Polarization-dependent plasmon resonances in sub-wavelength cruciform aperture arrays

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Abstract

We have fabricated square arrays of sub-wavelength asymmetric cruciform apertures and measured their infra-red transmission spectra. The spectra display two transmission maxima whose amplitudes can be tuned by varying the in-plane polarization of the incident beam. Field profile simulations show that these maxima correspond to polarization-dependent localized surface plasmon resonances in the two arms of the cruciform aperture. Between the maxima there is also a wavelength at which the amplitude is invariant for all polarizations. These combined characteristics make the arrays suitable for a broad range of applications.

1. Introduction

The optical properties of nanopatterned metallic films have inspired extensive research over recent years. One characteristic that has proven to be of particular interest is the resonant trapping and tight confinement of light in plasmonic nanostructures where the spatial domains are comparable to or smaller than the optical wavelength. This process leads to the formation of so-called localized surface plasmon (LSP) resonances [1, 2]. Recently some of us have theoretically predicted [3] that the properties of LSPs formed in a 2D array of asymmetric apertures in metallic films can be tailored so that the mid-infrared optical transmittance has a strong dependence on the polarization of the incoming field. Here we experimentally confirm this prediction by fabricating and characterising arrays of cruciform apertures. We also extend our theoretical and experimental analysis to include reflectance and absorptance. By introducing structural asymmetry in the design of the cruciform aperture, the optical transmission of a uniform, periodic array of such apertures is shown to exhibit enhanced optical anisotropy.

2. Fabrication

Our cruciform aperture arrays were fabricated on $0.5\ \mathrm{mm}$ thick single-crystal calcium fluoride substrates, due to the low absorption of this crystal at mid-infrared wavelengths. A $30\ \mathrm{nm}$ thick layer of Au was then thermally-evaporated onto the substrate, preceded *in situ* by a $5\ \mathrm{nm}$ thick Cr adhesion layer. Arrays of asymmetric cruciform apertures were then milled into the surface of the gold using a $30\ \mathrm{keV}$ gallium focused-ion-beam. The beam current was $50\ \mathrm{pA}$ and the dose $50\ \mathrm{pC}/\mu\mathrm{m}^2$. The device structure and a fabricated array are shown in Fig. 1. Each array has 15×15 unit cells and a periodicity in both the x and y directions of $\Lambda = 2\ \mu\mathrm{m}$; thus the array has dimensions $30 \times 30\ \mu\mathrm{m}^2$.

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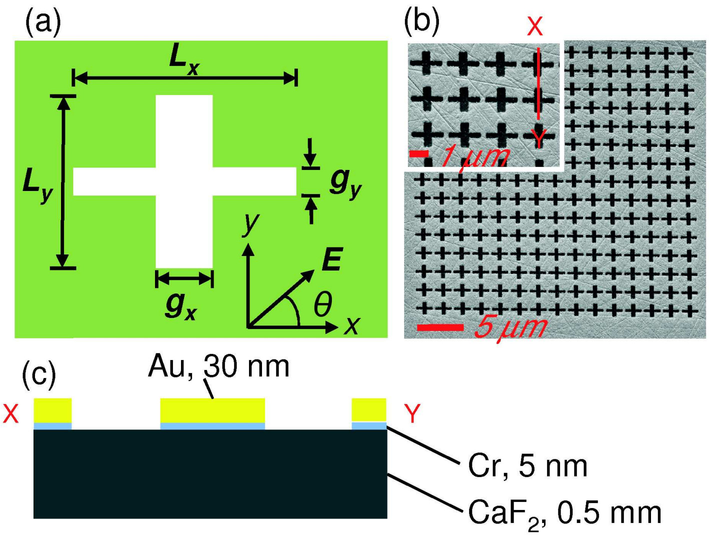

Fig. 1: (a) Schematic of the unit cell also showing the definition of the in-plane electric-field polarization angle, θ. (b) Scanning electron micrograph of an array with the inset showing magnified detail. (c) Schematic cross-section through the XY-segment, as shown in (b).

3. Transmission and reflection characteristics

The transmission and reflection spectra of the arrays were measured using Fourier-transform infrared (FTIR) microscopy. The resulting experimentally measured transmission spectra for the asymmetric cruciform array show two distinct peaks, A and B, the positions of which, to within the accuracy of the measurement, are invariant with respect to the polarization of the incident electric field (Fig. 2). As the polarization angle is changed from $\theta = 0$ to $\theta = 90°$, the amplitude of peak A decreases from its maximum value at $\theta = 0$ and eventually decays to below the noise level, while the peak B begins to emerge and increases in amplitude to reach its maximum at $\theta = 90°$. The spectra show another intriguing spectral point, I, at which transmission is independent of polarization. The absorption spectra extracted from the data in Fig. 2 are shown in Fig. 3(a).

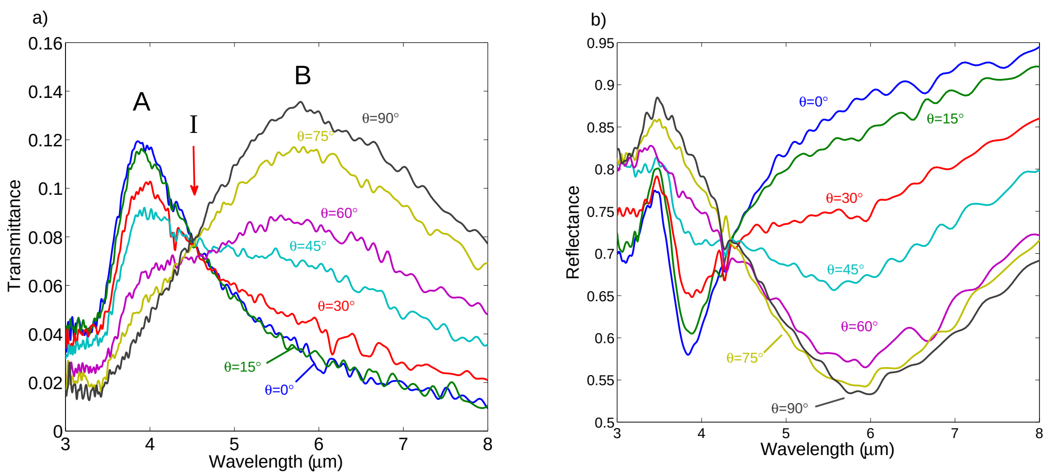

Fig. 2: a) Measured FTIR transmission spectra for an array of asymmetric cruciform apertures. Array dimensions are L_x=1675 nm, L_y=1003 nm, g_x=418 nm and g_y=165 nm. b) Corresponding FTIR reflection spectra.

In Fig. 3(b), for increasing values of L_y, the extracted spectral location of the resonant peaks A and B, as well as that of the isosbestic point I are plotted . Peak A (the shorter wavelength peak) shifts to longer wavelengths as the length, L_y, of the shorter arm increases, whereas peak B (the longer wavelength peak) is invariant with L_y. This confirms that peak A results from an LSP resonance in the shorter of the two arms of the apertures.

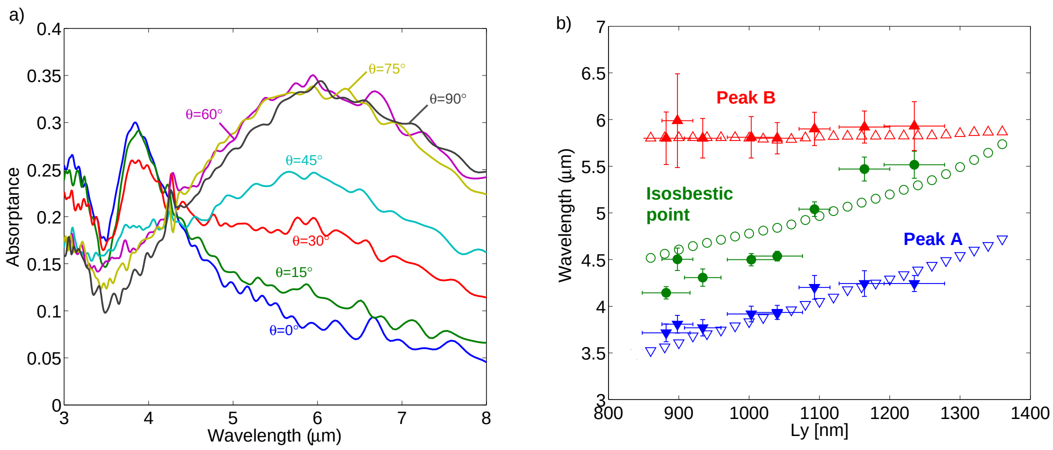

Fig. 3: a) Absorption spectrum obtained from transmission and reflection data. b) Simulation and experimental data for the L_y dependence of the wavelength of the LSP transmission resonances. Solid symbols represent experimental data, while empty symbols represent simulation data.

4. Conclusion

We have demonstrated that for metasurfaces characterised by strong form-anisotropy of the unit cell, the excitation of LSP resonances provides polarization-dependent transmission channels that strongly affect the transmission, reflection and absorption spectra of the plasmonic nanostructure. By properly engineering the shape and size of the unit cell of the array, it is possible to tune the transmission properties of the plasmonic arrays. Our findings have potential applications in plasmonics and nanophotonics, including polarization-selective absorbers, frequency-agile surfaces, plasmonic-based sensors for chemical and biomedical applications, strongly anisotropic metamaterials, and broadband negative index metamaterials.

References

[1] A. V. Zayats, I. I. Smolyaninov and A. A. Maradudin, Nano-Optics of Surface Plasmon Polaritons, *Physics Reports*, vol. 408, pp 131-314, 2005.

[2] F. Garcia-Vidal, T. Ebbesen, and L. Kuipers, Light passing through subwavelength apertures, *Review of Modern Physics*, vol 82, pp 729-787, 2010.

[3] R. M. Roth, N. C. Panoiu, M. M. Adams, J. J. Dadap and R. M. Osgood, Polarization-tunable plasmon-enhanced extraordinary transmission through metallic films using asymmetric cruciform apertures, *Optics Letters*, vol. 32, pp. 3414-3416, 2007.

