Purcell Enhancement of Free-Electron Spontaneous Light Emission Using Meta-surfaces

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Abstract: We experimentally demonstrate that spontaneous light emission from free electrons can be enhanced using resonant meta-surfaces in much the same way as spontaneous emission from atomic electrons is enhanced by placing them in resonant cavities.

Atomic electrons in vacuum undergo spontaneous emission as they transition from excited states to lower energy states, and the rate of transition can be suppressed or enhanced by introducing mirrors or cavities – a phenomenon known as the Purcell effect. Free electrons moving in vacuum can also radiate by spontaneous emission, but only when they are in close proximity to a slow-wave medium or optical inhomogeneity. The former gives rise to well-known Cerenkov radiation, the latter to so-called diffraction or Smith-Purcell radiation. Here, we demonstrate that spontaneous emission from free electrons, specifically Smith-Purcell emission, can also be enhanced using plasmonic meta-surfaces. The gold nano-slit arrays adopted here support resonances dependent on slit length, resulting in resonant enhancement of Smith-Purcell emission relative to that generated by standard diffraction gratings.

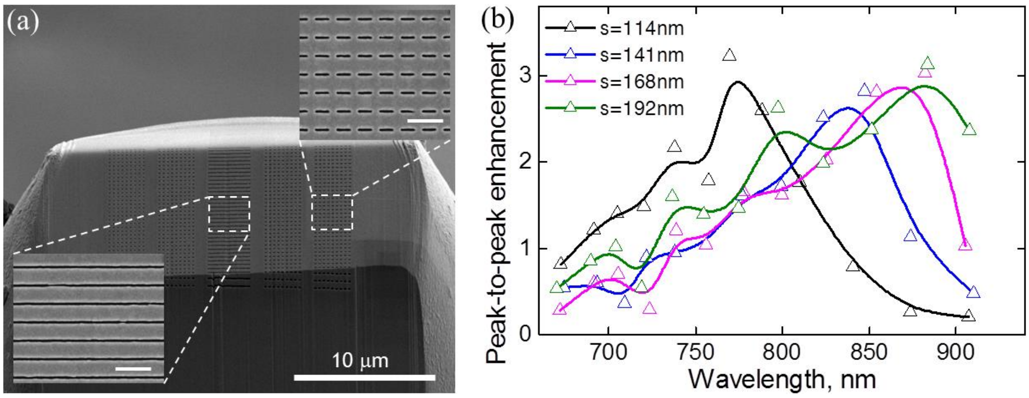

Figure 1: *Fig. 1: (a) Scanning electron microscope image of a gold-coated tapered optical fibre probe tip patterned with four nano-slit arrays and a reference grating, all with a 260 nm period in the electron propagation direction [inset scale bars = 500 nm]. (b) Spectral dispersion of emission enhancement by nano-slit arrays with a selection of slit lengths [as labelled] relative to reference grating emission.*

Momentum conservation in the Smith-Purcell emission configuration is satisfied by providing appropriate structural periodicity in the propagation direction of moving free electrons. This period is set to d = 260 nm in the present study such that the emission wavelength in the surface normal direction ranges from 914 - 660 nm for electron energies from 22 - 45 keV. Four nano-slit arrays and a reference grating are manufactured by focused ion beam milling in a 50 nm gold film on a single optical fibre probe tip (Fig. 1a). The nano-slits are resonant with an electric field polarization perpendicular to the long axis and designed here with lengths, s from 114 - 192 nm to provide resonances in the 750 - 900 nm wavelength range. The fibre end face is aligned parallel to the electron beam trajectory in a scanning electron microscope and the light generated from the nano-structures is collected via the fibre for spectroscopic analysis.

That Smith-Purcell emission is generated from both the nano-slit arrays and the reference grating is confirmed by electron-energy-dependent emission wavelengths matching theoretical Smith-Purcell wavelengths. The effect of the meta-surface resonances is illustrated in Fig. 1b, which presents the spectral dispersion of emission enhancement (relative to the grating emission) for each nano-slit array – the enhancement being maximized in each case around the meta-surface resonance.

Higher enhancement factors than the value of 3.2 obtained for s = 114 nm slits at an electron energy of 32 keV may be achieved via optimized meta-surface design. The finding that Purcell enhancement can be obtained from planar structures as opposed to bulk cavities offers promise for the realization of compact free-electron-driven light sources.