Abstract

Light-emitting diodes (LEDs) are excellent candidates to replace the widespread conventional incandescent and fluorescent light sources. This stems from their higher compactness and brightness, as well as their better performance in terms of energy efficiency, long lifetime and high color rendering qualities. Their potential use in a broad number of applications attracted enormous interest to the LED research and development. This translated in a rapid improvement of the LED characteristics as well as in their commercialization in past years. Further integration and miniaturization of these devices, for applications such as optical communications, requires a higher level of control in terms of LED emission characteristics control and a compact solution for any desired functionality on the output. Metasurfaces (structured surfaces with engineered characteristics) grant an unprecedented control over the wavefront of light, while retaining a subwavelength-thickness character (relative to the excitation light wavelength). Moreover, in some cases, they also offer opportunities for large scale industrial fabrication. Among the different types of metasurfaces, those based on dielectric and semiconductor materials typically exhibit lower losses comparing to metallic counterparts, which potentially enhances the efficiency of the integrated device.

The main focus of this dissertation is the compact and novel LED devices, with light emission characteristics on demand, by means of dielectric metasurfaces. For this purpose, highly efficient metasurfaces based on dielectric and semiconductor materials (Si, TiO_2, GaN) have been designed and fabricated. The functionalities realized with these include beam deflectors, polarization beam

splitters, complex light field generators and lenses. For the latter, a novel class of metasurfaces with asymmetric radiation profile was engineered. With them, light channeling into a single desired diffractive order has been achieved with efficiencies reaching 99%. Ultra high angle beam deflection metasurfaces operating in visible regime were demonstrated using TiO_2 for blue and green and Si for red part of the spectra. Based on this concept, a near unity numerical aperture (NA) lens was designed and fabricated, far exceeding any previously reported, both commercial and laboratory experimental models.

Moving towards direct metasurface integration in conventional LED platforms, *GaN* metasurfaces were etched directly into optically thick *GaN* slabs. Despite the low index contrast between metasurface and the substrate (both *GaN*), the metasurfaces exhibited high efficiencies within the operational wavelength range of the LED emission. However, when excited with the photoluminescence signal from the LED, the desired functionality was lost due to the low spatial coherence (Lambertian shape of radiation pattern) of the LED. Hence, the approach of direct integration of the metasurface on top of LED was shown to be inefficient.

To solve this issue, an external and internal cavity design solution for LED and metasurface integration was proposed and engineered. The efficient transformation of the Lambertian radiation pattern into plane-wave-like radiation, suitable for the metasurface to work, was experimentally demonstrated. Further integration with the designed metasurfaces allowed obtaining advanced functionalities for the LED emitted light, viz. beam deflection and vortex beam generation. Those were realized in a *GaP* LED architecture via optical pumping.

The results presented in this dissertation constitute a step forward towards compact, advanced, efficient and integrated optical devices, by leveraging on the attractive platform of LEDs and the emerging field of metasurfaces, which enables the unprecedented control of light. The method proposed can be applied to any other incoherent light sources beyond LEDs, and may find broad applications in optical communications, Li-Fi, displays, advanced lighting and many more.

Keywords: LED, dielectric metasurfaces, RCLED, high angle beam deflection, high NA lens, vortex beam, OAM, Si, TiO_2, GaP, GaN.