Metasurface Holographic Light Sources Driven by Electron Beam

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Abstract: We apply holographic principles to tailor light emission resulting from the injection of free electrons into a nanostructured surface and demonstrate robust control over the direction, divergence, wavelength and topological charge of radiation emission.

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We report here on the demonstration of a flexible approach allowing generation of optical radiation with prescribed wavelength, direction, divergence and topological charge, induced by point-injection of free-electrons into holographic plasmonic metasurfaces. The approach is illustrated via the generation of visible/near-infrared light at selected wavelengths in prescribed azimuthal and polar directions with brightness two orders of magnitude higher than from an unstructured surface, and the generation of vortex beams with topological charge up to ten (Fig. 1). Cross-talk between neighboring, or indeed overlapping hologram designs is low, providing for many emitters to be integrated such that optical output can be spatially and spectrally modulated by a scanning electron beam.

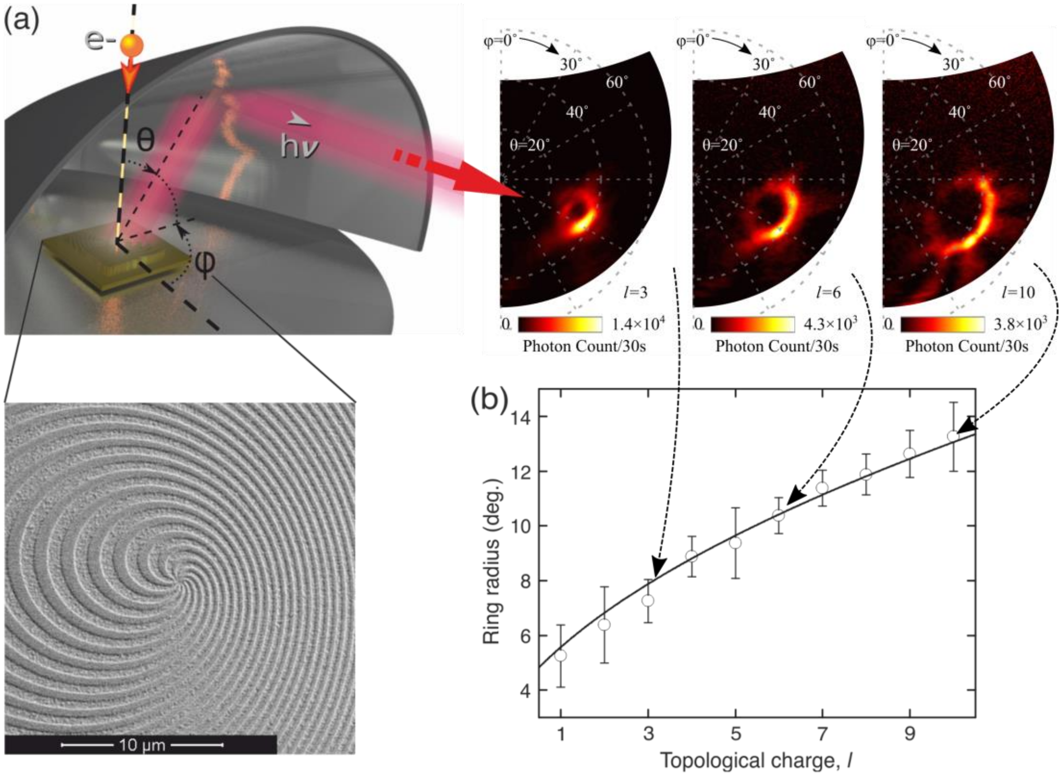

Fig. 1: Angle-resolved spectroscopy of vortex beam emission from holographic free-electron light sources: Schematic of the electron microscope-based arrangement for angle-resolved electron-induced light emission spectroscopy: Electrons impinge on samples through a small hole in a parabolic mirror, which collects and collimates emitted light, directing it to either a spectrometer or imaging CCD. To the right are presented the angular distributions of 800 ± 20 nm light emission for a selection of vortex-beam output holographic structures, an example of which is shown in the scanning electron microscope image [lower-left]. This mask, which is etched to a depth of ~60 nm in an optically thick gold film, is designed to generate a vortex beam of topological charge $l = 10$. (b) Radius of the ring-shaped vortex beam intensity profile as a function of topological charge l, showing a dependence of the expected $A(l+1)^{1/2}$ form.

Great attention has lately been focused on light generation via free-electron proximity and impact interactions with nanostructures including gratings, photonic crystals, nano-undulators, metamaterials and antenna arrays. These have enabled the development of nanoscale-resolution techniques for such applications as mapping plasmons, studying nanoparticle structural transformations and characterizing luminescent materials (including time-resolved measurements). Here we experimentally demonstrate individual and interlaced arrays of selectively addressable free-electron-driven light sources based upon holographic surface structures that provide control over the direction, divergence, wavelength and topological charge of light emission.

For a given desired far-field output wavefront, the requisite surface structure is obtained interferometrically using the near-field distribution of divergent broadband emission emanating from the impact point of an electron beam on a surface as the reference beam: Figure 1 shows a structure, realized by focused ion beam milling in an optically thick gold film, designed for a wavelength of 800 nm, to produce a vortex beam of topological charge *l* = 10 at an output polar angle of 30º. And it presents the corresponding spatial distribution of electron-induced light emission, which is recorded 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 electron-induced radiation emission imaging capability. An output with the characteristic ring-shaped intensity profile of a vortex beam is observed at an angle of 30º, as intended by design.

Cross-talk between holographic elements of this kind is minimal; with emission from a second mask overlapping a given target mask (both of diameter 20 µm) being attenuated by 3 dB relative to the target hologram when their centers are separated by only 2.5 µm. Several independent holographic sources can thus be interlaced over a given surface area, such that a scanning electron beam may sequentially or selectively target individual emitters to rapidly modulate the optical output signal over a half-spherical field of view (Fig. 2).

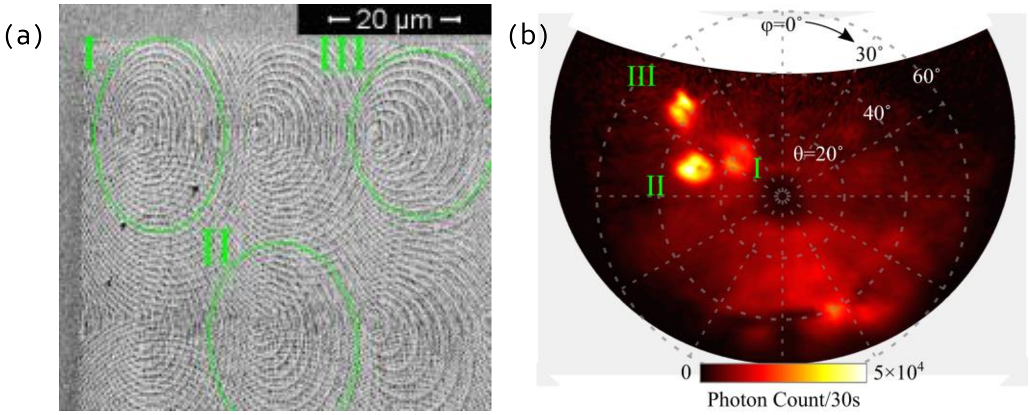

Fig. 2: Multiplexed holographic emitter: (a) Scanning electron microscope image of an array of interlaced holographic sources, each designed to generate a collimated 800 nm plane wave output beam at different azimuthal/polar angles [dashed lines enclose the central region of each]. (b) Composite of angular emission intensity distributions for electron injection at the target points of the three holographic elements highlighted in panel (a), designed for outputs at I/II/III: θ = 20/33/45º, Δφ = 0/-23/0º.

The control of energy transfer and conversion, in particular the generation of light, in nano-scale systems is a technological challenge of great and growing importance. With micron-scale dimensions and the freedom to fully control radiation parameters, holographic free-electron light sources offer novel applications in nano-spectroscopy, nano-chemistry and sensing, across a broad range of electron energies and target materials.

We will also discuss how the holographic design principles can be applied to proximity interactions between nanostructured surfaces and free-electrons flying over (but not striking) a surface - using the evanescent field of the moving electrons as the holographic reference source to once again to produce arbitrary output wavefronts at any desired wavelength.