Optical Properties of Annular Aperture Arrays in Plasmonic Thin Films

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Abstract

Nanoscale annular hole arrays form plasmonic crystals which allow the optical properties of metal films to produce such important effects such as enhanced transmission, filed enhancement and negative refraction index. In this paper we report on the optical characteristics resulting from variations in the geometrical parameters of annular aperture arrays. We discuss the role of the central pillar in the transmission of light through the crystal. Further investigations are performed on annular aperture arrays fabricated in multilayered thin metal films. Finally, plasmonic crystals with a nonsymmetric annular basis are optically characterized. By offsetting the central pillar, dark modes are accessed via Fano type resonance mechanisms.

1. Introduction

In classic waveguide theory coaxial apertures allow for the propagation of TEM modes without cutoff; [3] whereas cylindrical waveguides can only support propagation of evanescent modes beyond the cutoff frequency. Building on this foundation, fabrication of nanometric sub-wavelength annular apertures arrays (AAA) in thin metal films demonstrates significant improvement over the well studied cylindrical aperture arrays.[1, 2] Initial interest stems from the structures allowing the propagation of photonic modes in sub-wavelength apertures. This in turn leads to higher transmission efficiencies per unit of exposed area.[4, 5] Due to the difficulty in experimentally producing radially polarised light the TEM mode remains unobserved. On the other hand, large transmission efficiencies have been observed for both resonant modes associated with the aperture geometry as well as surface plasmon Bloch modes arising from the periodicity of the crystal. Computational and experimental de-convolutions of the mode structure for the AAA demonstrate that the Bloch surface modes propagate through the metal film by coupling into the aperture and launching cylindrical surface plasmons (CSP).[6, 7] Likewise the aperture resonance modes propagate via CSP modes through the individual apertures in the array. Effective tailoring of modal locations potentially allows for the two mechanisms to work in conjunction with one another to further enhance transmission. Finally, the AAA is predicted to be responsible for negative refraction under certain parameters of plasmonic nano-structures.[8]

In this work, we examine several features of the optical properties of AAA structures. First we look into the role the shape the central pillar plays in the spectral behaviour of the device.[9] This is then used to examine how the transmission of systems utilising high index of refraction materials can be controlled. Finally, the influence of deformations of AAA structure are explored for accessing dark modes.

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2. Experiment

We investigate the optical properties of various configurations of annular aperture arrays fabricated in a 100 nm Au film deposited on a glass or GaP substrate. This allows for an exploration of both the spectral properties of high index of refraction plasmonic devices and to also examine the role of geometrical and orientational properties of annular apertures. Plasmonic crystals with periods between 600 nm and 700 nm were fabricated using Focused Ion Beam (FIB) etching. FIB produces structures that are slightly deviated from the ideal geometry: variations in fabrication technique allowed us to investigate the deformation of a coaxial aperture as it morphs into a cylindrical hole. The resulting pillar geometries presented are shown in Fig. 1b.

The second set of devices fabricated examine the role of different combinations of multilayer films. The three configurations examined are 100 nm of Au, a multilayer deposition of 20 nm Ag with 80 nm Au and the final multilayer film of 20 nm Al combined with 80 nm Au. The AAA fabricated on each of the six samples use the optimised FIB milling parameters from the previous study [9] to produce an aperture profile that is closest to the theoretical ideal.

The final set of structures fabricated study deformations to the planer symmetry of the AAA device. For this set of devices, FIB milling etches the arrays into 150 nm of Au deposited onto a glass substrate. The structures examined are depicted in Fig. 2. Aside from fabrication of these deformed devices, Finite Element Method (FEM) models are developed to predict their optical properties.

For all three experiments far field optical data is collected, including polarisation and angular resolved spectra. To do this, the sample is illuminated by white light coming from a tungsten-halogen bulb. Directionality of the beam is provided by passing the incident light through a collimating lens and then a polarising cube. Reduction in the size of the light beam results from passing through a pinhole aperture before becoming incident on the sample. On the output side of the sample a long working distance objective lens collects the optical information transmitted through the structure. A beam splitter then channels the transmission signal towards two separate CCD cameras. The first camera images the illuminated region of the sample allowing for set up of the experiment. Before reaching the second CCD camera the light passes through an analysing polariser cube oriented parallel to the polarisation incident on the sample. After adjusting polarisation, the light couples into a multimode optical fibre. Guided along the fibre, the signal passes into the spectrometer, where the liquid nitrogen cooled CCD collects the signal to transform it into spectral information. By mounting the sample on a four axis stage the nano structures can be centred along the optical path. By rotating the sample relative to the incident beam the dispersive properties of optical materials can be investigated.

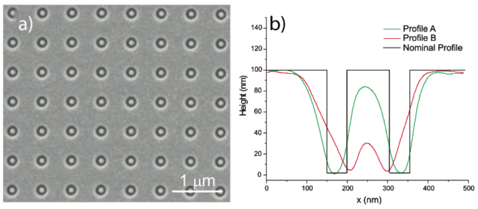

Fig. 1: a) Top down SEM image of AAA device fabricated using FIB milling. b) AFM profiles of a single co-axial aperture in the AAA; both theoretical (black), and fabricated. (green and red).

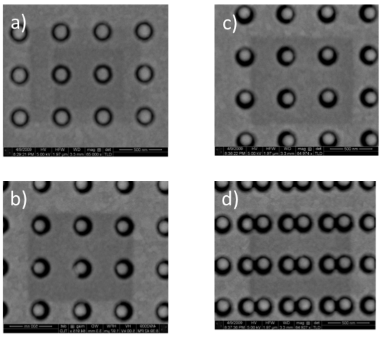

Fig. 2: Top down SEM images of aperture arrays. a) Reference AAA structure b) AAA with central pillar offset 8 nm to the left. c) Array of alternating offset pillars. d) Array of joined offset apertures.

3. Results and Discussions

In the initial study discussed in Ref. [9] the spectral results of AAA on GaP demonstrate that the pillar height and width play key roles in the shape and intensity of light transmitted by the AAA structure. As the height of the pillar reduces to a small nano-particle and then vanishes altogether the AAA eventually recovers the optical properties of the simple cylindrical hole structure. Further in this initial examination of GaP based structures interrogating the classic surface plasmon dispersion relation demonstrates that for $\lambda < 620$ nm shows that Bloch modes can not be supported on GaP-Au interface. This makes analysis of the optical properties for all devices on GaP substrates much simpler. However, surface modes are supported on the Air-Au interface; this still allows for coupling of plasmonic modes between the aperture modes and the surface modes. Further, when examining the transmission spectra and dispersion plots for the multilayer structures, the lack of surface modes on the GaP-Au interface means that the optical properties are governed by the Air-Au interface.

Finally, the optical properties of the deformed AAA structures shown in Fig. 2 offer a very complex set of transmission modes. We show that simply introducing asymmetry into the structure is not enough to fully exploit the localised modes. In order to allow for the dark modes to effectively be out coupled for enhanced transmission the device needs to offer multiple transmission paths. This is offered in this example by bringing two orthogonally offset apertures into close contact, allowing the neighbouring modes to interact.

4. Conclusion

We have investigated the role of the annular aperture parameters in optical properties of plasmonic crystals formed by their arrays. Examination of the optical properties of coaxial apertures fabricated on high index materials suggests applications for integration into light-emitting diodes (LEDs) and semiconductor lasers and solar cells. Additionally, by exploring deformations of the basic aperture geometry, applications in sensing and active plasmonic devices requiring strong field enhancement effects can be envisaged.

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