Opto-Electronic Science

Supplementary information

2022, Vol. 1, No. 12

DOI: 10.29026/oes.2022.220021

Directional high-efficiency nanowire LEDs with reduced angular color shift for AR and VR displays

Yizhou Qian, Zhiyong Yang, Yu-Hsin Huang, Kuan-Heng Lin and Shin-Tson Wu*

College of Optics and Photonics, University of Central Florida, Orlando, FL 32816, USA.

*Correspondence: ST Wu, E-mail: swu@creol.ucf.edu

This file includes:

Supplementary information for this paper is available at https://doi.org/10.29026/oes.2022.220021

Section 1: The parameters in FDTD simulation

Table S1 | | FDTD simulation parameters for InP nanowire LED

Source	Electric dipole	Wavelength	805 nm – 840 nm
Simulation time	1000 fs	Boundary condition	Steep angle perfect matched layer for *x*-, *y*-, *z*- direction
Mesh for nanowire	10 nm for *x*-, *y*- direction 20 nm for *z*- direction	Mesh for capping	5 nm for *x*-, *y*-, *z*- direction
Mesh for dipole	1 nm for *x*-, *y*-, *z*- direction		
Far-field monitor	2D *x*-, *y*- plane	Power monitor	3D *x*-, *y*-, *z*- box
Auto shut-off	$1e^{-5}$	Simulation temperature	300 K

Table S2 | | FDTD simulation parameters for InGaN/GaN nanowire LED

Source	Electric dipole	Wavelength	Blue: 400 nm – 500 nm Green: 500 nm – 600 nm Red: 550 nm – 800 nm
Simulation time	1000 fs	Boundary condition	Steep angle perfect matched layer for *x*-, *y*-, *z*- direction
Mesh for nanowire	10 nm for *x*-, *y*-, *z*- direction	Mesh for capping	5 nm for *x*-, *y*-, *z*- direction
Mesh for dipole	1 nm for *x*-, *y*-, *z*- direction		
Far-field monitor	2D *x*-, *y*- plane	Power monitor	3D *x*-, *y*-, *z*- box
Auto shut-off	$1e^{-5}$	Simulation temperature	300 K

Section 2: LEE dependence on *x*-axis

LEE in nanowire LED is significantly dependent on the dipole's position along *x*-axis. Due to thin multiple quantum dot layers, the LEE variation on the dipoles' position along *z*-axis is very small. Therefore, the thickness-averaged LEE is plotted in Fig. S1. As depicted in Fig. S1(a), the LEE of blue nanowire LED decreases from ~33% to ~15% with the increased radius for all the cases. According to Eq. 6(a, b), the outer dipoles have a higher weightage when calculating the total LEE, and the average LEE for blue nanowire is only 22%. For green nanowire (Fig. S1(b)), its LEE fluctuates with the variation of the dipoles' position along *x*-axis because of the competition between radial mode and whispering gallery mode[S1]. The average LEE calculated by Eq. (7) is about 49.5%. On the other hand, due to the smallest diameter and longest wavelength, high-order modes are more difficult to be excited in red nanowire than the other two. As a result, the red nanowire LEDs typically have the highest average LEE (57% in this case). As indicated in Fig. S1(c), LEE slightly increases from 52% to 58% (*x*-polarization) and 66% (*y*-polarization) as the *x*-axis position increases for red nanowires. In addition, the results from the dipoles along long axis and those along short axis overlap each other, indicating the excitation of the same waveguide mode due to small position variation.

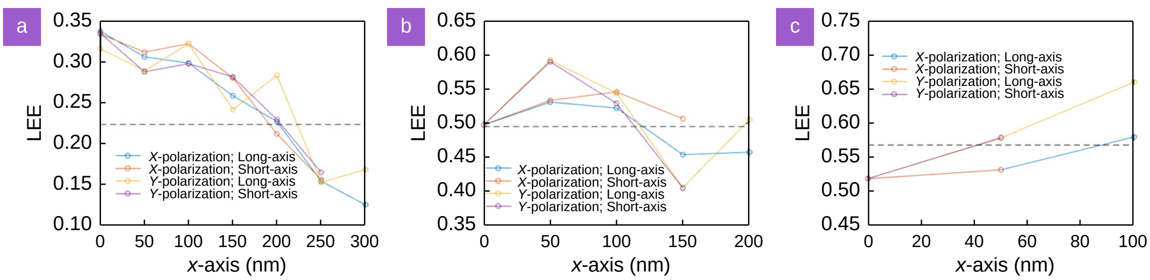

Fig. S1 | | Dependence of LEE on the dipole source position along *x*-axis for (**a**) blue, (**b**) green, and (**c**) red nanowire LEDs.

Section 3: Near-field distribution maps

To fully understand the angular distribution profile and LEE in each nanowire LED, we calculate the near-field distribution profiles of the electric field intensity $|E|^2$ for blue, green, and red LEDs as shown in Fig. S2. Unlike the traditional method which only plots the near-field maps from center dipoles with *x*-polarization, long-axis dipoles with both *x*- and *y*- polarizations at the edge of nanowires are selected since these dipoles carry the most weightage in Eqs. 2(a) and 6(a). Figure S2(a, d) reveals that intense $|E|^2$ is localized in the capping layer and the radiation is suppressed, resulting in a broad angular distribution and low LEE in blue nanowire LED. For green LED, $|E|^2$ hot spots are more concentrated at the surface of the capping layer (Fig. S2(b, e)), resulting in a higher LEE as Fig. S1(b) depicts. However, the radiation in the normal direction is suppressed, especially for *y*-polarization dipole, which causes the batwing effect as indicated in Fig. 3(b). On the other hand, Fig. S2(c, f) indicates that the radiation of red LED is the strongest and most of its power is concentrated in the normal direction, which agrees with previous far-field results.

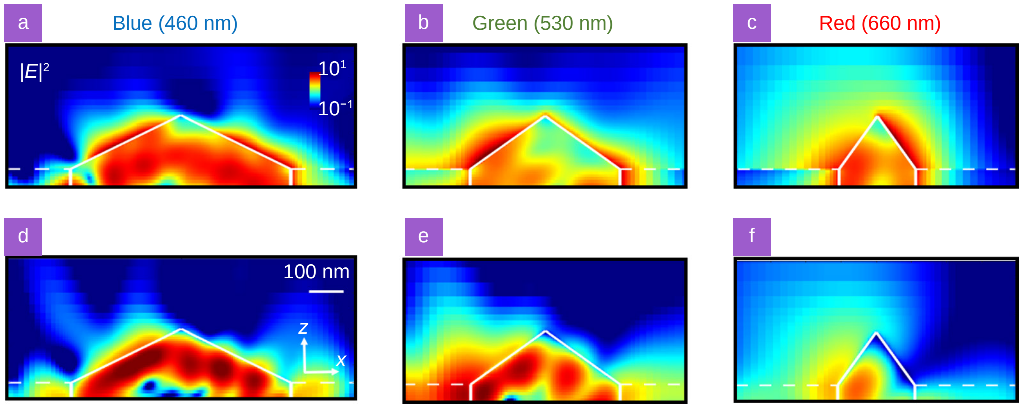

Fig. S2 | | FDTD-calculated distribution maps of $|E|^2$ at the capping layer with *x*-polarized dipoles for (**a**) blue, (**b**) green, and (**c**) red nanowire LEDs and *y*-polarized dipoles for (**d**) blue, (**e**) green, and (**f**) red nanowire LEDs.

Section 4: Total LEE dependence on n-GaN thickness and p-GaN capping height

Figure S3 illustrates the LEE dependence on the n-GaN thickness and the capping height. By varying the n-GaN thickness, different waveguide modes are excited in nanowires and each one has a different outcoupling efficiency. Besides, increasing capping height can increase the total LEE because high-order modes with a large off-axis angle along *c*-axis are easier to escape from the nanowire. On the other hand, an increased LEE does not necessarily mean that more light is received by the imaging system. The effective LEE is calculated in Fig. 5(d–f).

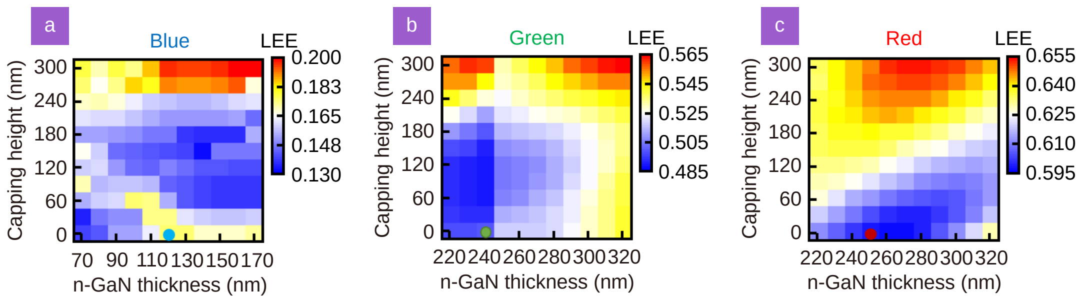

Fig. S3 | | (**a**–**c**) 2D colormap of total LEE as a function of n-GaN thickness and p-GaN capping height for (a) blue, (b) green, and (c) red nanowire LEDs.

References

S1. Ryu HY. Evaluation of light extraction efficiency of GaN-based nanorod light-emitting diodes by averaging over source positions and polarizations. *Crystals* **8**, 27 (2018).