

# Theoretical modeling of subwavelength structure integrated LEDs for enhanced extraction efficiency and uniform field distribution

G. J. Lee, J. H. Lee, and Y. M. Song\*

Department of Electronics Engineering, Pusan National University, 2 Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea

\*E-mail : ysong@pusan.ac.kr

**Abstract-** In this work, we show on theoretical modeling of light-emitting diodes (LEDs) with antireflective subwavelength structures (SWSs) for enhanced light extraction efficiency and uniform field distribution. Theoretical analysis and geometrical optimization of SWSs are described based on rigorous coupled-wave analysis (RCWA) and finite-difference time domain (FDTD) methods. The results show the effect of period of SWSs on the extraction efficiency and field distribution.

## I. INTRODUCTION

Light-emitting diodes (LEDs) have been widely used in various applications, such as the traffic signal, backlight units for liquid-crystal display (LCD), and indoor/outdoor displays. These practical applications require high performance LEDs. However, the light extraction efficiency of LEDs is strongly limited by massive total internal reflection and Fresnel loss due to the high contrast of refractive index between LEDs and air. Although the internal Fresnel reflection can be reduced by using graded index layers, these layers require highly thin thickness as much as subwavelength and stack of many films of materials having continuously refractive indices. It is quite difficult process to fabricate graded index multi-layer films for antireflection purpose without the light scattering. The microlens array structures are expected to reduce the total internal reflection at the surface, but these structures have scattered some of the light by microlenses [1]. However, surfaces with tapered subwavelength structures (SWSs) behave as graded refractive index media that have the impressive effect of reducing the Fresnel reflection by providing continuously varied refractive indices from substrate to air (Fig. 1 inset) [2]. Moreover, since LED with SWSs are considered as a homogeneous medium, these have uniform field distribution [3]. Thus, the tapered SWSs have been one of promising candidates to obtain high-efficiency and uniform light distribution.

While many researches have been reported on LEDs with the SWSs, there are only few researches on theoretical modeling of the SWSs integrated LEDs. In order to achieve the conditions for improved light output efficiency and uniform light distribution on the LEDs, this paper deals with the theoretical analysis of the red LED with SWSs.

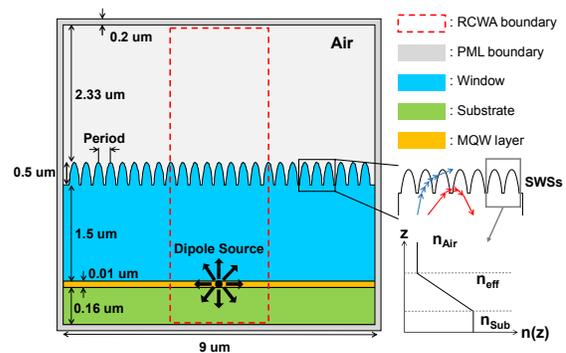


Fig. 1. Schematic illustration of simulation model of LEDs with SWSs. Blue and red line represent the Fresnel reflection and the total internal reflection at the surface, respectively.

## II. SIMULATION MODELING AND RESULTS

The period of the SWSs with a tapered profile play major roles in light extraction. Hence, it was necessary to calculate the Fresnel reflection according to the period of SWSs in order to determine the optimal period of the SWSs. To obtain polarization independent property, the symmetry of parabola SWSs was designed by a 6-fold hexagonal symmetry. Fig.1 shows the schematic illustration for simulation model of LED with SWSs.

Fig.2 (a) shows the contour plots of the reflectance variation the LEDs caused by the internal reflection as a function of SWS period and wavelength at normal incidence by using RCWA. The model used in calculation which designs GaP SWS with a parabola shape on a GaP substrate was used, as depicted Fig.2 (a) inset. The SWS with a period of 200 nm exhibit very low reflectance, almost 4%, in the LED model at an incident wavelength of 650 nm. However, if above the period of SWS around 400 nm, then reflectance is high above 40% due to higher order diffraction at the normal incidence.

In order to calculate precise far-field patterns, a large scale simulation boundary and the dipole source are needed in 3D FDTD. However, under the large scale simulation condition, 3D FDTD method requires a large amount of memory and computation time [4]. To more efficiently simulate the far-field patterns of the LEDs, RCWA method was used to calculate by using commercial software (DiffractionMOD, RSoft Design Group, USA). However, since the implementation of the dipole source is impossible in RCWA method, we realize

the dipole source as the sum of omnidirectional plane waves with a same wavelength (Fig. 3) [5].

Fig.2 (b) represents the calculated far-field pattern of the red color LED for a few of periods using by RCWA with a superposition of plane waves. From the results in Fig.2 (b), the period of SWSs 650 nm and 975 nm have the non-uniform far-field patterns and low extraction efficiencies due to the higher order diffraction. On the other hand, high extraction efficiency and uniform far-field pattern are obtained at the period of 200 nm. These results can be explained by the grating equation. When the grating period becomes much smaller than the wavelength, it is found that only zeroth-order diffraction is allowed to reflect and all the higher orders are evanescent [6].

In addition, a SWS with parabola shape has linearly graded refractive index profile from the refractive index of a window to that of air. This gradually decreasing refractive index effect is identical with the effect of graded index thin film coating which has improved output light intensity and uniform far field pattern (Fig.2 (b)) [3]. Hence, the distance between the SWSs should be smaller than 200 nm in order to reduce the Fresnel reflection with uniform far field pattern, as depicted in Fig.2.

The theoretical calculations of field distribution were done by using FDTD method with commercial software (FullWave, RSoft Design Group, USA), as shown in Fig. 4. If the period of SWSs is larger than 200 nm, then the light scattering occurs due to higher order diffractions whereas the SWSs with a period of 150 nm have uniform field distribution without scattering at 633 nm monochromatic wavelength.

All of these simulations consider materials dispersion and TM polarized lights.

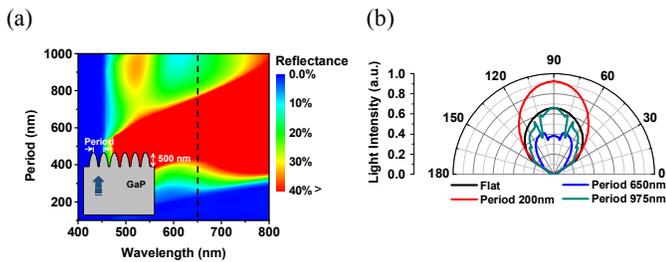


Fig.2 Theoretical calculation of red color LEDs. (a) The reflectance graph verse wavelength of red color LEDs. (b) Calculated far-field patterns of the LED with SWSs.

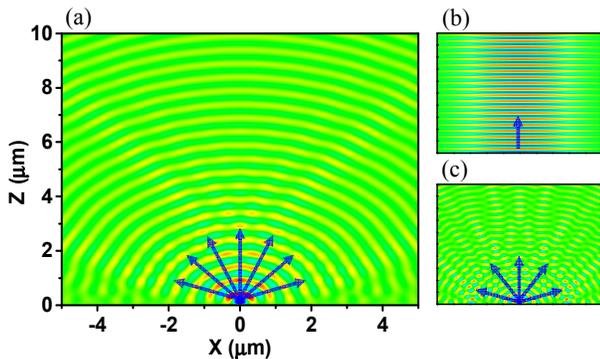


Fig.3 Dipole source realization by sum of plane waves. (a) Sum of the 31 plane waves. (b) Only one plane wave. (c) Sum of the 17 plane waves.

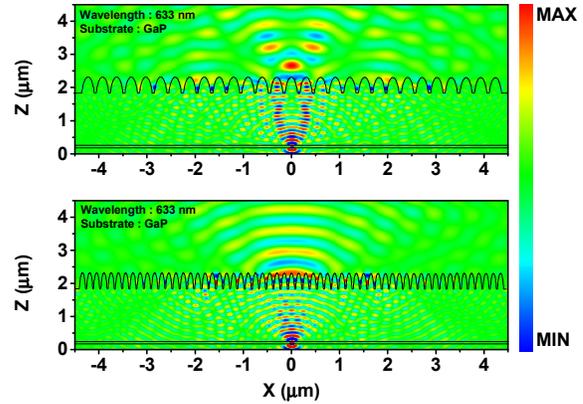


Fig.4 Field distributions of LEDs variation SWSs period with the dipole source at  $y=0$ . (a) SWSs period : 300 nm. (b) SWSs period : 150 nm.

### III. CONCLUSION

In summary, we investigated optimum period of GaP SWSs with parabola shape on the LED using by FDTD and RCWA methods. From theoretical calculations of above mentioned, we found that a SWS period of below 200 nm is needed to reduce the internal Fresnel reflection with uniform field distribution. From these results, we believe that the LED with SWSs is suitable for high-efficiency light source and directional display applications.

### ACKNOWLEDGMENT

This work was supported by the Korea Basic Science Institute grant (D34500), Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT&Future Planning (2014R1A1A1005945), and BK21PLUS, Creative Human Resource Development Program for IT Convergence.

### REFERENCES

- [1] E. K. Kang, Y. M. Song, S. J. Jang, C. I. Yeo, and Y. T. Lee, "Increased light extraction from GaN light-emitting diodes by  $\text{SiN}_x$  compound eyes," *IEEE Photonics Technology Letters*, vol. 25, no. 12, 2013.
- [2] Y. M. Song, E. S. Choi, G. C. Park, C. Y. Park, S. J. Jang, and Y. T. Lee, "Disordered antireflective nanostructures on GaN-based light-emitting diodes using Ag nanoparticles for improved light extraction efficiency," *Appl. Phys. Lett.*, vol. 97, 093110, 2010.
- [3] Hisao Kikuta, Hiroshi Toyota, and Wanji Yu, "Optical elements with Subwavelength structured surfaces," *Optical Review*, vol. 10, no. 2, pp. 63-73, 2003
- [4] Deifen Zhu, Guangyu Liu, Jing Zhang, and Nelson Tansu, "FDTD analysis on extraction efficiency of GaN light-emitting diodes with microsphere arrays," *Journal of Display Technology*, vol. 9, no. 5, 2013.
- [5] George C. Sherman, A.J. Devaney, and L. Mandel, "Plane-wave expansions of the optical field," *Optics Communications*, vol. 6, no. 2, 1972.
- [6] Y.M. Song, E. S. Choi, J. S. Yu, and Y. T. Lee, "Light-extraction enhancement of red AlGaInP light-emitting diodes with antireflective subwavelength structures," *Optics Express*, vol. 17, no. 23, 2009