Mie Resonances of Silicon Meta-atoms at Visible Frequencies

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***Abstract* — Mie resonances of cubic meta-atom arrays based on silicon-on-insulator (SOI) wafers are investigated at visible frequencies. The model takes into account cubic silicon resonators fabricated on a thick silica base. Transmission and reflection spectra as well as local electromagnetic fields are presented. It is shown that the first two Mie resonances, electric and magnetic dipole resonances, appear in the region of visible frequency band (around 520 nm). Electromagnetic field is enhanced in silicon resonators when Mie resonances happen. Due to the low loss characteristic of silicon, the dielectric absorption is small and scattering contributes most to the light extinction. It is found that light transmission through meta-atom arrays can be dramatically suppressed by mirror effect of the two kinds of resonances. Reflection and transmission could be tailored at will by designing shapes of meta-atoms and lattice constants of periodic arrays, and electromagnetic transparency could be induced by interference between the two resonant states. In general, the meta-atoms provide potential applications in the field of optical metamaterials such as mirrors, metamaterial Huygens' surface, perfect absorbers, and subwavelength cavities.**

Index Terms — electromagnetic scattering, metamaterial antennas, mirrors, nanotechnology, optical resonance, silicon

I. Introduction

Atoms of natural crystals are arranged with lattice constants far less than wavelength; therefore, materials in nature are homogeneous bulks in eyes of light. Artificial materials, consisting of periodic unit cells in nano scale, exhibit novel characteristics when interact with light. They could be regarded as effective homogeneous material because lattice constants are still smaller than the wavelength. These artificial materials are named as metamaterials [1], [2]. When tracing the origin of metamaterials, we are amazed at the history of metamaterials. One most famous example is the Lycurgus Cup exhibited in the British Museum. Ruby glass is embedded by nano gold particles; thus, the cup appears green in reflected light while reddish in transmitted light. Resonances of nanoparticles arranged with artificial lattice constants play the key role behind this phenomenon. Recently, nanotechnology provides human beings with the power to make artificial nanoparticles which can be also named as meta-atoms. They are nanoparticles with carefully designed shapes, composed of numerous real atoms. The shapes and lattice constants decide resonances that make further effect to manipulate both amplitude and phase of transmitted and reflected waves.

Split rings and metallic wires were used to create magnetic and electric atoms at microwave band. When the two different

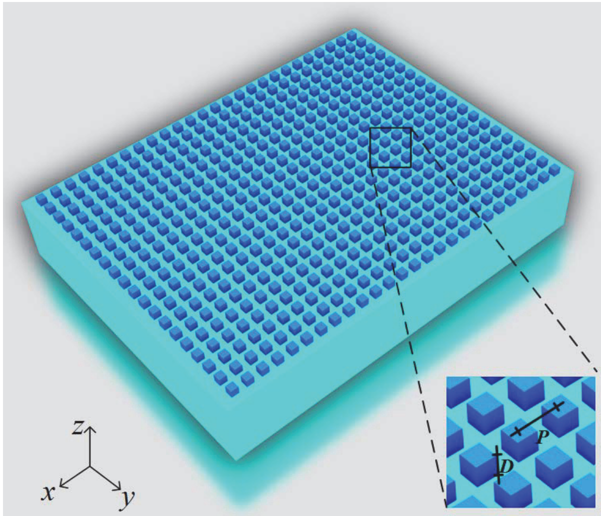

Fig. 1. Silicon meta-atom arrays on silica base where the inset picture show detailed information. (Dimension of cubic meta-atoms is *D*; Lattice constant of the meta-atom array is *P*).

atoms are arranged together, abnormal refraction phenomenon can be observed [3]. Metallic structures indeed behave as perfect conductors at microwave frequencies; however, Ohmic loss increases rapidly at optical frequencies. Therefore, instead of metallic particles, dielectric particles are considered as more desirable basic elements free of Ohmic loss [4]–[6]. Silicon-on-insulator (SOI) wafers are widely used for advanced silicon devices, extending silicon devices into the nanometer region. Optical applications of SOI require high refractive index contrast between two different media, like silicon and silica, providing possibilities of lens manufacturing [7], [8]. In this paper, cubic silicon resonators fabricated on the interface of silica base and vacuum are investigated at visible frequencies, as shown in Fig. 1. Electromagnetic field of two Mie resonances, electric and magnetic resonances, is strongly localized in cubic meta-atoms. It is demonstrated that we can control electromagnetic fields at will by changing both meta-atoms and lattice constants. Detailed field distributions at two resonant frequencies are also shown. Moreover, transmission and reflection spectra indicate that light transmission is suppressed by Mie resonances; however, electromagnetically induced transparency (EIT) occurs under some conditions. Using the proposed meta-atoms, one can not

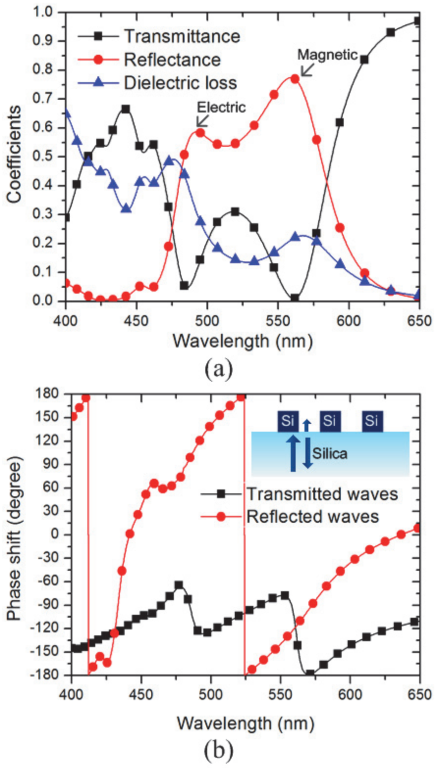

Fig. 2. Simulated reflection and transmission of the proposed meta-atom array. (a) Reflectance and transmittance. (b) Phase shift of reflected waves and transmitted waves.

only manipulate the reflected waves but also the enhancement of localized electric and magnetic fields.

II. Design of Silicon Meta-atoms

Mie scattering of a 2D cubic meta-atom array fabricated on the interface between a silica bulk and vacuum are studied. As shown in Fig. 1, meta-atoms are (dimension of *D*) located on the x-o-y plane at z = 0 with lattice constants (length of *P*) along x and y axis. Below the surface (z < 0) is the silica bulk while above the surface (z > 0) is the vacuum. Note that silicon meta-atoms are fabricated on the surface of silica base and implanted into the vacuum. The dielectric constant of silica is set as 2.38, and within the whole visible frequency band, real part of dielectric constant of silicon is high, while the imaginary part is negligible. High index contrast between silicon and silica makes it convenient to realize Mie scattering. The array is excited by normal incidence of an optical wave propagating from silica base. Electronic field E is along x-axis, and magnetic field H is along y-axis. When the cubic meta-atoms are excited to resonant states, electric and magnetic dipole resonances occur respectively. We consider a full structure whose cubic lattice constant is 240 nm consisting of cubic meta-atoms dimensioned of 120 nm. Fig. 2 presents the simulated transmission and reflection characteristic. Magnetic (1st) and electric (2nd) dipole resonances can be recognized

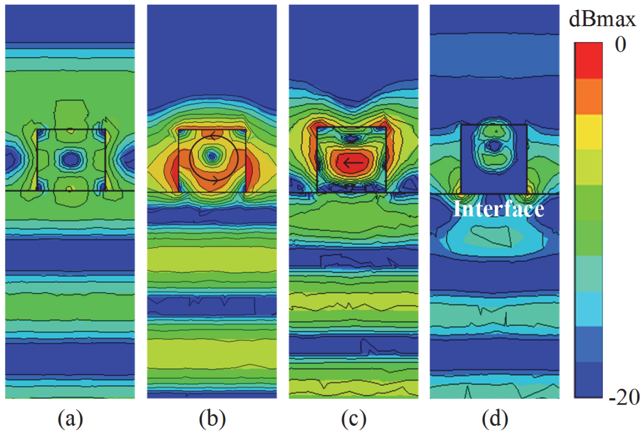

Fig. 3. Simulated electric magnitude distributions on the cross section of a single meta-atom. (a) Transmission status at 630 nm wavelength. (b) Reflection status due to magnetic dipole resonances at 562 nm. (c) Reflection status due to electric dipole resonances at 485 nm. (d) Transmission status at 410 nm.

easily. It should be mentioned that the phase shift range of reflected waves is much wider than phase shift of transmitted waves, and there is an approximate 180° phase change between electric and magnetic resonances.

Fig. 3 shows electric field distributions at different frequencies. Fig. 3(a) and Fig. 3(d) show electric field distribution within transmission band, below and above the reflection band, respectively. The structure behaves as almost a transparent glass to light waves. Wave propagations could be found through the interface. As shown in Fig. 3(b) and Fig. 3(c), when resonances happen, the structure behaves as a mirror. Magnetic dipole resonance is the first order resonance and electric dipole resonance is the second order resonance. When magnetic resonance happens, the structure behaves as a magnetic mirror, and the magnetic field of the reflected wave experiences a 180° phase shift. Similarly, when electric resonance happens, the structure behaves as an electric mirror, and the electric field of the reflected wave experiences a 180° phase shift. Field distributions vindicate the existence of magnetic and electric mirrors. Antinodes and nodes of electric field of standing waves can be found below the interface. In Fig. 3(b), when magnetic mirror occurs, electric field on the interface is an antinode. In Fig. 3(c), when electric mirror occurs, electric field on the interface is a node.

To demonstrate the potential manipulation of light propagation, we present results of structures with different lattice constants and different cubic dimensions. In Fig. 4, we calculate transmittance and reflectance of arrays with different lattice constant (*D* = 120 nm, *P* ranging from 200 nm to 280 nm). In Fig. 5, we calculate transmittance and reflectance of arrays with same lattice constant (*P* = 240 nm, *D* ranging from 100 nm to 120 nm). It is found that the change of lattice constant has negligible effects on resonant frequencies of both electric and magnetic dipole resonances; however, dimensions of cubic resonators have strong influences on resonant

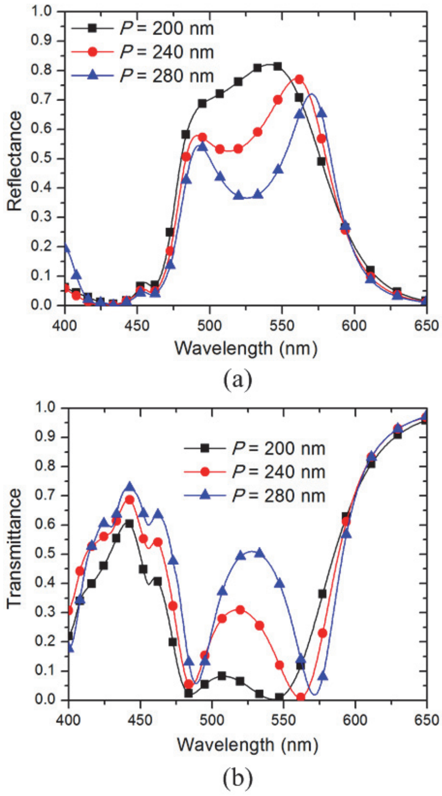

Fig. 4. Reflectance and transmittance of meta-atom arrays with different lattice constants (The dimension of cubic meta-atom D is 120 nm).

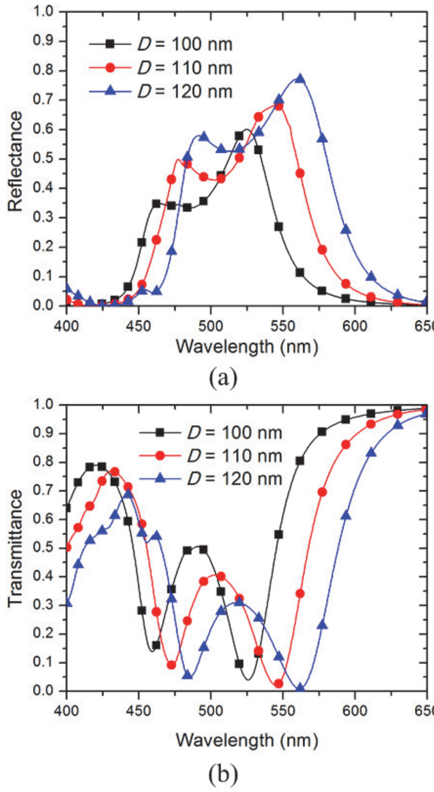

Fig. 5. Reflectance and transmittance of meta-atom arrays consisting of different cubic meta-atoms with different dimensions (The lattice constant of meta-atom arrays is 240 nm).

frequencies. As shown in Fig. 4(b), it is interesting that electromagnetic transparency can be induced by interference between electric and magnetic dipole scattering when we adjust the lattice constant.

III. Conclusion

Mie scattering of silicon meta-atoms at visible frequencies have been investigated in this paper. Electric and magnetic dipole resonances are excited by plane waves; thus, electric and magnetic mirrors are observed. Moreover, reflection and transmission spectra of different meta-atom arrays are simulated. It is demonstrated that light transmission could be suppressed by electric and magnetic resonances; however, interference between electric and magnetic resonances could cause electromagnetic transparency under some circumstances.

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