Babinet principle for plasmonic antennas: complementarity and differences

Horák, M.[1]

[1] CEITEC - Central European Institute of Technology, Brno University of Technology, Brno, Czech Republic

Localized surface plasmons (LSP) are self-sustained collective oscillations of free electrons in metal nano- and microstructures, often called plasmonic antennas, coupled to the local electromagnetic field. LSP resonances can be characterized by electron energy loss spectroscopy (EELS) and cathodoluminescence. Both techniques utilize an electron beam that interacts with the metallic nanoparticle and excites the LSP resonances. EELS measures the energy transferred from electrons to the LSP. Cathodoluminescence deals with the light which the LSP emit during their decay. Both techniques are sensitive to the electric near field of LSP.

Babinet principle, originating in the wave theory of light and analysis of diffraction, relates the properties of a planar plasmonic antenna (particle) and a complemetary aperture in a thin metal film of the same size and shape. In particular, the energies of localized surface plasmon (LSP) resonances in both antennas shall be identical and the corresponding near fields shall be complementary with the electric field distribution of the solid antenna corresponding to the magnetic field distribution of the complementary aperture. This link allows studying the magnetic near field, for example, by measuring the electric near field by EELS in the complementary structure.

We present an experimental study of Babinet principle of complementarity in plasmonics. We have studied a set of elementary plasmonic antennas - gold discs and disc-shaped apertures in a gold layer - to investigate the basic properties of complementary structures and describe similarities and differences. While the qualitative validity of Babinet principle has been confirmed, quantitative differences have been found related to the energy and quality factor of the resonances and the magnitude of related near fields. As it is found by comparing the experimental data with a theoretical model, differences originate both from the limited theoretical validity of the Babinet principle and from different operational conditions. In particular, apertures were found to exhibit stronger plasmonic response than solid antennas, which makes them a remarkable alternative of the usual plasmonic antennas design. We also show non-existence of plasmonic breathing mode in the apertures and examine magnetic near field imaging based on the Babinet principle. Figure below shows cathodoluminescence spectra of gold disc antennas and apertures (a), dispersion relation of the LSP resonance (b), and dark field micrographs of a gold disc (c) and aperture (e) with the diameters of 100 nm with corresponding intensity maps (d,f) of the LSP resonance measured by EELS.

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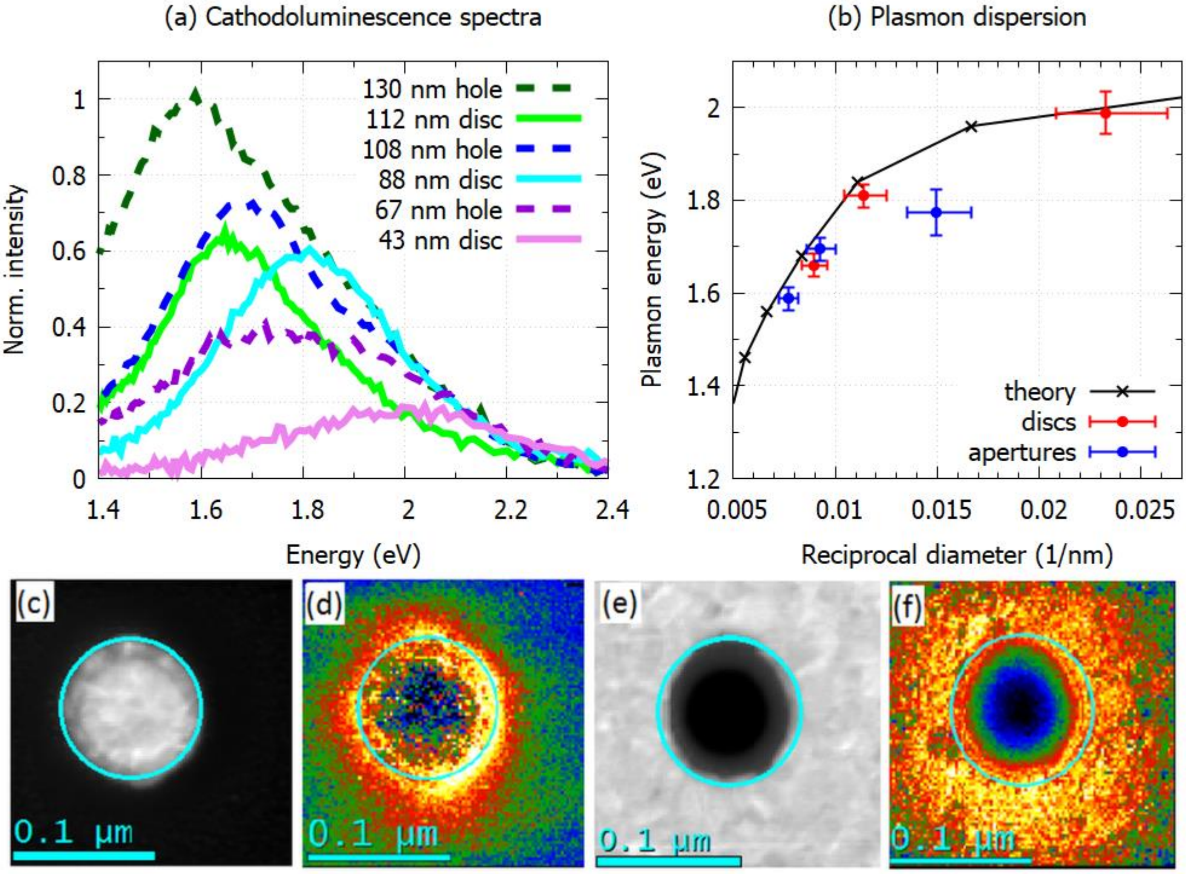

(a) Cathodoluminescence spectra
130 nm hole
112 nm disc
108 nm hole
88 nm disc
67 nm hole
43 nm disc
Norm. intensity
0
0.2
0.4
0.6
0.8
1
1.4
1.6
1.8
2
2.2
2.4
Energy (eV)
(b) Plasmon dispersion
theory
discs
apertures
Plasmon energy (eV)
1.2
1.4
1.6
1.8
2
0.005
0.01
0.015
0.02
0.025
Reciprocal diameter (1/nm)
(c)
0.1 µm
(d)
0.1 µm
(e)
0.1 µm
(f)
0.1 µm