Holographic Control of Free-electron Light Emission

Guanhai Li[1, 2], Brendan Clarke[1], Jinkyu So[1], Kevin F. MacDonald[1], Xiaoshuang Chen[2], Wei Lu[2], and Nikolay I. Zheludev[1, 3]

1. Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of 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, Singapore 637371, Singapore

We report on the design and demonstration of holographic nanostructures via which the wavefront of light emanating from singular nanoscale emitters can be manipulated. Locating such a source within an engineered nanostructural environment enables the conversion of typically highly divergent and often spectrally broad radiation patterns into virtually any desired wavefront with controlled directionality, divergence and spectral composition (Fig. 1a).

Here we utilize the impact point of a free electron beam on a surface as the singular, highly localized source. Such impacts generate transition radiation with a dipolar emission distribution and in plasmonic media (i.e. especially the noble metals) surface plasmons propagating with cylindrical symmetry away from the excitation point, which contributing to free-space light emission only in the presence of a decoupling mechanism such as a grating. For a given desired far-field output wavefront, the requisite holographic pattern 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. Figure 1a shows a model nanostructure designed to produce a minimally divergent, radially polarized beam with an output polar angle of 30º at a wavelength of 800 nm.

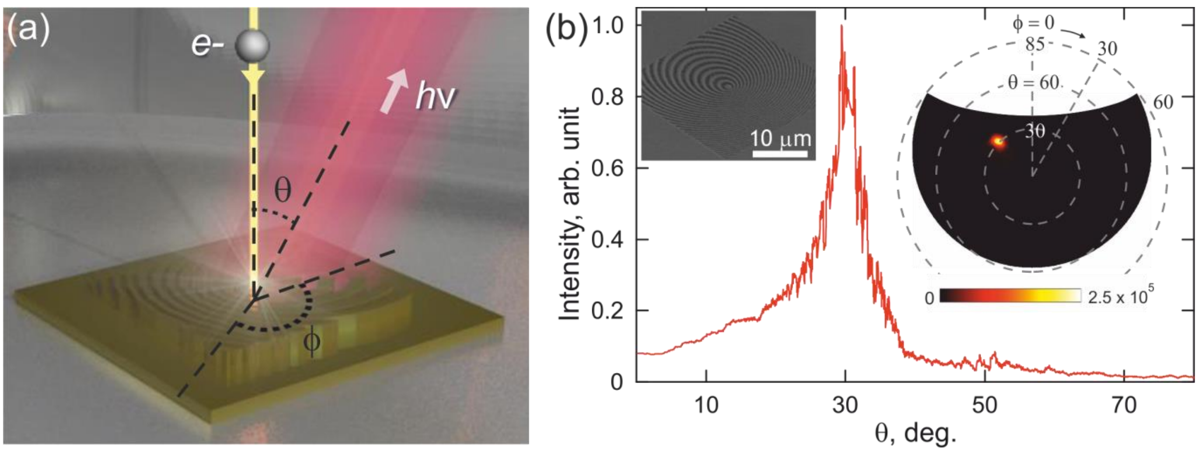

Fig. 1 (a) Artistic impression of direction/divergence controlled far-field light emission from electron impact on a holographic mask. (b, left inset) Scanning electron microscope image of a holographic structure produced in a gold surface to generate a low-divergence 800 nm output beam at 30° to the surface normal [i.e. to the incident electron trajectory]. (b, right inset) Angular distribution of 800 ± 20 nm electron-induced light emission from said hologram. (b) 800 nm emission intensity as a function of polar angle.

The left inset to Fig. 1b shows a realization of this binary holographic nanostructure, by focused ion beam milling, on an optically thick gold substrate. The spectral and spatial distribution of electron-induced light emission from such structures is analysed 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. The right inset to Fig. 1b presents the 800 nm light emission distribution for electron injection on at the centre of the holographic mask, showing strongly directional emission at $\theta = 30°$ (Fig. 1b) as intended by design.

In the case of metals such as gold, the surface plasmons generated by electron impact make a significant contribution to the emission but the approach may be adapted at the holographic design stage to a variety of nanostructured metal, semiconductor and dielectric media (and indeed to other nanoscale 'point sources' such as quantum dots or fluorescent molecules). We demonstrate that holographic structures can also be designed to produce complex wavefronts such as high-order vortex beams.