Beam divergence measurements of InGaN/GaN micro-array light-emitting diodes using confocal microscopy

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Abstract

The recent development of high-density, two-dimensional arrays of micrometer-sized InGaN/GaN light-emitting diodes (micro-LEDs) with potential applications from scientific instrumentation to micro-displays has created an urgent need for controlled manipulation of the light output from these devices. With directed light output these devices can be used in situations where collimated beams or light focussed onto several thousand matrix points is desired. In order to do this effectively, the emission characteristics of the devices must be fully understood and characterised. Here we utilise confocal microscopy to directly determine the emission characteristics and angular beam divergences from the individual micro-LED elements. The technique is applied to both top (into air) and bottom (through substrate) emission in arrays of green (540nm), blue (470nm), and UV (370nm) micro-LED devices, at distances of up to 50μm from the emission plane. The results are consistent with simple optical modelling of the expected beam profiles.

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PACS: 85.60.Bt, 85.60.Jb, 87.64.Tt

Several groups have reported recently on the development of high-density, two-dimensional arrays of micrometer-sized InGaN/GaN light-emitting diodes.[1-3] The latest advances[3] have provided matrix-addressable, high-performance arrays of up to ~12,000, 20-micron-sized emitters at 1200 dots per inch. The ability to programme the emission patterns of these arrays, together with the important spectral coverage they offer across the 370-600nm range (and potentially 280-370nm with Al-containing III-N alloys) opens up a wide range of scientific and instrumentation uses for these devices. Examples include novel microdisplays[1] and excitation sources for micro-array format fluorescently-tagged biomolecules[4]. Biological and chemical applications of these LED arrays are of particular interest as they provide an opportunity to develop multi-well plate readers in fluorescence lifetime assays.

To form a useful illumination source for these purposes it is necessary for the light from each element to be precisely imaged, collimated or manipulated for projection onto an applications plane. Arrays of refractive microlenses positioned in registry with each emitter element can in principle offer this control, and preliminary microlens formation with selected compatible materials (polymers,[2] GaN,[5] sapphire[6]) have been reported for such a purpose. To accurately collect and manipulate the emission in this manner, however, requires a full knowledge of the light emission characteristics of the micro-LED elements. Here, we report a detailed study of these characteristics for blue, green and ultraviolet micro-LED arrays, respectively. We have utilised confocal microscopy for these measurements, and determined that the predominant emission pattern both upwards (into air) and downwards (towards the substrate) is confined to a cone whose characteristics are accurately determined by this method. Confocal microscopy has been used previously to characterise the photoluminescence of GaN-related devices[7].

The micro-LEDs studied were 64x64 arrays of micro-disk elements, each 20-μm in diameter, within an overall active footprint of 3mm x 3mm, and were matrix-addressable via a contact grid. The wafer details and fabrication process for the blue and green devices has been described previously[3]. The key processing step is the production of sloping sidewalls in the InGaN/GaN micro-pillars by inductively-coupled plasma dry etching, to facilitate conformal metal coverage. The resulting truncated conical emission elements were sheathed by metal on their sidewalls. The ultraviolet devices[8] were fabricated by the same basic approach, and their electrical and power performance details will be reported in full elsewhere. All structures were grown on 2-inch c-plane sapphire substrates by metal-organic chemical vapour deposition. The ultraviolet structure, not described previously in this context, consists of 2.3μm of undoped GaN and 1.4μm of n-doped GaN, over which was a 200nm cladding layer and a 7-period multi-quantum well, capped with 100nm of Mg-doped AlGaN cladding and a 20nm Mg-doped GaN contact layer. The quantum well was of seven periods, of 2nm InGaN (In~0.05) and 10-nm AlGaN (Al~0.2) barriers. The blue, green and ultraviolet arrays were operated with 3.4V, 4V, and 12V respective forward bias voltages at around 1μA. These values were chosen to be above the turn on voltages, to produce sufficient detectable light output from the devices. The blue device was also studied at 4V to determine whether a higher voltage altered the beam divergence.

The emission characteristics of individual micro-LED elements were determined using a commercial confocal microscope, as illustrated in Fig.1. A commercial confocal scan head was connected to an upright microscope equipped with a x20, 0.75NA objective lens. The emission from the electrically excited LED elements was imaged back through the confocal scan head and detected on one of the three photomultipliers therein, the choice being determined by the emission wavelength of the device. The confocal aperture before the detector enabled optical sectioning of the LED output, as only light from the focal plane will reach the detector. Previous measurements[9] had shown the axial and lateral resolutions of this system to be 0.8 (±0.1) µm and 0.25 (±0.02) µm, respectively, at a wavelength of 488 nm. In order to obtain the emission profiles, the system was scanned for the blue and green devices in sections in the Z direction from -50µm to +50µm, in steps of 1µm, with the element surface designated as 0µm. In the case of the UV device, the scan was taken from -25µm to +25µm, due to the relatively low sensitivity of the photodetector to light below 400nm wavelength. Care was taken to ensure that the detection system did not become saturated at any point during the scan. The images were then examined using commercial software. Each XY section was analysed and an intensity histogram used to determine the full width half maximum value for each plane. The values were then plotted in a standard plotting package and the beam divergence calculated from the resulting profile.

In a simple representation of the emission pattern with a 20µm wide aperture, the LEDs may be expected[10-12] to emit in a roughly Lambertian pattern, so to simulate the emission profile a Lambertian emission profile of the following form[12] was used:

$$I_{air} = \frac{P_{source}}{4\pi r^2}\frac{{n_{air}}^2}{{n_s}^2}\cos\Phi \tag{1}$$

Here I_{air} is the light intensity in air, P_{source} is the total source power, r is radial distance from the source, n_{air} is the refractive index of air, n_s is the semiconductor refractive index ($n_s = 2.456$ for GaN at 470nm) and Φ is the angle of a ray refracted out of the surface. The emission distribution was simulated using 2000 source components in a 20μm wide line. Although not allowing for diffraction effects, the model provides a suitable system to assist in the interpretation of the recorded images under the conditions encountered here.

Reconstructed X-Z sections through the centre of the XYZ stacks of the measured device beam profiles are shown in Fig.2. For clarity, negative intensity illustrations are used. They show a clearly defined cone shape to the beams in the upward (+Z) emitting direction, whilst light in the downward (-Z) direction is still conical, but with a less well-defined distribution. This is likely to be due to photons emitting downwards from the quantum well scattering back up through the wafer.

As a representative example, intensity-mapped representations of the transverse intensity distribution from a blue device emission profile at Z=10μm and Z=30μm, respectively, are shown in Fig. 3(a) and (b), along with the simulated results. Also shown are three dimensional optical X-Y sections. It should be noted that the intensity distributions are shown using spatial (microns) units rather than the angular distribution more normally used in LED emission profile measurements.[10-12] This has been done to facilitate measurement of the second moment[13, 14] beam divergence values, and the results of equation (1) have been similarly expressed to allow a comparison between theory and measured values. All plots have been normalised with respect to the maximum measured intensity value at Z=10μm, and, given the simplicity of the model, the simulated results provide a consistent fit to the measured intensity profiles. From the abrupt levelling-off of the measured linescans near zero, we can infer that most of the light emitted by the LED is contained within the cone shape seen in the X-Z profiles.

The simulated plot at Z=30μm is somewhat rounder than the measured plot, and noise in the measured plot contributes to its non-zero minimum. However, the simulated value at this distance is very similar to the measured value and thus gives a divergence result comparable to that of the actual LEDs. In addition, simulations of a 20µm wide disk of material with refractive index equal to GaN were performed using a commercially available non-sequential ray-tracing package. This produced a flat-topped emission profile at distances greater than 30µm from the disk when a reflective surface was positioned below the disk. This reflector has the effect of redirecting light emitted downward from the source back up through the disk and contributing to the overall emission profile, thereby forming the 'top hat' profile similar to that seen in device measurements. Fresnel reflections from the sapphire substrate due to the difference in refractive index are likely to contribute to the observed beam shape in this way.

Table I shows second moment beam divergences measured for the three wavelengths of micro-LED array, together with the simulated result. It can be seen that the simulated results are in close agreement to the measured green and blue divergences. The small disparity with the UV device may be attributed to the smaller measurement range (± 25µm) of the UV profile. As a final verification that the confocal system was collecting all or most of the light from each element and therefore not giving a false divergence measurement, a 1.35NA x20 oil-immersion lens, with oil of refractive index 1.51, was used to measure the divergence of a blue micro-LED element. The 1.35NA lens is capable of collecting all the light within 128° (full angle) emitted upwards by the micro-LED. The measurement using the 1.35 NA lens was actually smaller than divergence angles measured using the 0.75 NA lens, implying that the emitted light cone is not restricted by the by the 0.75NA limiting full angle of 98°. Increasing the drive voltage on the blue device to 4V did not significantly change its emission angle, implying a reasonable degree of independence of the observed profile to drive conditions.

In conclusion, we have measured the emission beam profiles of micrometer scale InGaN/GaN LEDs, for the first time to our knowledge. Specific data has been obtained for devices emitting at blue, green and ultraviolet wavelengths, respectively. Confocal microscopy has been utilized for this purpose, as a powerful means of resolving light emission from the devices. The technique provides a detailed image of the light distribution as opposed to conventional emission profile measurement techniques that are based entirely in the far field and therefore unsuitable for micro optical elements. The knowledge gained should allow determination of the exact requirements for optimising micro-optical elements in registry with the emitters, to manage the light emission for practical applications.

Acknowledgements This work was supported by UK EPSRC and Scottish Enterprise. The authors would like to thank Nitride Semiconductor Co. Ltd. (Japan) for support with the UV wafers.

Thanks go to Marijn Zandvliet of the Institute of Photonics for constructive discussions on second moment beam divergence measurement methods.

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Figure captions

Fig. 1:- Confocal microscope setup

Fig.2 :– Negative intensity X-Z profiles of micro-LEDs, showing a) blue device, b) green device, and c) UV device

Fig. 3:- Measured and simulated beam profiles of blue micro-LED at a) Z= 10μm and b) Z= 30μm. 3-D plots of the measured beam profiles at the same distances are shown on the right.

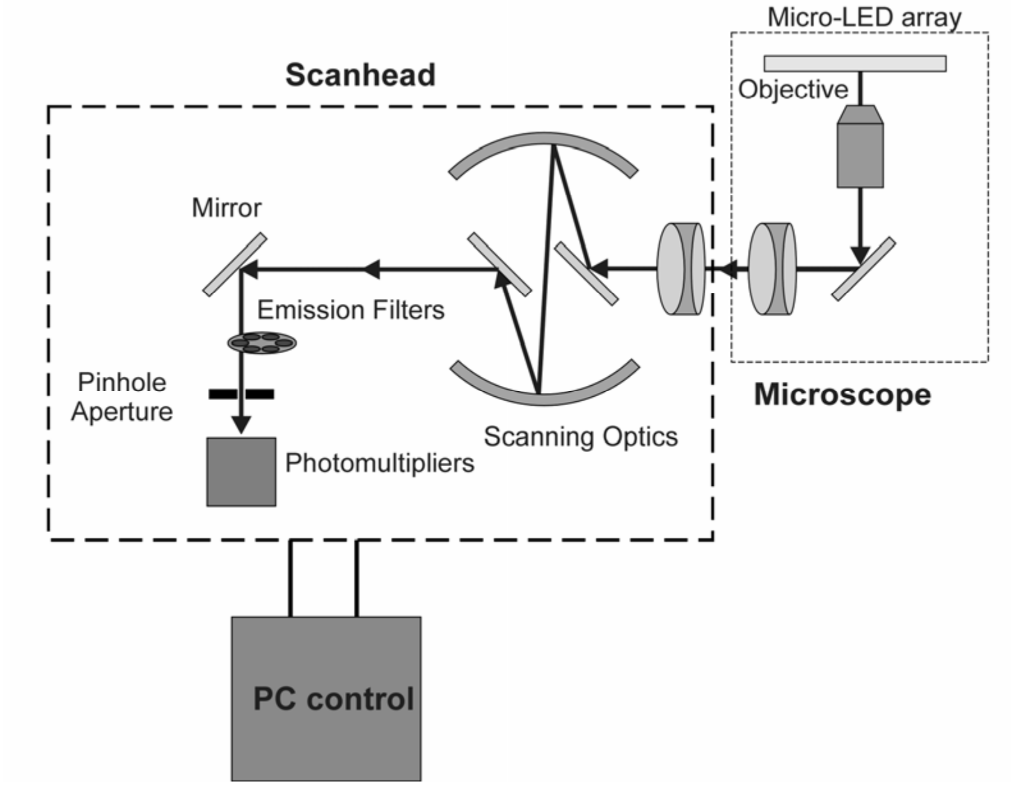
Micro-LED array
Scanhead
Objective
Mirror
Emission Filters
Pinhole
Aperture
Microscope
Scanning Optics
Photomultipliers
PC control

Fig. 1

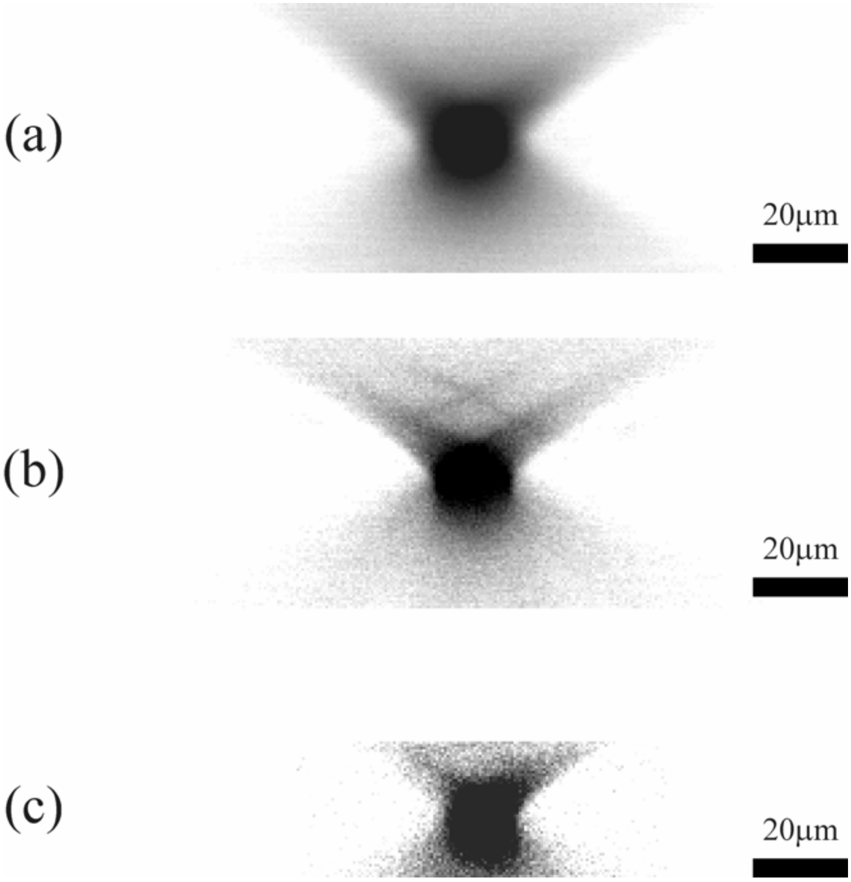

Fig.2

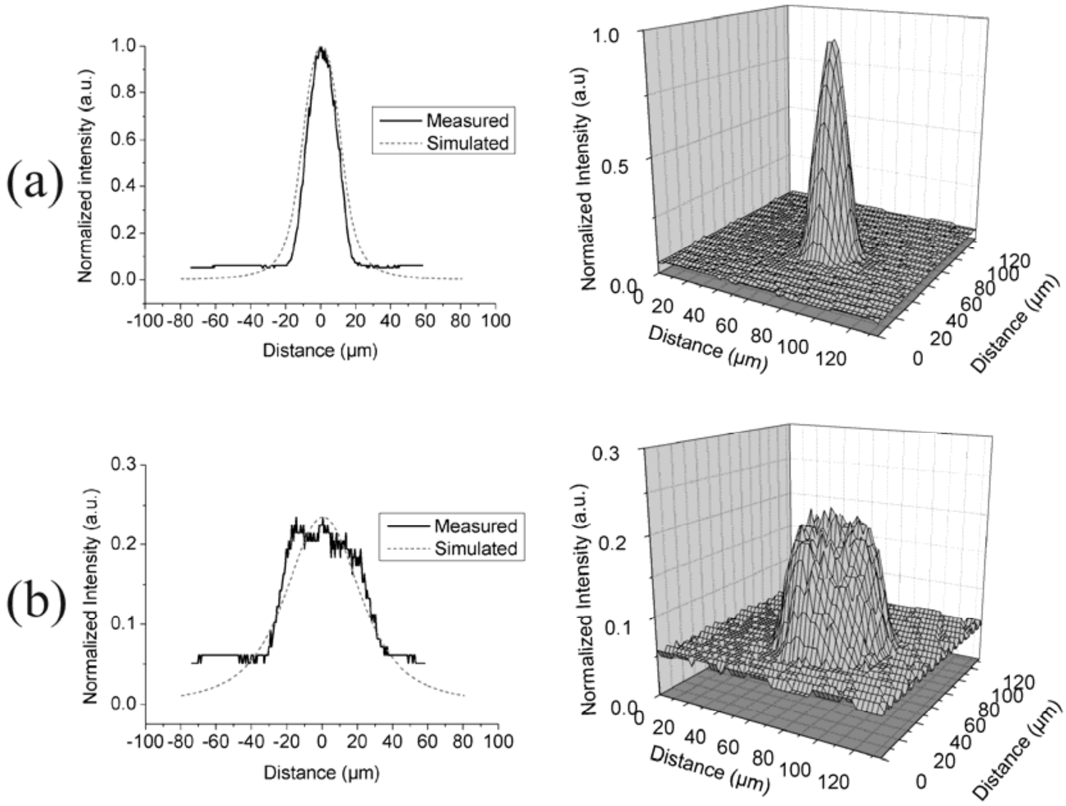
(a)
Normalized intensity (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
-100 -80 -60 -40 -20 0 20 40 60 80 100
Distance (µm)
Measured
Simulated
Normalized Intensity (a.u.)
1.0
0.5
0.0
0 20 40 60 80 100 120
Distance (µm)
0 20 40 60 80 100 120
Distance (µm)
(b)
Normalized Intensity (a.u.)
0.3
0.2
0.1
0.0
-100 -80 -60 -40 -20 0 20 40 60 80 100
Distance (µm)
Measured
Simulated
Normalized Intensity (a.u.)
0.3
0.2
0.1
0.0
0 20 40 60 80 100 120
Distance (µm)
0 20 40 60 80 100 120
Distance (µm)

Fig. 3

Table I: LED beam profile results

Colour	**Wavelength (nm)**	**Objective NA**	**Second moment Beam divergence (full angle)**
Green	510	0.75	72 ± 5°
Blue	468	1.35	65 ± 5°
Blue	468	0.75	70 ± 5°
UV	370	0.75	75 ± 3°
Simulated	-	-	71°