Design and Simulation of Superperiodic Photonic-Crystal Light Emitting Diodes with Highly Directive Luminance Characteristics

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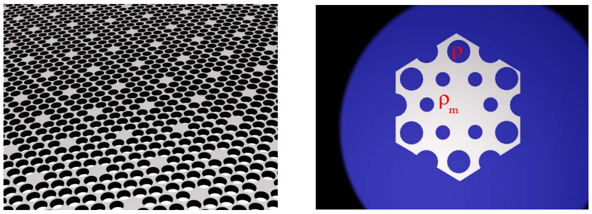
***Abstract*—By use of finite-differene time-domain analysis for lightwave devices, a novel super-periodic photonic-crystal light-emitting diode (LED) design exhibiting high-luminance patterns is proposed for applications that require highly-directive vertical light extraction. The device design is made on the theoretical consideration on the density of radiation modes within the photonic band coupled with far-field diffraction of the spontaneously-emitted light from a structure with double periodicity.**

Photonic crystals (PhCs) are dielectric periodic structures that have great potential for the realization of integrated photonic circuits. With this scope in mind, a significant amount of research efforts has been made in designing and fabricating prototype optical components such as waveguides, channel-drop filters [1], and nano-cavity lasers [2], based on the PhC structure. Especially, some of the most demonstrative PhC devices are designed to utilize the photonic-band gap in the wavelength-vs.-wavevector dispersion diagram.

The device principle of such a photonic-band design requires a substantal contrast in the dielectric-constant profile to open up the bandgap that is sufficiently wide. For this reason, semiconductor dielectric materials that are interfaced directly to the air and are interacting with light in the infrared-to-visible range, are usually employed. With such designs, actual devices must be fabricated with the period range of 200–600 nm with the shorter side for those in the visible spectrum.

In order to analyze the field theoretic performance of many such nano-scale optical devices, the FDTD simulation is probably the only numerical method that gives reliable results. Historically, the reliability of the method has been greatly enhanced when the so-called perfectly-matched anisotropic layers [3] that had refined the original simpler PML boundary condition [4]. To give the most proper analysis for an active medium that produces light, the FDTD method was further improved with the so-called recursive-convolution technique that was modified to model the gain medium by a single pole [3] interfraced with each perfectly-matched anisotropic layer [5].



(a) (b)

Fig. 1. Schematics for (a) the super-periodic PhC plate and (b) its in-plane unit super-cell. Radius ρ of the etched periodic holes is normally set at $0.43\,a$, except for radius ρ_m of the outer-most six holes in the defect. These outer-most holes are subsequently pulled into the center with distance l. The plate thickness t and the distance between the adjacent defects d_c are set at $0.5\,a$ and $4\,a$, respectively.

In the present work currently using the passive version of the FDTD program, we design and numerically demonstrate a high-power light-emitting PhC plate with highly-directive radiation for various applications; displays, lightening, and illumination, etc. To achieve this goal, doubly periodic patterns have been implemented on a simulated GaN plate, as shown in Fig. 1. This design is referred to as a 'super-periodic photonic crystal (super-PhC) with monocell defects' based on the principle of far-field diffraction from the double-periodic structure whose radiation mode, rather than the resonance mode, was tailored to give the desired luminance pattern [6].

The design specifically aims at two simultaneous effects: 1) enhancing the light-extraction efficiency, and 2) tailoring the divergence angle of the radiated beam. The first effect has been investigated previously based on numerical simulations [7] and experimental demonstrations by employing some geometrical features of the PhC theory. Strictly speaking, the differentiating the PhC effect from the commonly called surface texturing is rather difficult.

In this presentation, we show a series of our efforts of maximizing the second effect through the use of the super-PhC structure of our own original design. The defect structure of the super-PhC structure provides a significantly enhanced density of radiation modes from the three-dimensional frequency-vs.-wavevector relation *within the photonic band*, rather than in the bandgap, matched with the gain spectrum of the LED that

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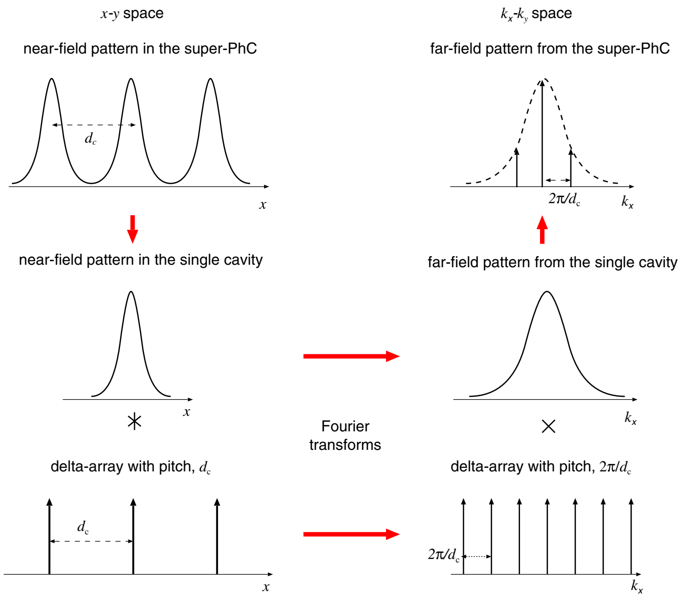

Fig. 2. Schematic illustration explaining the principle of optimizing the far-field luminance pattern with the super-PhC structure. d_{c} is the distance between the adjacent point-defects. Excitation of the fundamental mode has been optimally enhanced by tuning ρ_{m}.

is placed on top of the base reflector-plate materials of the common GaN epitaxy.

The diagram given in Fig. 2 explains the schematics of the design principle. The super-periodic structure of the design provides an effective means for sharpening the vertical beam in the far-field diffraction, based on the discrete-Fourier-transform theory. Subsequent simulations based on the passive FDTD analysis have verified the effectiveness of the design principle as illustrated as in Fig. 3.

Although the nano-fabrication technology is being developed at a phenomenal speed recently, the current state-of-the-art electron-beam fabrication technology dealing with the required hole-to-hole size of 200 nm of PhC semiconductor structures has not been within our reach. For this reason, we believe that the simulation with practically realizable designs must be performed to overcome the difficulty of actual fabrication. Along the line of simulation efforts, we are working on verification of the design principle of the super-periodic PhC LED through the afore-mentioned active simulation codes.

ACKNOWLEDGMENT

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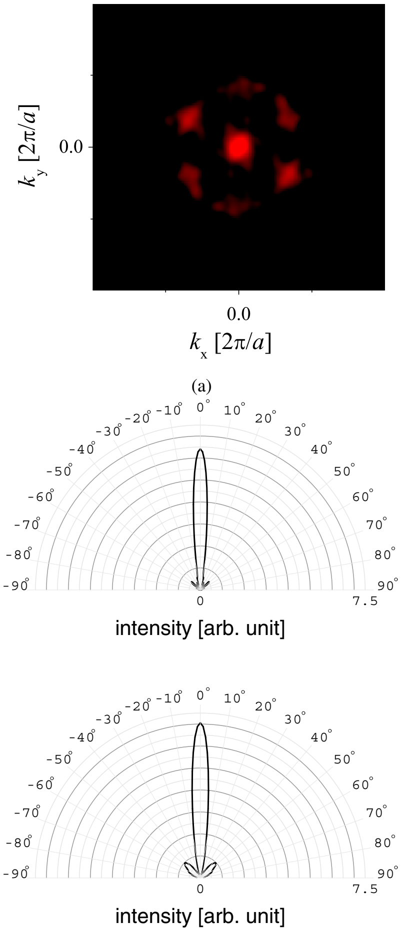
REFERENCES

[1] K. H. Hwang and G. H. Song, "Design of a high-Q channel add-drop multiplexer base on the two-dimensional photonic-crystal membrane structure," *Optics Express*, vol. 13, pp. 1948–1957, 2005.
[2] H. G. Park, S. H. Kim, S. H. Kwon, Y. G. Ju, J. K. Yang, J. H. Baek, S. B. Kim, and Y. H. Lee, "Electrically Driven Single-Cell Photonic Crystal Laser," *Science*, vol. 305, pp 1444–, 2004.



(a)

(b)

Fig. 3. Time-averaged far-field intensity plots for the radiated beam from the optimized super-PhC structure. (a) The luminance is plotted for all solid angles in the logarithmic scale. The dashed circle represents the escape light cone. (b) Top and bottom polar-plots are obtained by scanning the luminance in the linear scale along vertical and horizontal lines of (a), respectively.

[3] Z. S. Sacks, D. M. Kingsland, R. Lee, and J.-F. Lee, "A perfectly-matched anisotropic absorber for use as an absorbing boundary condition," *IEEE Antennas Propagat.*, vol. 43, pp. 1460–1463, 1995.
[4] J.-P. Berenger, "A perfectly-matched layer for the absorption of electromagnetic waves," *J. Computational Physics*, vol. 114, pp. 185–200, 1994.
[5] G. H. Song, S. Kim, and K. Hwang, "FDTD simulation of photonic-crystal lasers and their relaxation oscillation," *J. Opt. Soc. Korea*, vol. 6, pp. 79–85, 2002.
[6] C. M. Lim and G. H. Song, "Design of super-periodic photonic-crystal light-emitting plates with highly-directive luminance characteristics," J. Opt. Soc. Amer. B, vol. 26, pp. 328–336, 2008.
[7] S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, "High extraction efficiency of spontaneous emission from slabs of photonic crystals," Phys. Rev. Lett., **78**, pp. 3294–3297, 1997.
[8] M.-K. Seo, G. H. Song, I.-K. Hwang, and Y. H. Lee, "Nonlinear dispersive three-dimensional finite-difference time-domain analysis for photonic-crystal lasers," *Opt. Exp.*, vol. 13, pp. 1948–1957, 2005.