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Controlling the Direction, Topological Charge, and Spectrum of Transition Radiation with Holographic Metasurfaces

G. Li [1, 2], B. Clarke [1], J. K. So [1], K. F. MacDonald [1], X. Chen [2], W. Lu [2], and N. I. Zheludev [1, 3]

[1] Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, UK
[2] National Key Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 200083, China
[3] Centre for Disruptive Photonic Technologies, Nanyang Technological University, 637371, Singapore
bpc1e13@soton.ac.uk

Abstract **– We show experimentally that wavefront - the direction, spectral composition and phase profile of light emission - stimulated by free electron injection into plasmonic and dielectric media can be controlled with high finesse using holographic nanostructures.**

I. INTRODUCTION

Controlling the emission of light from nanoscale sources is a challenge of growing technological relevance in photonics, optoelectronics and bioscience. Here, we demonstrate that by locating such sources within an engineered nanostructural environment one may convert the typically highly divergent output radiation pattern into virtually any desired wavefront with controlled directionality, divergence, spectral composition, and phase profile (Fig. 1).

Photonic crystals [1], surface waves [2], optical nanoantennas [3], and photonic metamaterials [4] can provide some measure of control over the coupling of light from the nanoscale into well-defined free-space modes but are typically constrained to manipulating the direction and polarization of emitted light. In this work, we propose a flexible means of precisely controlling the wavefront of light emanating from a singular nanoscale emitter.

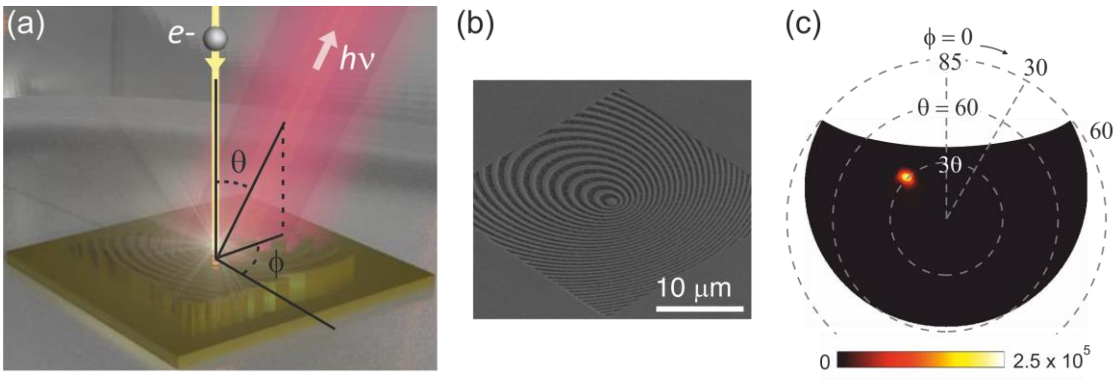

Fig. 1. (a) Artistic impression of wavelength, direction and divergence controlled far-field light emission from an electron impact (transition radiation) point-source on a holographically nanostructured surface. (b) Scanning electron microscope image of a holographic structure to generate a low-divergence 800 nm output beam at θ = 30° to the surface normal. (c) Angular distribution of 800 nm light emission generated by electron-beam impacting the centre of the hologram in panel (b).

II. METHODS, RESULTS & DISCUSSION

Our source is the impact point of a free electron beam on a surface. Such impacts generate transition radiation with a dipolar emission distribution and, in plasmonic media, surface plasmons with cylindrical symmetry propagating away from the impact point (the latter only contributing to free-space light emission in the presence of a decoupling structure such as a grating). The holographic interference pattern required to generate a given far-field output wavefront is obtained computationally using the near-field distribution of an electric dipole above the surface (mimicking the free-electron impact source) as a reference beam.

Holographic nanostructures are fabricated by focused-ion-beam milling and their electron-induced radiation emission performance is studied in a scanning electron microscope (operating in fixed-spot mode with a spot size of 50 nm, electron energy of 30 keV, and beam current ~10 nA) equipped with angle-resolved cathodoluminescence imaging capability [4]. Figure 1b shows a nanostructure realized in an optically thick gold film, designed to produce a minimally divergent, radially polarized beam with an output polar angle θ = 30º at a wavelength of 800 nm. Figure 1c presents the 800 ± 20 nm light emission distribution for electron injection on at the centre of the holographic mask, showing strongly directional emission at θ = 30° (Fig. 1b) as intended by design. The intensity profile of the output beam as a function of polar angle is presented in Fig. 2.

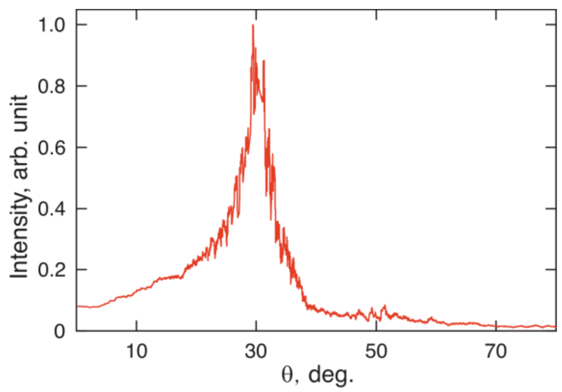

Fig. 2. Intensity of 800 nm light emission from the plane-wave generating hologram (Fig. 1b) as a function of polar angle.

Holographic patterns can be engineered to produce complex wavefronts such as high topological charge optical vortex beams, as illustrated in Fig. 3, and may be designed for a wide variety of metal, semiconductor and dielectric substrate media (in the case of metals such as gold, the surface plasmons generated by electron impact make a significant contribution to the emission but are not essential to the emission control paradigm).

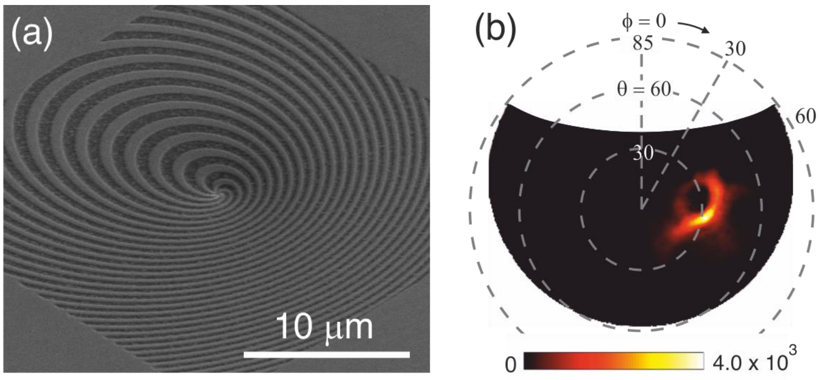

Fig. 3. (a) SEM image of a holographic nanostructure to generate an 800 nm output beam with vortex phase-profile with topological charge of 6 at θ = 30° to the surface normal. (b) Angular distribution of a light emission generated by electron-beam impacting the centre of the hologram in panel (a) showing the characteristic ring shaped intensity profile of an optical vortex beam.

IV. Conclusion

We have shown that the wavefront of light emission from single nanoscale emitters can be manipulated by design using holographic nanostructures. The concept is demonstrated in application to light emission induced by the impact of free-electrons on surfaces, with structures engineered to produce directional, low-divergence beams, including optical vortex beams, at selected wavelengths as opposed to the broadband divergent emission ordinarily generated. It may equally be applied to nano-scale sources such as quantum dots and fluorescent molecules in a variety of photonic and spectroscopic applications.

Acknowledgement

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