Photonic Crystal LEDs

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A team comprising of EPFL, OSRAM Opto Semiconductor and CSEM set out to look at the possibilities of enhancing the directionality of LEDs by etching a photonic crystal in its surface.

Thin-film LEDs can have efficiencies in excess of 35%. While these efficiencies are impressive, LEDs are Lambertian sources, i.e., they emit light into all directions from their surface. For many applications, such as backlights for LCD displays and in LED projectors, a directional light source would be advantageous. Recently there has been a growing interest in using 2 dimensional photonic crystals (PhC) etched into the surface of LEDs to control both the light emitted in the plane of the device and how the light is extracted. PhCLEDs are now finding their way into the marketplace. The goal of the project was to assess the potential of PhCLEDs for improved directionality without loss of efficiency.

CSEM has a strong know-how in LED modelling, while the EPFL team are leaders in 2-D photonic crystal design, fabrication and testing. The teams used a variety of tools to examine the prospects of PhCLEDs based on the commercial structures of OSRAM, while developing general design rules.

A 2D photonic crystal can be used in three ways: The first is to place it at the edge of the device as side-mirrors that will extract the light travelling in the plane of the device. This approach was rejected as the state-of-the-art devices already have facetted sidewalls which reproduce this function. The second is to make a deep etched crystal which goes into the active region of the device, in order to use PhC effects for spontaneous emission control, i.e., mainly by inhibiting in-plane emission. The drawback is that any etching near the active region lowers the internal quantum efficiency of the device by producing non-radiative defects. The third approach is to etch a relatively shallow crystal in the surface. In this case the PhC plays the role of a complex 2D grating.

Photonic crystal extractors (gratings) have become popular in the last few years particularly for GaN based LEDs, where thin film LED techniques used in AlGaInAsP are not available. PhC LEDs are now available commercially with more improved directionality than standard LEDs. The open questions are: How much can the directionality be improved using 2D PhC and what structure is the best ?

The work consisted of two parts, one was to look at the spontaneous emission inside the Osram LED, its mode structure and the overlap of the modes with an PhC extractor. In order for the extraction to be efficient this overlap should be large. At the same time the PhC should not perturb the mode too much otherwise new modes will appear that are de-coupled from the PhC.

The mode structure and the fraction of light emitted into each mode were successfully modelled (Figure 1). Up to 40% of the light is emitted into in-plane guided modes and is typical for most double heterojunction AlGaInAsP LED.

For extraction, an ideal structure has to diffract these modes out regardless of the in-plane direction. Equivalently the Fourier Transform of the extractor should be a circle. The real space structure needed is therefore one without translational symmetry, i.e., no preferred direction, while having a well-defined mean length. A good candidate is a highly polycrystalline close-packed monolayer of sub-micron beads.

Even with this ideal structure, calculations show that only 60% improvement in directionality can be achieved, becoming closer to 30% in practice due to finite spectral linewidth of the LED and limitations in the structure of the LED imposed by technological limitations such as efficient current injection.

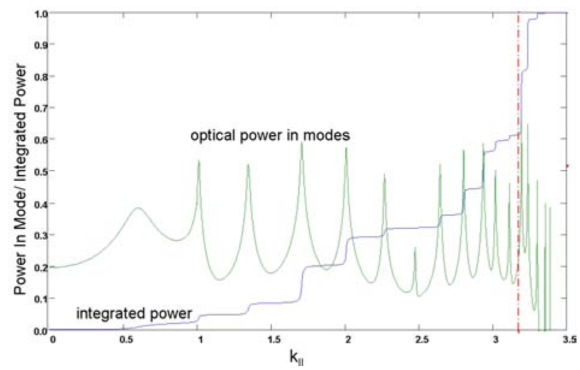

Figure 1: Calculated power emitted by the different modes of the thin-film LED and the integrated power as a function of the effective index or $k_{||}$ of the mode. The modes which are trapped in a waveguide around the active layer are to the left of the dot-dashed line and represent about 30% of the total optical power.

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