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Merging Magnetic and Electric Resonances for All-Dielectric Nanoantenna Arrays

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Abstract: We spectrally overlap the magnetic and electric resonances in all-dielectric silicon nanodisk arrays by tuning the disk aspect ratio. This offers new opportunities for functional metasurfaces and conceptually new all-dielectric unidirectional nanoantennas.

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High permittivity dielectric nanoparticles are well known to support both electric and magnetic Mie modes due to the existence of oscillating displacement currents inside the particle. As such all-dielectric nanoparticles provide a complete analogue of plasmonic magnetic resonators, such as split-ring resonators, with the advantage of complete elimination of the metallic losses. Overlapping of the electric and magnetic resonances at the same spectral position results in suppression of backward scattering and offers intriguing new opportunities for all-dielectric nanophotonic devices. In particular, for the case of metal-dielectric core-shell particles it was recently predicted that backscattering can be completely eliminated as a result of interference between the particle electric and magnetic resonances brought into spectral overlap [1]. The predicted strong unidirectional scattering [1] has important implications for novel types of directional nanoantennas, which opens up a route towards a fundamentally new concept of all-dielectric nanoantennas. Furthermore, the spectral overlap of electric and magnetic resonances is the key ingredient for the realization of all-dielectric optical metamaterials [2].

However, to date most experiments on magnetic response of all-dielectric nanoparticles have been focused on designs with high-permittivity dielectric spheres or cubes, governed by only one geometrical parameter and having spectrally separated magnetic and electric resonances. As such, the lowest order resonance of a high-index dielectric sphere or a cube is always the magnetic mode. Therefore, such designs do not allow for the independent control over the spectral positions of the lowest-order electric and magnetic Mie modes. Here, we overcome this limitation and demonstrate experimentally that all-dielectric silicon disks enable the independent control over the induced electric and magnetic resonances of the particles. Our design offers the opportunity to choose either the electric or the magnetic mode as the lowest order resonance by adjusting the disk aspect ratio [3]. Importantly, choosing the appropriate aspect ratio allows for complete overlap of the spectral position of the particle electric and magnetic resonances.

The idea behind this spectral control is illustrated in Fig. 1 (a), showing the calculated transmittance spectra for silicon disk arrays embedded into a homogeneous dielectric with refractive index $n = 1.5$, where the disk diameter (d) has been systematically varied while the height (h) is kept fixed. Two distinct resonances can clearly be identified for the largest disk diameter of $d = 650\,\mathrm{nm}$. The calculated mode profiles (see insets) allow us to identify the character of the observed resonances (electric or magnetic). The two resonances move closer together as the disk diameter decreases and merge at around $d = 550\,\mathrm{nm}$. Remarkably, instead of getting more pronounced, resonance strength is reduced as the two resonances move into overlap. The increase of the transmission at the mode overlap in our case can be explained by improved impedance matching of the nano-disk array to air ($\varepsilon = \mu$) when both electric and magnetic dipole moments are present within the same frequency range.

To prove this concept experimentally we fabricate arrays of silicon disks by electron-beam lithography (EBL) on silicon-on-insulator (SOI) wafers (3μm thick SiO_2), followed by a directive reactive-ion etching process. Negative electron-beam resist is used as an etch mask. Since the height of the disks is fixed to the thickness of the top silicon layer of the SOI wafer ($h = 220\,\mathrm{nm}$), we vary the aspect ratio by changing only the diameter of the silicon disks

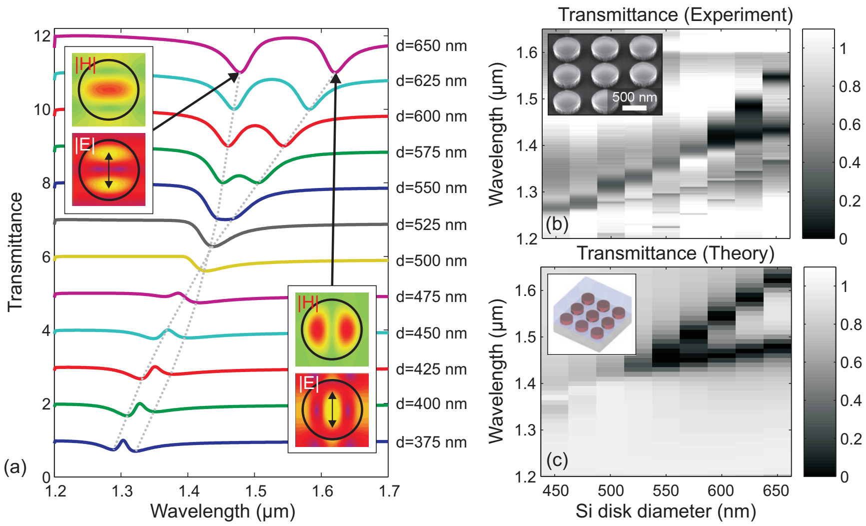

Fig. 1. (a) Calculated transmittance spectra for silicon disk arrays with systematically varied disk diameter embedded into an $n = 1.5$ medium. Spectra for different diamaters are displaced vertically. The insets show the mode profiles of the electric and magnetic resonances for a disk diameter of $d = 650$ nm, where the arrows indicate the electric field polarization of the exciting plane wave. (b) Measured transmittance spectra for silicon disk lattices embedded into SiO_2. The inset shows a scanning electron micrograph of a typical fabricated silicon disk sample with $d \approx 550$ nm before LPCVD. (c) Calculated transmittance spectra plotted for direct comparison with experimental data.

while keeping their height constant. The nominal diameter d of the disks has been varied between 450 nm and 650 nm, resulting in disk aspect ratios $\chi = h/d$ ranging from 0.49 to 0.34. The lattice constant of the fabricated arrays is $a = 800$ nm, ensuring that the first order magnetic and electric resonances appear at longer wavelengths than the system's first Wood anomaly. In order to embed the silicon disks in a homogeneous optical environment, we cover them with 550 nm of SiO_2 using low-pressure chemical vapor deposition (LPCVD). Linear-optical transmittance spectra of the embedded silicon disks have been collected using a home-built setup operating in the telecommunication infra-red frequency range. The measured transmittance results are shown in Fig. 1 (b), where it is clearly visible that for larger disk diameter there exist two independent dips in the transmission spectrum (at 1.55 μm – magnetic dipole and at 1.43 μm – electric dipole). These resonances move closer together as the disk diameter decreases and merge for a disk diameter of approximately 550 nm, which is accompanied by a reduction of resonance strength. The measured spectra show excellent agreement with numerical calculations plotted for comparison in Fig. 1 (c).

In conclusion, we have fabricated and optically characterized square arrays of all-dielectric subwavelength silicon disks exhibiting simultaneous electric and magnetic resonances at optical frequencies. We have measured experimentally and calculated numerically the structures' transmittance spectra, demonstrating that their electric and magnetic resonances can be brought into spectral overlap by appropriately adjusting the disk aspect ratio. In the latter case, we have observed a reduction in resonance strength, indicating improved impedance matching due to the overlap of electric and magnetic optical response of the silicon disks, and opening up a new route towards functional metasurfaces and all-dielectric unidirectional nanoantennas.

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