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SPIE.

Transmission and reflection features of all-dielectrics metasurfaces with electric and magnetic resonances

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ABSTRACT

The effective multipole decomposition approach is applied to study the optical features of the silicon metasurface in the near-infrared. The spectral regions of perfect transmission and reflection have been analyzed using the Cartesian multipole decomposition. It is shown that transmission peaks appear due to the mutual interaction of multipole moments up to the third order, while reflection peaks are due to the dominant contribution of one of the multipole moments. The results of this work can be broadly applied to design novel metasurfaces, sensors, and optical filters.

Keywords: Metasurface, multipole, silicon, dielectric, infrared

1. INTRODUCTION

Dielectric nanophotonics is the intensively studied area of modern science with high potential for device applications. Optical properties of dielectric nanostructures attract significant attention of scientific groups over the world.[1–4] Dielectric materials provide the opportunity to manipulate both electric and magnetic components of light using the simple particle geometries. In other words, such sub-wavelength particles support the excitation of strong electric and magnetic multipole resonances. These resonances can be used to control light scattering by changing material, shape, and aspect ratio of nanoparticles.[5,6] The mutual interaction between multipole moments can be used in a wide range of applications such as nanoantennas,[7,8] sensing,[9–12] cloaking,[13,14] solar cell technology[15] and functional metasurfaces.[16,17] Moreover, the multipole decomposition approach has recently been applied to analyze dielectric structures in the terahertz frequency range[18] and even macroscopic objects like the Great Pyramid.[19]

In this work, we study the periodic array of silicon nanocubes embedded in air. We study the optical properties of the structure using a multipole decomposition approach and analyze the features of transmission and reflection spectra. Obtained results can be used to design novel optical sensors and filters and multi-functional metasurfaces for the near-infrared.

Further author information:
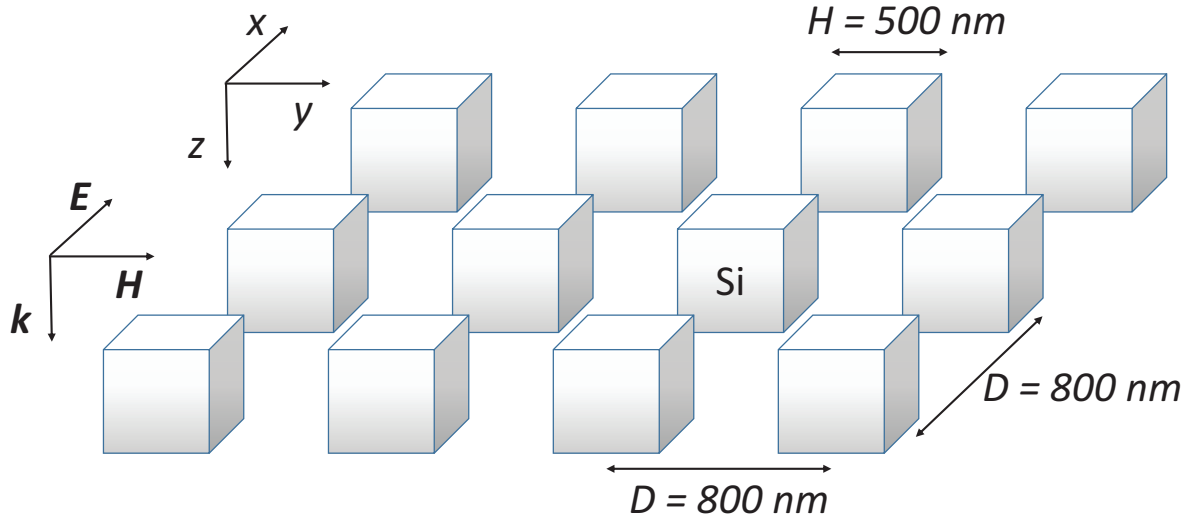P.D.T.: E-mail: terekhovpd@gmail.com

Figure 1. The artistic representation of the studied system.

2. THEORETICAL BACKGROUND

Here we use the multipole decomposition approach reported in Ref.[20] to study the cubic silicon metasurface in near-infrared. The infinite two-dimensional (2D) array of nanocubes is placed in (xy) plane and illuminated with a linearly polarized plane wave with x-polarization.

In this case, the electric field reflection r and transmission t coefficients of the array can be written as[20]

$$r = \frac{ik_d}{E_0 2 S_L \varepsilon_0 \varepsilon_d} \left(p_x - \frac{1}{v_d} m_y + \frac{ik_d}{6} Q_{xz} - \frac{ik_d}{2v_d} M_{yz} - \frac{k_d^2}{6} O_{xzz} \right) , \tag{1}$$

$$t = 1 + \frac{ik_d}{E_0 2 S_L \varepsilon_0 \varepsilon_d} \left(p_x + \frac{1}{v_d} m_y - \frac{ik_d}{6} Q_{xz} \frac{ik_d}{2v_d} M_{yz} - \frac{k_d^2}{6} O_{xzz} \right) , \tag{2}$$

where $k_d = k_0 \sqrt{\varepsilon_d}$ is the wavenumber in a surrounding medium (k_0 is the wavenumber in vacuum), S_L is the area of a lattice unit cell ($S_L = D^2$ for the square lattice, where D is the lattice constant), ε_0 is the vacuum permittivity, ε_d is the permittivity of a surrounding medium, $v_d = 1/\sqrt{\mu_0 \varepsilon_0 \varepsilon_d}$ is the speed of light in the surrounding nonmagnetic medium, p_x and m_y are the x and y components of total electric (TED) and magnetic dipole (MD) moments, respectively, Q_{xz}, M_{yz} and O_{xzz} are the corresponding components symmetrized and traceless tensors of electric quadrupole (EQ), magnetic quadrupole (MQ), and electric octupole (EOC) moments, respectively.[21]

The reflection and transmission coefficients are

$$R = |r|^2, \qquad T = |t|^2. \tag{3}$$

Then the absorption coefficient A could be derived from the following expression $A = 1 - R - T$.

In next section, we numerically prove that the multipole expressions for T and R obtained above are in an excellent agreement with the direct numerical calculations of the transmission and reflection for periodic dielectric metasurfaces.
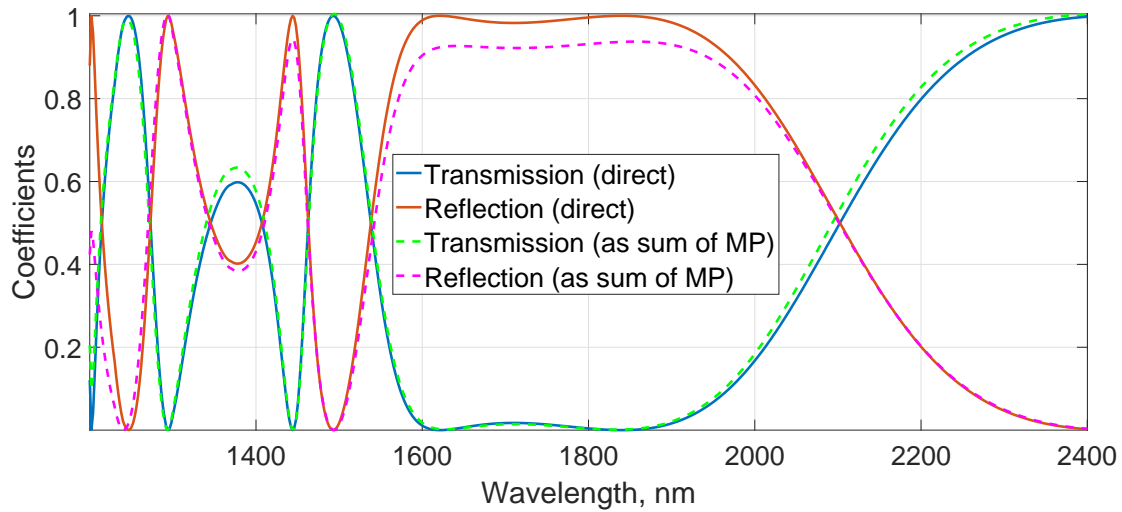
Figure 2. Spectra of the transmission T, reflection R, and absorption A coefficients of the metasurfaces composed of silicon nanocubes of height $H = 500$ nm with period $D = 800$ nm
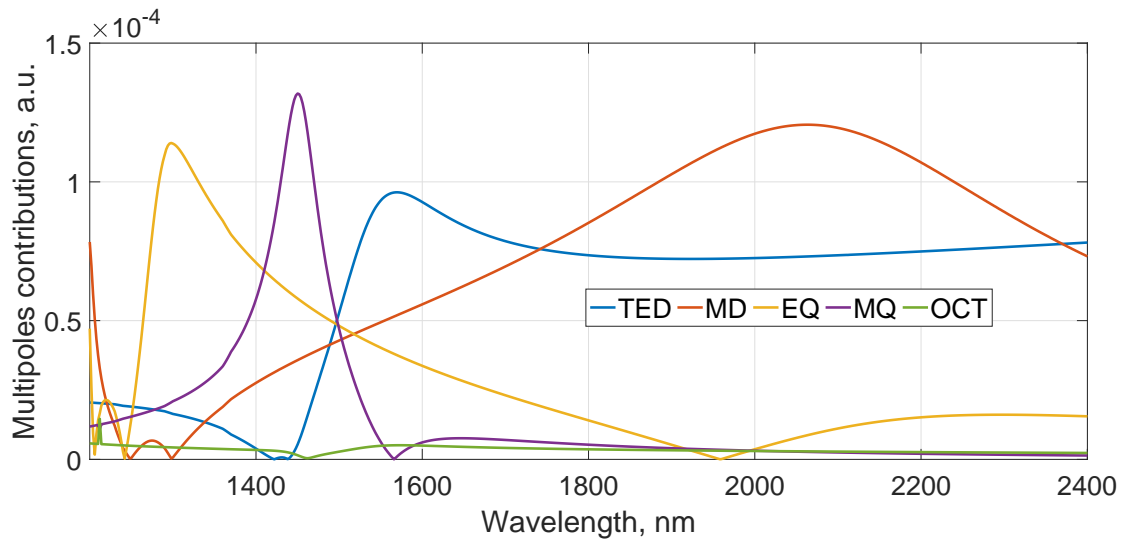

Figure 3. Absolute values of the multipole contributions in the electric field reflection and transmission coefficients r and t of the metasurfaces composed of silicon nanocubes of height $H = 500$ nm with period $D = 800$ nm

3. RESULTS AND DISCUSSION

Here we apply the multipole decomposition approach to study the optical properties of the metasurface in Fig. 1. The base edge of each nanocube is equal to $H = 500$ nm and the lattice constant is $D = 800$ nm.

Fig. 2 presents the transmission and reflection spectra of the metasurface in near-infrared. Note that absorption can be neglected due to transparency of silicon in the considered range. The direct calculations of transmission and reflection parameters are in the excellent agreement with the results obtained with multipole decomposition approach (Eq. 3). We note three wavelengths of the perfect transmission through the metasurface($\lambda \approx 1246$ nm, $\lambda \approx 1494$ nm and $\lambda \approx 2400$ nm) and four wavelengths of the perfect reflection appears($\lambda \approx 1294$ nm, $\lambda \approx 1444$ nm, $\lambda \approx 1622$ nm and $\lambda \approx 1844$ nm). Fig. 3 presents the absolute values of
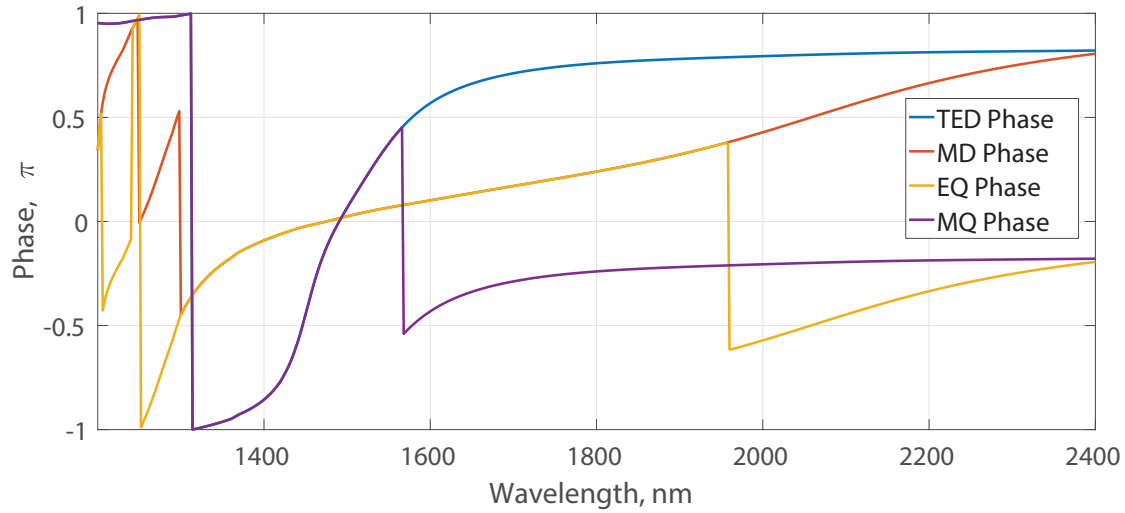
Figure 4. Phases of the multipole terms in the amplitude reflection and transmission coefficients of the metasurface composed of nanocubes of height $H = 500$ nm with period $D = 800$ nm

the multipole moment contributions to the electric field reflection and transmission coefficients r and t for the considered metasurface. We use this multipole analysis together with the phases of multipole contributions (Fig. 4) to study the origins of optical properties of the metasurface.

The interesting case of perfect transmission can be seen at $\lambda \approx 1494$ nm. The contributions of TED, MD, EQ, and MQ moments in the r and t coefficients are approximately equal at this wavelength (Fig. 3). Moreover, the phases of these contributions are also equal to each other (Fig. 4). Similar conditions provide homogeneous side scattering for the single particle[22, 23] and so-called lattice invisibility effect for the infinite array.[20] In turn, at $\lambda \approx 1294$ nm multipole contributions are not equal to each other; TED and MQ provide dominant contribution at this wavelength. The phases of multipole contributions are equal as well as for $\lambda \approx 1494$ nm (Fig. 4). At $\lambda \approx 2400$ nm usual Kerker conditions[24, 25] fulfillment leads to the perfect transmission through the metasurface.

As for the perfect reflection features of the studied metasurface, there are two sharp peaks at $\lambda \approx 1294\ nm$ and $\lambda \approx 1444\ nm$ and the region of high reflection with two perfect reflection spectral points at $\lambda \approx 1622\ nm$ and $\lambda \approx 1844\ nm$ (Fig. 3). Every peak is provided mainly by one multipole moment contribution: EQ for $\lambda \approx 1622\ nm$, MQ for $\lambda \approx 1444\ nm$, TED for $\lambda \approx 1622\ nm$ and MD for $\lambda \approx 1844$ nm. It is worth noting that for $\lambda \approx 1622\ nm$ and $\lambda \approx 1844\ nm$ phase difference between TED and MD moments is equal to $\pi/2$ (Fig. 4, and it corresponds to the forward scattering suppression according to Kerker conditions.

4. CONCLUSIONS

In this work, we utilized the multipole decomposition approach to analyze the cubic silicon metasurface in the near-infrared. We studied transmission and reflection features to explain their origins with multipole theory. It has been shown that transmission peaks mainly provided due to the mutual interaction of different multipole moments. In contradiction, reflection peaks appear due to the dominant contribution of TED, MD, EQ or MQ moment.

Multipole decomposition of transmission and reflection spectra provides the useful tool for semi-analytical analysis of arrays of non-spherical nanoparticles in near-infrared spectral range. Our results can be used to design novel photonic devices, sensors, and optical applications.

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