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Tuning the asymmetric response of metasurfaces for optical spatial filtering

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ABSTRACT

The spatial filtering of optical signals has been demonstrated previously with metasurface thin-films created from arrays of structured optical elements. We consider the problem of changing the symmetry of their response with changes to the in-plane wavevector $\mathbf{k}_p \rightarrow -\mathbf{k}_p$ and show it can be tailored or even dynamically tuned. Our work is based on a general theory of metasurfaces constructed from non-diffracting arrays of coupled metal particles. We present the optical transfer function of such a metasurface, identify the physical properties essential for asymmetry and demonstrate its behaviour experimentally.

Keywords: Metasurface, spatial filter, plasmonics

1. INTRODUCTION

Prior to the development of high speed computers, all-optical image processing techniques were devised to recognise complex objects in scenes.[1] These methods were based mainly on optical Fourier transforms performed by bulky lens systems. With the push to miniaturise camera systems and the desire to reduce power consumption, high speed and computationally intensive processes are less desirable, renewing interest in compact optical systems that can perform optical signal and optical image processing. In this regard optical metasurfaces will play a dominant role. These devices are artificial thin-films created from subwavelength arrays of structured elements engineered to respond in ways not found in natural materials. It was suggested recently that multilayers of metasurfaces could be used for forward and inverse optical Fourier transforms[2] enabling complex mathematical operations such as differentiation and integration to be performed in Fourier space. In this work we discuss how plasmonic metasurfaces can be designed to display asymmetric behaviour to optical spatial frequencies and show experimentally that this possible.

2. THEORY AND EXPERIMENT

We have already shown that metasurfaces created from subwavelength arrays of metal structures supporting localised surface plasmon (LSP) resonances are sensitive to the angle of incidence,[3] or the in-plane wave vector $\mathbf{k}_I$, and therefore can perform spatial filtering including phase imaging. We are interested in creating devices that respond differently to waves with $\mathbf{k}_I$ compared to $-\mathbf{k}_I$. A general formula for the response of a metasurface composed of a subwavelength array of cells containing coupled metal structures supporting localised surface plasmon resonances was given recently by Roberts et al.[4] This takes the form of an optical transfer function[5] represented by the matrix $\mathbb{O}(k_x, k_y)$ that maps the incident electric field $\mathbf{E}_i$ to the transmitted field $\mathbf{E}_t(k_x, k_y) = \mathbb{O}(k_x, k_y) \cdot \mathbf{E}_i(k_x, k_y)$,

$$\begin{aligned}\mathbb{O}(k_x, k_y) = &\sum_m p_m^2 \hat{p}_m \hat{p}_m C_{mm} \\ &+ \sum_{m,n>m} C_{mn} p_m p_n \left[(\hat{p}_m \hat{p}_n + \hat{p}_n \hat{p}_m) \cos \mathbf{k}_I \cdot (\mathbf{s}_n - \mathbf{s}_m) + i(\hat{p}_m \hat{p}_n - \hat{p}_n \hat{p}_m) \sin \mathbf{k}_I \cdot (\mathbf{s}_n - \mathbf{s}_m) \right].\end{aligned} \tag{1}$$

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The metal structures in the unit cell are labelled by integers m and n with LSP dipole moments $p_m\hat{p}_m$, $p_n\hat{p}_n$ at positions $\mathbf{s}_m$ and $\mathbf{s}_n$ respectively that are constrained to the $x-y$ plane. The factor C_{mn} represents the coupling of LSP n to LSP m and is symmetric $C_{mn} = C_{nm}$. The in-plane wave vector is $\mathbf{k}_I = (k_x\hat{x}+k_y\hat{y}) = k\sin\theta(\cos\phi\hat{x}+\sin\phi\hat{y})$ that depends on the angle of incidence θ. The last term in Eq. (1) depends on $\sin\mathbf{k}_I\cdot(\mathbf{s}_n-\mathbf{s}_m)$ that changes sign for $\mathbf{k}_I \to -\mathbf{k}_I$. This term shows asymmetric behaviour provided that the directions of the dipole moments in the coupled system satisfy $\hat{p}_m\hat{p}_n \neq \hat{p}_n\hat{p}_m$– that is, they are not parallel.

We demonstrate the asymmetric behaviour experimentally using the plasmonic Wheatstone Bridge (WB) in Fig. 1. The structure has two parallel rods that couple to a third rod at right angles (Fig 1(a)). Two polarisers control the incident and transmitted field directions (Fig. 1(b)). The spectra (Fig. 1(c)) clearly show asymmetric transmission with k_x that is controlled by the orientation ψ of the first polariser. The theoretical expression for this metasurface,[5] derived from Eq. (1), shows excellent agreement with experiment (Fig. 1(d)).

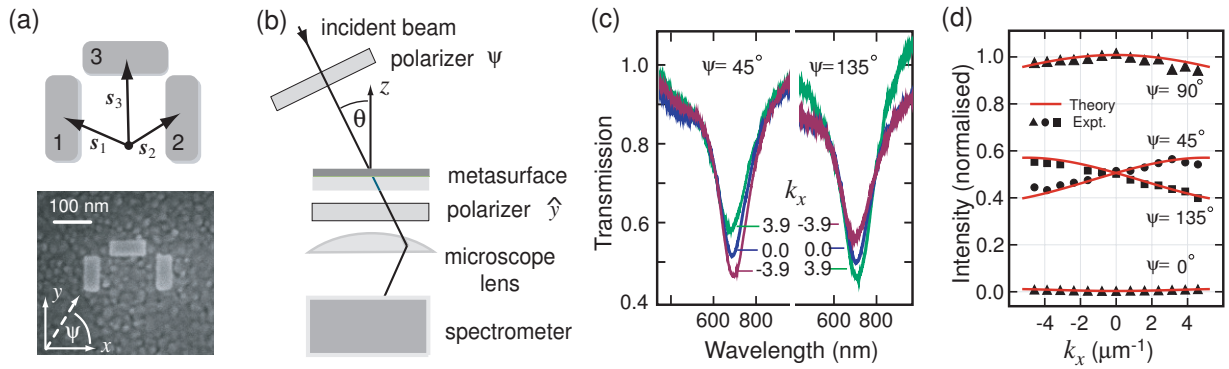


Figure 1. Experiment to measure asymmetric response of metasurface to in-plane wave vector k_x. (a) The configuration of metal rods in the unit cell showing the in-plane coordinates, an SEM image of a WB structure during fabrication and the orientation of the first polarizer. This structure is repeated over the sample surface with a period of 400 nm in both directions; (b) The experiment configuration showing the incident angle θ, the first polarizer set to angle ψ and the second polarizer aligned with the $\hat{y}$ axis; (c) Experimental spectra from the metasurface for different spatial frequencies k_x and polarizer settings ψ showing the asymmetric response; (d) Comparison between theory (solid lines) and experiment (points) (Figure adapted from Ref.[5])

Here we presented the optical transfer function of an arbitrary arrangement of resonant nanostructures, highlighting the properties essential for asymmetry. Our method lays the foundations for more complex metasurface designs for manipulating the information content in images.

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