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Emission characteristics of light-emitting diodes by confocal microscopy

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ABSTRACT

The emission profiles of light-emitting diodes have typically be measured by goniophotometry. However this technique suffers from several drawbacks, including the inability to generate three-dimensional intensity profiles as well as poor spatial resolution. These limitations are particularly pronounced when the technique is used to compared devices whose emission patterns have been modified through surface texturing at the micrometer and nanometer scales,. In view of such limitations, confocal microscopy has been adopted for the study of emission characteristics of LEDs. This enables three-dimensional emission maps to be collected, from which two-dimensional cross-sectional emission profiles can be generated. Of course, there are limitations associated with confocal microscopy, including the range of emission angles that can be measured due to the limited acceptance angle of the objective. As an illustration, the technique has been adopted to compare the emission profiles of LEDs with different divergence angles using an objective with a numerical aperture of 0.8. It is found that the results are consistent with those obtained by goniophotometry when the divergence angle is less that the acceptance angle of the objective.

Keywords: Light-emitting diodes, confocal microscopy

1. INTRODUCTION

Angular light intensity distribution from a light source is commonly measured using a technique known as goniophotometry, whose typical setup consists of two components: a fixture and a photo detector. While goniophotometry measures light in the far-field (distances >> wavelength) and is largely suitable for most light sources, it may not provide sufficient accuracy nor sensitivity for smaller or weaker light sources such as light-emitting diode (LED) chips (not lamps). For such miniature light sources, measurements at closer distances are desirable (distances comparable to the scale of the emitters), although this is often not feasible with a goniophotometric setup. Optical measurements at closer ranges (micrometer scale) can be achieved using conventional optical microscopy, except that angular scanning cannot be performed for generating angular emission patterns. As such, confocal microscopy may be a suitable candidate as the optical signals from the sample is collected on a point-by-point basis, providing optical information in the "mid-field" regime between far-field and near-field [1].

Confocal microscopy is capable of filtering out-of-focus background signals by inserting a pinhole which is conjugate to the focal point of the lens in the optical path. Without the interference of background light, the resultant images obtained will be of high quality and resolution, and multiple planar images from adjacent planes can be obtained to generate 3-dimensional diagrams. The technique has successfully been applied to the study of the integration of micro-lenses to LEDs [2][3], light emission from micro-LEDs [4], as well as to the investigation of optical cross-talk from micro-LED [5]. In the study of the emission properties of LED chips, 3D emission profiles from the devices can be constructed from multiple planar intensity maps, from which rich information can be extracted. For instance, 2D emission profiles of the LED can be extracted from any specified plane within the 3D emission diagrams for further analysis; this allows the device engineer to gain better understanding of the emission characteristics, and thus design devices for specific desired properties. The objective of this work is to study the ability of confocal microscopy to obtain reliable and accurate angular emission profiles from LEDs, as well as to determine its limitations for this purpose. The collected data will be compared with those measured with photogoniometry, highlighting the merits and limitations of this technique.

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2. EXPERIMENTAL DETAILS

Blue LEDs are used for investigations in the present studies. The epitaxial structure of the devices in this work are grown by metal-organic chemical vapor deposition (MOCVD) on c-plane sapphire, which consists of a 3-μm-thick undoped GaN layer, a 3-μm-thick Si-doped GaN layer, 10 periods of InGaN/ GaN quantum wells, capped with a 0.25-μm-thick Mg-doped GaN layer. A 200 nm-thick indium tin oxide (ITO) is deposited as a p-type current spreading layer. The mesas of the LEDs with dimensions of 1.9 x 1.9 mm^2 are patterned by photolithography and etched by Cl_2-based inductively-coupled plasma etching. After definition of contact pad regions, Ti/Al/Ti/Au (40/150/20/40 nm) is deposited by electron beam evaporation followed by annealing. The fabricated devices emit at a peak wavelength of ~470 nm with spectral width of ~35 nm full-width at half-maximum (FWHM). The chips are diced by laser micro-machining with a diode-pumped solid-state (DPSS) ultraviolet (UV) pulsed laser at 349nm. The separated chips are epoxy-mounted onto specially-designed ceramic substrates with copper conductor layers and are wire-bonded using Al wires.

The measurements are conducted using a Carl Zeiss LSM700 laser scanning confocal microscope in the collection mode without laser illumination. Emission from the LED is coupled into the confocal scanning head via a 50x objective with a numerical aperture (NA) of 0.8 and a working distance of ~1mm. To avoid contact with the bond wire, the first (lowest) scanning plane is set to just above the top of the wire loop. The total scanning range of the experiment is 20000 μm in the vertical direction in steps of 200 μm. A total of 101 confocal planes are obtained during the scan; the dimensions of each plane is ranges from 40000μm x 25μm to 40000μm x 40000μm. Cross-sectional emission profiles of the LEDs can be reconstructed using a data analysis software (Matlab) based on the raw data collected.

3. RESULTS AND DISCUSSION

Figure 1 shows a 3-D emission diagram obtained by confocal microscopy from a blue LED. A and B are cross-sectional images slices from their respective planes.

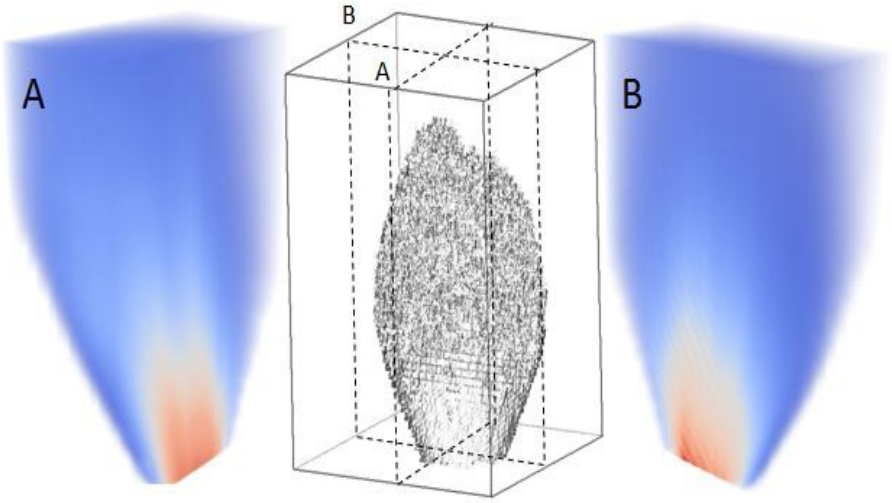

Figure 1. 3-D emission diagram from a blue LED chip.

In order to be able to analyze the data analytically, the 2-D emission profiles are re-plotted using raw data for a specific plane cutting through the center of the LED, as shown in Figure 2(a). Angular emission profiles of the LED at different distances away from the chip surface can be extracted from the generated plots, which are then directly comparable with plots obtained by goniophotometry. As illustrated in Figure 2(b), the dash lines indicate semicircular paths with specified radii of data to be extracted for generation of the angular plots.

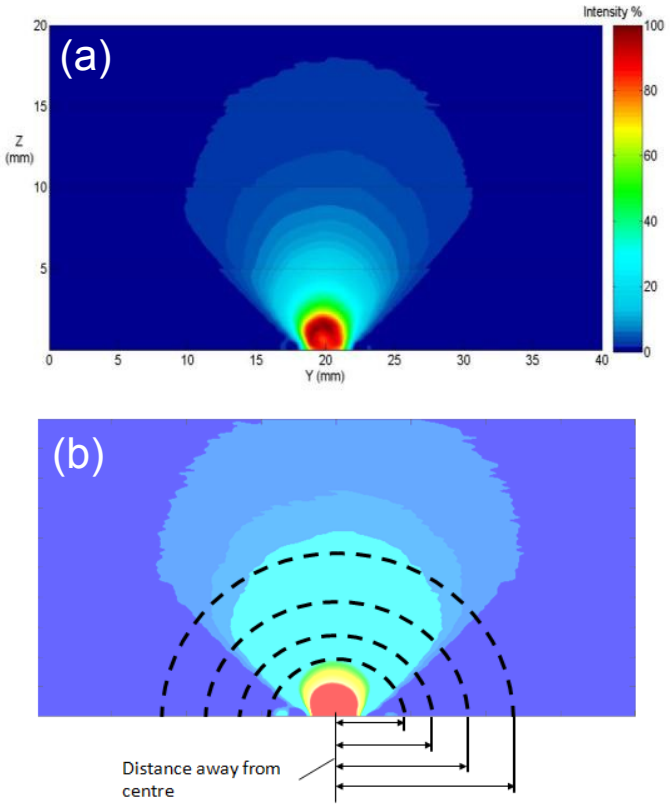

Figure 2. (a) Cross-sectional emission intensity profiles of an LED as measured by confocal microscopy. (b) Extraction of angular emission profiles from the cross-section emission intensity profiles at different distances from the center of the LED.

Intensity data is extracted at the distances of 2 mm, 5 mm, 10 mm, 15 mm and 20 mm with respect to the center of emission from the device for generation of angular emission plots, which are plotted in Figure 3. It is observed that the profile narrows with an increase of distance away from device, but becomes invariant as the distance exceeds 10 mm. When the distance is short (~2 to 5 mm away from LED surface), dimensional effects on the emission profiles is strong. As the distances are enlarged, the LED behaves increasingly like a point source, thereby dimensional effects become negligible. It is noted that the measurement distances in goniophotometry are typically large so that the light sources behave as point sources too. By using data points at distances sufficiently far away from the LEDs, dimension-independent angular emission profile can be obtained, which can be compared with plots from goniophotometry.

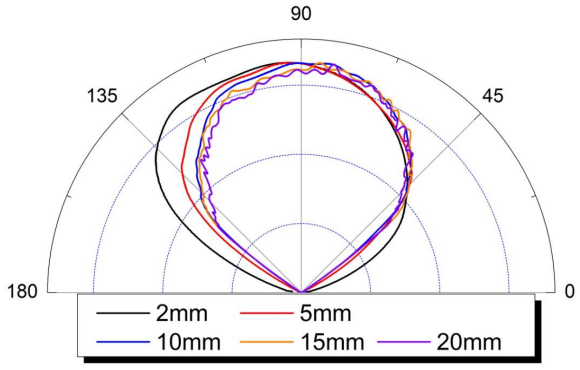

Figure 3. Angular emission profiles extracted from Fig. 2(a) at various distances.

The angular emission profile of the same LED chip is measured using a goniophotometer. The distance between the LED and the photodetector of the goniophotometer is fixed at 100mm. The device is mounted onto a rotational stage which rotated at 1° per second from -90° to 90°. Based on the data obtained from both methods, the angular emission profiles are plotted in Figure 4.

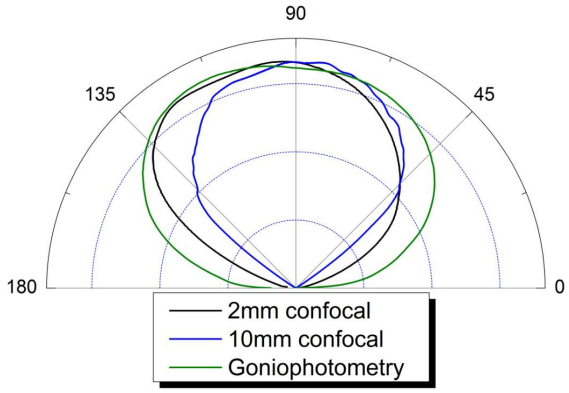

Figure 4. Angular emission profile extracted from confocal microscopy (2mm and 10mm) and goniophotometry.

The angular emission profiles obtained by goniophotometry are apparently wider than those from confocal microscopy. In goniophotometry, either the photodetector or the light source is rotated with respect to the other component, as illustrated in the schematic diagram of Figure 5(a). All the light rays travelling towards the detector window are collected within each angular interval. Therefore, no light rays emitted by the LED should be excluded from the measurement. In confocal microscopy, multiple planar scans are collected instead of rotating the detector around the device. The numerical aperture of the objective limits the angular range of light collected, as in optical microscopy in general. In this case, the N.A. of the chosen objective is 0.8, giving an angle of acceptance cone of 53.13^{o}. This is a relatively large N.A. for a dry objective. As a result, a portion of the emitted light emitted at larger angles cannot be collected by the objective. This sets a limitation on the use of confocal microscopy for this purpose. Nevertheless, as long as the emission is within the acceptance cone of the objective, this technique can be applied successfully. As a matter of fact, most packaged LEDs have lenses attached in order to reduce the emission angles. As demonstrations, various LED with different emission angles are used for characterization by confocal microscopy, and compared with data from obtained from goniophotometry.

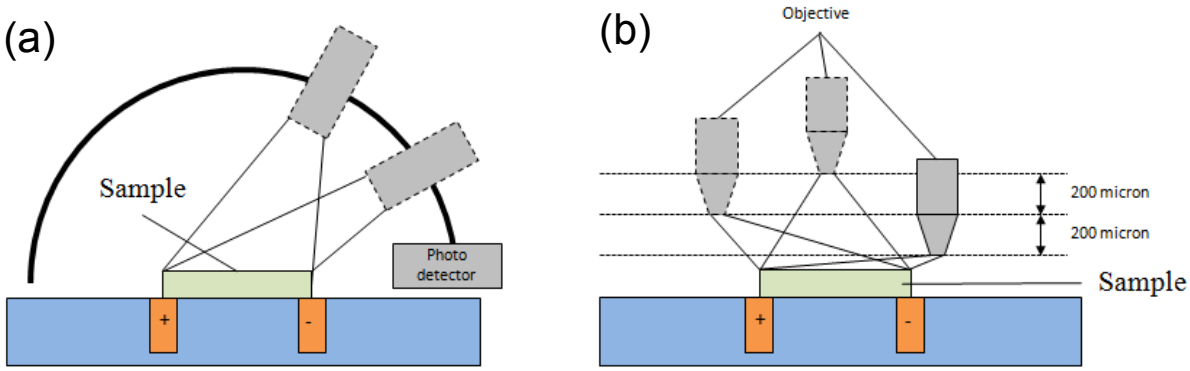

Figure 5. Schematic diagrams illustrating the measurement schemes of (a) goniophotometry and (b) confocal microscopy.

Figures 6 (a) to (d) show angular emission intensity profiles for 4 different commercially-available LEDs with dome lenses as measured by goniophotometry and confocal microscopy. The specified angles of the LEDs are (a) 10^{o}, (b) 23^{o}, (c) 45^{o} and (d) 60^{o}. As can be seen from the plots, the results obtained from both techniques are identical for the LEDs with smaller divergences angles, as all the light emitted can be captured by the objective. For the LEDs with wider divergence angles, discrepancies are indeed observed, especially at larger angles. As acknowledged, this is a fundamental limitation of this technique based on optical microscopy. Nevertheless, it also offers capabilities beyond goniophotometry, including the generation of 3-D emission profiles, as well as significantly higher resolutions and accuracies.

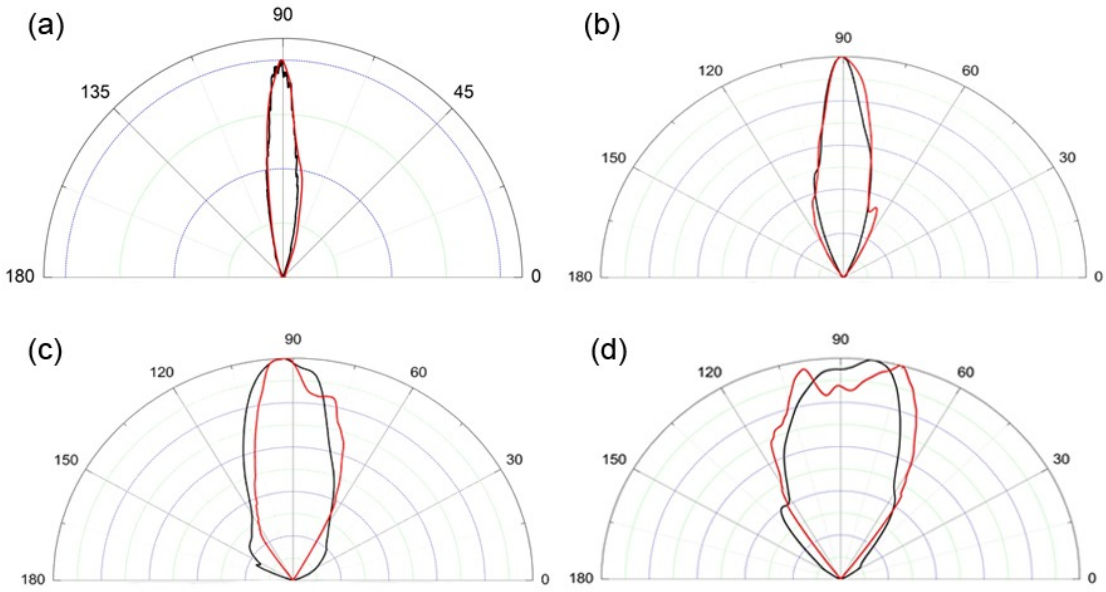

Figure 6. Angular emission intensity profiles for LEDs of different emission angles as measured by goniophotometry (black) and confocal microscopy (red).

4. CONCLUSION

The feasibility of confocal microscopy for obtaining angular emission profiles from LEDs has been explored. It is found that apart from the generation of 3-D emission profiles, 2-D emission maps can also be obtained from the measured data for direct comparison with goniophotometry. The emission profiles are correct and accurate as long as the emitted rays are captured by the objective of the microscope. Therefore, the numerical aperture of the objective governs and limits the angular range of the measurement. The technique has been verified with a series of commercially-available LEDs with dome lenses. The technique is able to accurately measure angular emission profiles as long as the angular divergence is within the acceptance cone of the objective.

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