m* and E//*c* modes.

To understand how Purcell effect is influenced by the crystal orientation, we first compare the measured intensity of PhCLED with that of PLED. Ratios of intensities ($r_a = I_a^{\mathrm{PhC}}/I_a^{\mathrm{planar}}$) are shown in Table I, in which r_a of E//*m* modes ($r_{\mathrm{E}//m}$) is higher than that of E//*c* modes ($r_{\mathrm{E}//c}$) in both vertical and integrated light measurement. The higher $r_{\mathrm{E}//m}$ suggests the asymmetric enhancement in PhCLED. Furthermore, $r_{\mathrm{E}//m}/r_{\mathrm{E}//c}$ is related to the combined effect of the extraction efficiency and Purcell effect in PhCLED. The equation is expressed as:

$$\frac{r_{E//m}}{r_{E//c}} = \frac{\eta^{\mathrm{PhC}}_{\mathrm{ext}(E//m)}}{\eta^{\mathrm{PhC}}_{\mathrm{ext}(E//c)}} \cdot \frac{F_{P,E//m}}{F_{P,E//c}} \tag{2}$$

where $F_{P,\mathrm{E}//m}$ and $F_{P,\mathrm{E}//c}$ are factors of Purcell effect of E//*m* and E//*c* modes in the PhCs. As in our case, the value of $r\mathrm{E}//m / r\mathrm{E}//c$ (shown in Table I) higher than 1 indicates that the combined effect of the extraction efficiency and Purcell effect contributes to the larger light output enhancement of E//*m* photons, as compared with that of E//*c* photons.

The above discussion can't distinguish extraction efficiency from Purcell effect. To understand the role of Purcell effect, we fabricated the same PhC structure on *c*-plane

TABLE I

RATIOS OF INTENSITIES AND THE COMBINED INFLUENCES OF THE EXTRACTION EFFICIENCY AND PURCELL EFFECT

Ratio of light output intensity ($r_a = I_a^{\text{PhC}} / I_a^{\text{planar}}$) between PhCLED and PLED			
	Vertical	Integration (of all the angles)	
		a-c plane	*a-m* plane
E//*m* modes ($r_{\text{E}//m}$)	1.47	1.30	1.30
E//*c* modes ($r_{\text{E}//c}$)	1.20	1.12	1.13
Light output intensity ratio between $r_{\text{E}//m}$ and $r_{\text{E}//c}$ (by considering both the extraction efficiency and Purcell effect)			
	Measured Conditions		
	Vertical	E//*m* on *a-c* scan to E//*c* on *a-m* scan	E//*m* on *a-m* scan to E//*c* on *a-c* scan
$\frac{r_{\text{E}//m}}{r_{\text{E}//c}} = \frac{\eta^{\text{PhC}}_{\text{ext(E}//m)}}{\eta^{\text{PhC}}_{\text{ext(E}//c)}} \cdot \frac{F_{P,\text{E}//m}}{F_{P,\text{E}//c}}$	1.22	1.15	1.16

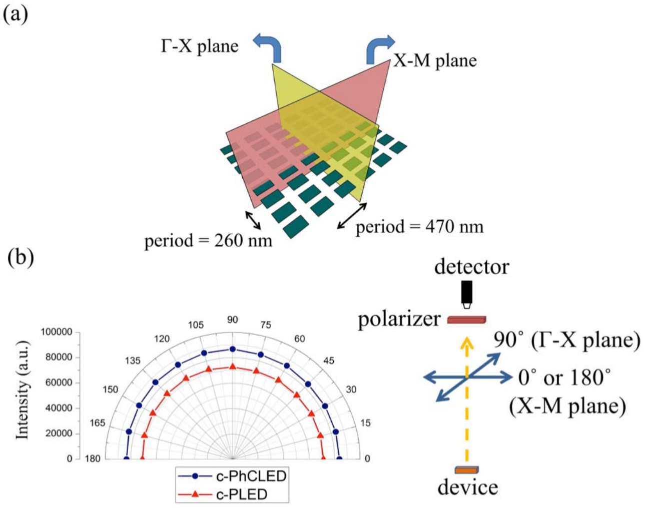

Fig. 5. (a) Measurement of the radiation profile from the *c*-plane LED. The radiation plane along the long PhC period (470 nm) is X-M plane while Γ-X plane is along the short period (260 nm). (b) Optical intensities of *c*-PhCLED and *c*-PLED at different polar angles (rotated with c-axis or. . .). The measurement setup is the same as in Fig. 2(b).

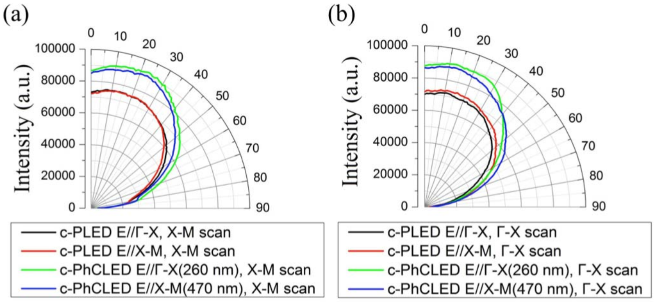

Fig. 6. Radiation profiles of *c*-PLED and *c*-PhCLED along (a) X-M and (b) Γ-X planes. For both devices, E//Γ-X (E//X-M) indicates that the electric field is along Γ-X (X-M) plane.

TABLE II

ENHANCEMENTS OF E//260 AND E//470 MODES IN *c*-PhCLED AS COMPARED WITH THAT IN *c*-PLED

	Vertical	Integration (of all the angles)	
		Along X-M plane	Along Γ-X plane
E//260	25.2%	20.3%	22.7%
E//470	20.8%	17.3%	16.7%

GaN LED. Due to the identical transition rate in the heavy- and light-hole states in *c*-plane GaN QWs, Purcell effect is regarded the same in all crystalline directions. As a result, the extraction efficiency is only correlated to the asymmetric PhC design in *c*-plane GaN epi-structure. Also, because the same PhC structures are fabricated on both *a*-plane and *c*-plane GaN LEDs, the extraction from *c*-plane PhC is the same as the *a*-plane PhC case. By understanding the extraction ratio between E//*m* and E//*c* photons in *a*-plane PhCLED, Purcell enhancement can be derived.

To verify, we prepare additional samples with conventional *c*-plane GaN LED epi-structure. The nomenclature of the PhC and planar devices on *c*-plane GaN is *c*-PhCLED and *c*-PLED, respectively. In order to correlate the scan direction of *c*-plane devices with that of *a*-plane, we define Γ-X and X-M planes for *c*-PhCLED and *c*-PLED. For *c*-plane GaN, Γ-X plane is similar to *a-m* plane (*a*-plane), and X-M plane to *a-c* plane (*a*-plane) because of the PhC periodic arrangement. In Fig. 5(a), *c*-PhCLED possesses the PhC periods of 260 nm and 470 nm along Γ-X plane and X-M plane, respectively. The angular emission profiles of *c*-PhCLED and *c*-PLED in the vertical direction are shown in Fig. 5(b). At 90°, the direction of electric fields can only exist along Γ-X plane, while at 0° or 180°, the electric fields are only along X-M plane. In *c*-PLED, it's not surprising to observe nearly the same intensity at both polarizations, because of weak energy band separations (of heavy- and light-hole states). On the other hand, as for the polarized emission properties of *c*-PhCLED, the intensities at 90° and 0° (or 180°) are different, which is attributed to the electric field interaction with the PhCs. Fig. 6(a) and (b) show the radiation profiles of *c*-PLED and *c*-PhCLED scanned along X-M and Γ-X planes, respectively. The light output enhancements of *c*-PhCLED over *c*-PLED are compared in Table II for the electric field parallel to 260 nm period (E//260 modes) and 470 nm period (E//470 modes). The intensity enhancement of E//260 modes is larger than that of E//470 modes, which is associated with the extraction efficiencies of the interaction of lateral propagation modes with the PhC lattice (see Table III), despite the same transition probability from conduction to valence band. For both PhCLED and *c*-PhCLED, we assume the same extraction efficiency when the electric field interacts with the same PhC periodic arrangement. Thus, light extraction from the GaN/air interface of E//260 for c-plane case will be the same as the E//*m* modes for the nonpolar case, while E//470 for the c-plane is the same as the E//*c* modes for the a-plane case. Based on Eq. (2), Purcell effects are derived from the extraction ratio of E//*m* modes to E//*c* modes in PhCLED, which is obtained from the optical properties of c-plane LEDs in Fig. 5 and 6.

TABLE III

RATIOS OF THE EXTRACTION EFFICIENCY IN *c*-PhCLED AND PURCELL EFFECT OF E//*M* MODES TO E//*C* MODES IN PhCLED

	c-PhCLED	PhCLED
	Extraction efficiency $(\eta^{c\text{-PhC}}_{\text{ext(E//260)}}/\eta^{c\text{-PhC}}_{\text{ext(E//470)}})$	Purcell effect $(F_{P,\text{E}//m}/F_{P,\text{E}//c})$
Vertical: Ratio of E//*m* (E//260) to E//*c* (E//470)	1.04	1.18
Integration of all angles: Ratio of E//*m* (E//260) along *a*-*c* (X-M) to E//*c* (E//470) along *a*-*m* (Γ-X)	1.03	1.12
Integration of all angles: Ratio of E//*m* (E//260) along *a*-*m* (Γ-X) to E//*c* (E//470) along *a*-*c* (X-M)	1.05	1.11

As a result, once the extraction ratio was obtained and plugged in Eq. (2), ratios of Purcell effect of E//*m* modes to E//*c* modes ($F_{P,\text{E}//m}/F_{P,\text{E}//c}$) are calculated to be in the range of 1.11–1.18 (in Table III). Purcell enhancement of E//*m* modes is higher than that of E//*c* modes. In general, Purcell effect is proportional to the transition rate in the energy band [14], [20]. Due to the intrinsic properties of *a*-plane GaN, the transition rate of the lower energy level (E//*m* modes) is larger than that of the higher band (E//*c* modes). In PLED, the value of $\Gamma^{\text{planar}}_{\text{E}//m}/\Gamma^{\text{planar}}_{\text{E}//c}$ (which $\Gamma^{\text{planar}}_{\text{E}//m}$ and $\Gamma^{\text{planar}}_{\text{E}//c}$ are the spontaneous emission rates of E//*m* and E//*c* modes, respectively) is 2.32. On the other hand, in our PhC structure, the value of $\Gamma^{\text{PhC}}_{\text{E}//m}/\Gamma^{\text{PhC}}_{\text{E}//c}$ is 2.74 in PhCLED. The result shows that the spontaneous emission rate of E//*m* modes is further enhanced by Purcell effect as compared with that of E//*c* modes.

Purcell effect modifies the spontaneous emission rate and changes the internal quantum efficiency. With a suitable PhC structure, it means that more photons can be generated and the corresponding light output is increased. Also, Purcell effects of polar and non-polar GaN LEDs with the same PhC structures are different. The transition probabilities of E//*m* modes and E//*c* modes in non-polar *a*-plane GaN are different due to the separation of the valence bands. The transition probability of E//*m* modes is higher than that of E//*c* modes. Thus, Purcell effect exhibits different ratio of emission rate enhancement which is dependent on the transition probability. In our non-polar LEDs, spontaneous emission of E//m modes is enhanced more than E//c ones by Purcell effect.

IV. CONCLUSION

The optical performance of the *a*-plane GaN LEDs with two-dimensional PhCs was demonstrated. It was found the E//*m* modes possesses higher light output than E//*c* modes, which is mainly due to the higher valence band transition probability of the E//*m* modes. In order to understand Purcell enhancement on the internal quantum efficiency, we conduct the experiment work to compare light extraction from the PhC GaN/air interface of E//*m* and E//*c* modes. Light extraction from a *c*-plane GaN LED with asymmetric PhC arrangement was measured and the results feedback to the non-polar device with the same PhCs. Due to different transition probabilities, E//*m* photons are favored. Purcell effect exhibits asymmetric modification of the emission rates in *a*-plane GaN PhCs. The ratio of emission rate of E//*m* to E//*c* modes increases from 2.32 in the planar device to 2.74 in the device with our PhC arrangement. Therefore, Purcell effect primarily enhances the spontaneous emission rates of E//*m* photons, dedicating to the larger E//*m* photon generations as compared with E//*c* modes.

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