Light-Emitting Metasurfaces: A Metalens Approach for Focusing Spontaneous Emission

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Abstract: We present a metalens design made from GaN nanopillars with embedded quantum-well emitters. We fabricate, using nanolithography, metalenses with different focal lengths and observe that the proposed design can effectively focus the emitted photoluminescence.
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1. Introduction

Semiconductor metasurfaces consist of arrays of high-index resonators wherein the electromagnetic phase and amplitude are engineered by changing the shape or size of the resonator [1,2].While phased-array metasurfaces have been extensively studied as flat alternatives for wavefront shaping, much less emphasis has been put on their capability to tailor spontaneous emission. Significant brightness enhancement and control over far-field radiation patterns were recently demonstrated in spatially uniform symmetry-broken light-emitting metasurfaces [3]. In another recently proposed design, control over far-field radiation pattern can be substantially increased by more complex phased-array structures, enabling e.g. highly directional beaming (i.e. phased-array metasurfaces) [4].

In this work, we demonstrate beaming and focusing of photoluminescence (PL) using two-dimensional metasurface axicons and lenses. Transmission phase is varied by modifying the radius of approximately-1-um-tall GaN nanopillars at the emission wavelength (510-590 nm) of embedded InGaN quantum wells. Building upon our understanding of initial 1-D light emitting beam deflectors, we design 2-D axicons with preferred emission along defined output momenta and 2-D lenses with varying focal lengths.

2. Design, fabrication, and optical characterization

Typical metasurface lenses are designed to focus normally incident light. Light emission from the embedded GaN/InGaN quantum wells, however, is peaked beyond the critical angle, at a transverse momentum of $1.06k_0$. To redirect these oblique rays into a normal exitance focused beam, we use an off-axis phased-array lens equation

$$\varphi(r) = -k_0 n(\sqrt{f^2 + r^2} - f) + 1.06 k_0 r, \qquad (1)$$

where, n is the index of refraction of the focusing medium, k_0 is the wavenumber in free space, f is the focal length, and r is the radial distance from the center of the lens. The second term in eq. (1) accounts for the phase accumulation imparted by traveling surface waves.

The sample was grown hetero-epitaxially on (0001) c-plane double side polished sapphire substrate by atmospheric pressure metal-organic chemical vaper deposition (MOCVD). The whole structure consisted of an AlGaN nucleation layer, an ~0.85-µm unintentionally doped (UID) GaN layer, three-period multiple quantum wells (MQWs) with a 3 nm InGaN QW, a 2 nm Al0.3Ga0.7N cap and a 10 nm GaN barrier. Finally, a 100 nm UID GaN protective buffer is grown on top to serve both as a protection layer for the emitting QW from fabrication damage and also as the necessary boundary conditions for the emitted light to be channeled through the etched nano-pillar into the substrate.

420 nm of SiO_2 was deposited on the substrate accompanied by 32 nm of ruthenium deposition to serve as the hard mask for the GaN etch. Hydrogen silsesquioxane (HSQ) was spun as a negative resist for electron beam lithography and then developed after the exposure. A ruthenium etch, followed by a SiO_2 etch, followed by another

ruthenium etch was used to transfer the pattern to the GaN surface. The GaN was then etched in an inductively coupled plasma (ICP) etcher and the remaining SiO_2 was removed using hydrofluoric acid (HF). Fig. 1(a) shows an SEM image of a portion of a metalens designed to focus the PL at a focal length of 100 um, into the sapphire substrate.

To perform the measurements, we mount the samples on the stage of an inverted microscope and pump them from below through a 20-X objective lens using a 405-nm LED. The incident light is passed through a diffuser to create a uniform excitation. The emitted PL is then collected from the bottom through the same objective lens and imaged by a camera (the diffuser is not in the collection path). We then scan through the sapphire substrate and record the real-space images. Fig. 1(b)-(e) show the focusing performance of a lens designed to focus the PL 100 um away from the surface into the substrate (i.e. at z=100 um). The PL gets focused at z=100 um and gets de-focused as we move to z=200 um, and z=300 um, respectively.

The presented results are especially promising, since they facilitate development of light sources with metasurface-derived functionalities such as direct focusing and directionality with low beam divergence.

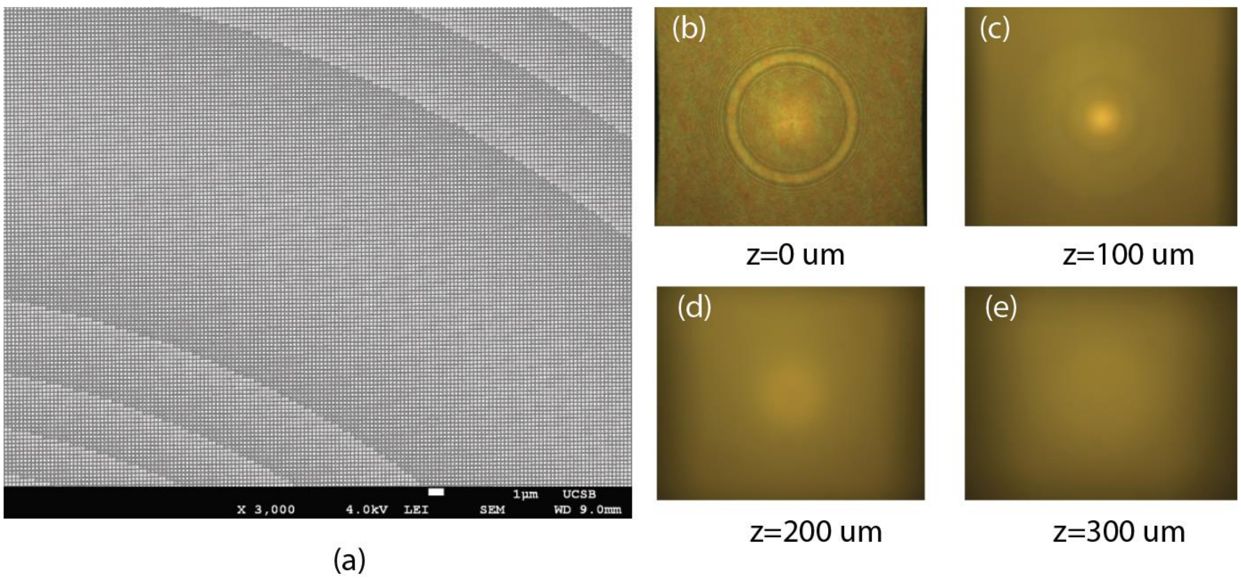

Fig. 1. (a) SEM image of a portion of a metalens designed to focus the PL at z=100 um. (b)-(e) Real-space images of the PL at different z values for the lens designed to have a focal length of 100 um.

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3. References

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