Angle resolved cathodoluminescence spectroscopy on plasmonic nanoantennas

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Abstract

We present both radiation patterns and emission spectra for two antenna geometries, measured using a novel cathodoluminescence spectroscopy technique. We investigate the emission of a plasmonic Yagi uda antenna consisting of five gold nanoparticles and a plasmonic gold ridge resonator. For both geometries we find evidence for directional emission of light that depends strongly on the excitation position and emission wavelength.

1. Introduction

Nanoantennas have gained great interest due to their ability to enhance and redirect the radiation emission from single emitters. In this paper we study two different nanoantenna geometries using angle resolved cathodoluminescence (CL) spectroscopy. Linear arrays of metal nanoparticles act as efficient nanoscale receiving antennas for light, as we have demonstrated earlier [1,2]. These antennas concentrate an incident light beam at a well-defined wavelength-dependent position on the antenna array, similar to Yagi Uda antennas well known for millimeter waves. Vice versa, metal particle arrays can also be used to direct light into a well-defined wavelength-dependent direction. A different type of nanoantenna is a metal ridge resonator on which a guided surface plasmon polariton (SPP) mode can be excited. The ridge end facets act as mirrors for the SPPs giving the structure Fabry-Pérot type plasmon resonances when an integer number of $\lambda_{spp}/2$ fits into the length of the resonator [3]. Such a resonator bears many similarities to a metal rod antenna which is known to be an efficient nanoantenna geometry [4].

Both types of nanoantennas are excited using a 30 keV electron beam in an electron microscope. Each incident electron and its image charge in the substrate act effectively as a point dipole with a broad band spectrum that can be accurately positioned at any location on the antennas by positioning the beam. The excitation probability per incoming electron is known to be proportional to the local density of states (LDOS). The emitted radiation is collected by an Al paraboloid mirror, collecting radiation over a large solid angle. The collected radiation is directed onto the imaging plane of a 2D CCD-array: each pixel in the CCD image then corresponds to a zenithal angle θ and azimuthal angle φ of the antenna emission. The CL-imaging technique also enables imaging spectroscopy of antenna emission with a spatial resolution of 10 nm. The e-beam was raster-scanned over the antennas in 10 nm steps yielding excitation maps of the CL-intensity for different wavelengths

2. Plasmonic Yagi Uda antennas

Linear particle array antennas consisting of five Au nanoparticles with a diameter of 98 nm and 135 nm pitch were fabricated on a silicon substrate using e-beam lithography (Fig.1 (a)). In Fig. 1 (b) a CL excitation of the structure is shown for 600 nm. The outer particles are clearly brighter which is due to an elevated local density of states at that position.

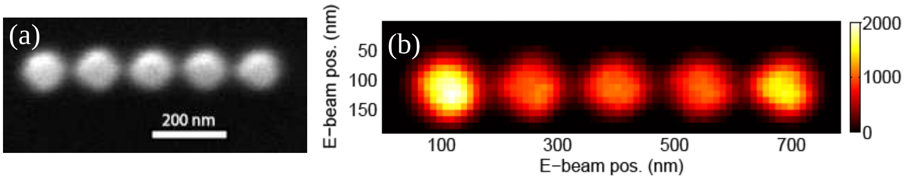

Fig. 1 (a) SEM image of a gold nanoparticle array. (b) CL excitation map of the nanoantenna for 600 nm

Subsequently we excite each of the particles and collect the radiation pattern for different wavelengths. Figs. 2 (a-c) shows the data collected for 500 nm and for excitation at outer left, center and outer right particle respectively. It is clear for excitation of the outer particles that the emission is highly directional. In Fig. 2 (b) the emission pattern is approximately symmetric as we expect from the antenna symmetry.

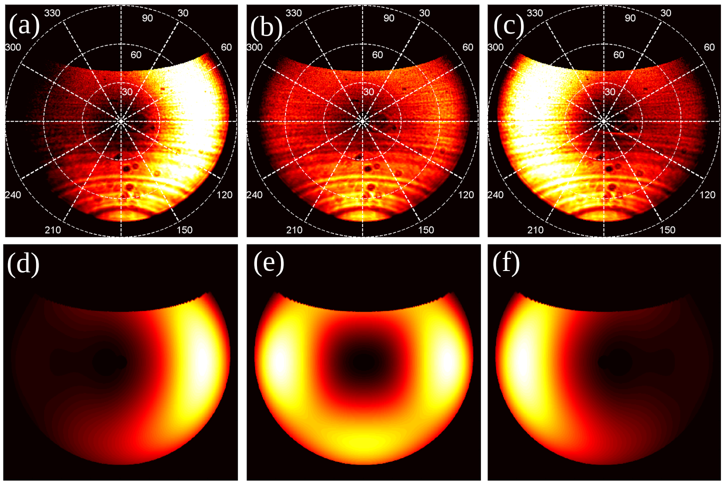

Fig. 2: Experimental and theoretical radiation patterns collected at 500 nm for excitation of (a,d) outer left particle, (b,e) center particle and (c,f) outer right particle. The antenna is oriented horizontally in these measurements.

This experimental data is well reproduced with an intuitive coupled dipole model (Figs. (d-f)) in which we place a vertically oriented dipole emitter very close to a particle to simulate the electron beam excitation.

3. Single crystalline gold ridge

A single crystalline gold ridge of 600 nm length was milled into a single crystalline gold surface using focused ion beam milling (FIB) (Fig.3 (a)). Figs. 3 (b,c) shows excitation maps of the ridge for 600 nm and 750 nm. We can distinguish standing wave patterns with 4 and 3 antinodes, corresponding to a λ and $3\lambda/2$ resonance. The λ resonance cannot be excited with free space light under normal incidence because of symmetric charge distribution but a point emitter like an electron beam can. Subsequently we collected radiation patterns for both resonant wavelengths by positioning the electron beam in antinode of the standing wave and spectrally selecting the resonance with a color filter. The results are shown in Figs. 4 (a,b) . At 600 nm the radiation pattern clearly has three radiation bands perpendicular to the antenna axis. At 750 nm, however we see only two bands, similar to a quadrupolar emission pattern. If we approximate this antenna as two radiating end facets, an increase in the number of bands for higher order resonances is indeed expected.

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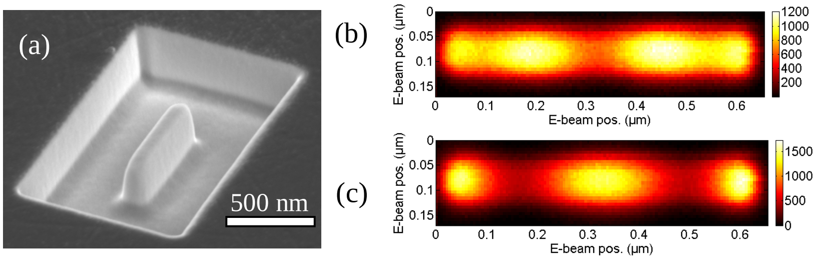

Fig. 3 (a) SEM image of a gold ridge milled in gold. (b,c) CL excitation maps of the ridge for 600 nm and 750 nm

It can also be seen that at 750 the antenna does not radiate into θ=0 direction so from reciprocity follows that this resonance indeed cannot be excited at normal incidence with light.

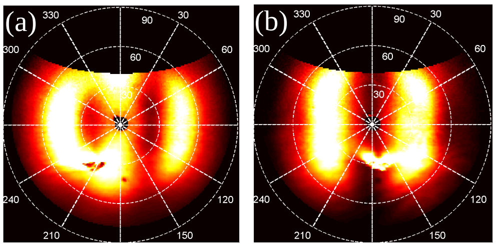

Fig. 4 Radiation patterns collected for (a) 600 nm and (b) 750 nm.

4. Conclusion

In conclusion we have shown both excitation maps and radiation patterns of two antenna geometries using angle resolved CL spectroscopy. For the Yagi Uda antenna we find that the emission pattern depends strongly on excitation position. This behaviour can be described accurately by using a coupled dipole model. For the ridge antenna we find standing wave resonances of which we also resolve the radiation pattern. We have found distinct radiation patterns for two standing wave resonances. These results illustrate how CL spectroscopy can be used to characterize nanoantennas.

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