Electron-beam-driven nanoscale metamaterial light sources

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Nanoscale light (ultimately laser) and surface plasmon (ultimately 'spaser') sources for numerous potential nanophotonic applications have generated and continue to generate considerable research interest, with a variety of optically- and electrically-pumped sources recently demonstrated. We show experimentally that beams of free electrons can be used to induce light emission from nanoscale planar photonic metamaterials, at wavelengths determined by both the metamaterial design parameters and the electron energy.

We studied planar metamaterial arrays of asymmetrically-split ring (ASR) resonators supporting *collective* trapped-mode plasmonic resonances, manufactured by focused ion-beam milling through ~70 nm gold films evaporated either onto free-standing silicon nitride membranes or onto the end faces of standard or tapered optical fibers. These sample configurations provided for the investigation of electron-beam pumping trajectories both perpendicular and parallel to the metamaterial plane (see Fig. 1). Experiments were performed in a scanning electron microscope, which provided simultaneously for imaging and targeted electron beam excitation of samples. Emitted light was collected for spectroscopic analysis either using a parabolic mirror positioned above the sample (perpendicular excitation of free-standing metamaterial films, Fig. 1a) or via the optical fiber substrate (parallel pumping trajectory, Fig. 1c).

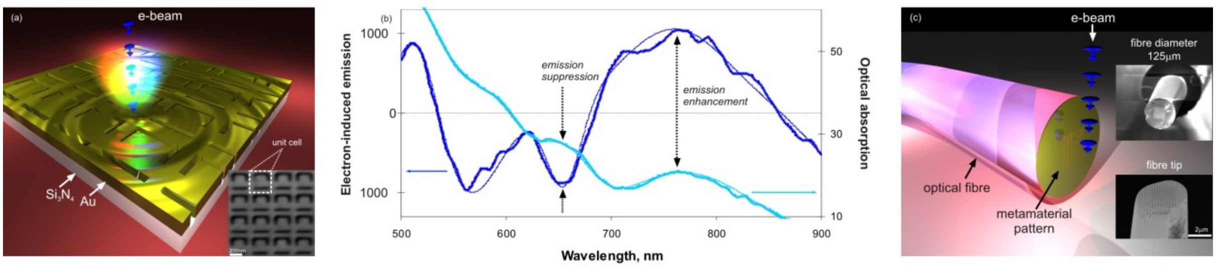

Fig. 1 (a) Artistic impression of a free-standing gold ASR metamaterial on a Si_3N_4 membrane excited by normally incident electrons. The inset shows an electron microscope image of a section of an experimentally studies ASR array; (b) Electron induced emission and optical absorption spectra for a ASR array with unit cell size of 320 nm (perpendicular electron excitation trajectory, absorption spectrum recorded using a microspectrophotometer). Arrows indicate absorption resonance wavelengths and corresponding enhancement/suppression of electron-induced light emission; (c) Artistic impression of a fibre-coupled gold ASR array excited by an electron beam with a trajectory parallel to the surface. The insets show ASR arrays on cleaved single mode and tapered fibre tips.

In both cases, energy is coupled from incident electrons to the plasmonic modes of the metamaterial structure for which propagating light modes then constitute a decay channel. A direct correlation is found between the spectral positions of metamaterial optical absorption resonances and the enhancement (or suppression) of electron-induced metamaterial light emission relative that of unstructured gold (Fig. 1b). Emission wavelengths are seen to red shift with increasing ASR size. Numerical simulations show that the in-plane and transverse spatial structure of the plasmonic modes excited in the metamaterial cells dictate the efficiency with which they can couple to light in free space.

In summary, we show that low energy beams of free-electrons can act as a broadband excitation sources for the collective plasmonic modes of photonic metamaterials, thereby driving resonant light emission at wavelengths determined by the structural design parameters of the metamaterial, which may be adjusted for operation across the visible to infrared range.