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# Double Resonance Perfect Absorption in a Dielectric Nanoparticle Array

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We propose a reflector-type perfect absorber with double absorption lines using electric and magnetic dipoles of Mie resonances in an array of silicon nanospheres on a silver substrate. In the visible range, hundreds of nanometer-sized nanospheres show strong absorption lines up to 99%, which are enhanced by the interference between Mie scattering and reflections from the silver substrate. The air gap distance between the silicon particles and silver substrate controls this interference, and the absorption wavelengths can be controlled by adjusting the diameter of the silicon particles over the entire range of visible wavelengths. Additionally, our structure has a filling factor of 0.322 when the absorbance is nearly 100%.

*Keywords* : Mie scattering, Dielectric, Nanoparticle, Perfect absorber
*OCIS codes* : (160.3918) Metamaterials; (050.6624) Sub-wavelength structures; (260.5740) Resonance

## I. INTRODUCTION

Nano-optical devices have attracted a large amount of interest due to their ability to effectively control light on the nanoscale. Examples of such nano-optical devices are lenses [1-3], color reflectors [4-6], antennas [7, 8], and perfect absorbers [9, 10], and plasmonic resonance is based on such nano-metallic structures. However, these plasmonic resonances have the serious drawback of energy loss in the visible range, which deteriorates the performance and limits their miniaturization for practical use. Thus, low absorption dielectrics have recently been studied for use in nano-optical devices [11]. These dielectric structures allow for control of the absorption in the visible range [12]. The dielectric particles exhibit resonant Mie scattering due to electric dipoles (EDs), magnetic dipoles (MDs), and higher-order resonances [13, 14]. The magnetic dipole response of dielectric particles is due to the circular displacement currents inside the particle being excited by incident light. Further, the resonant wavelengths of the ED and MD modes have resonant shifts according to the scale and shape of the nanoparticles. The magnetic dipole approximately occurs at $\lambda / n = d$, where $\lambda$ is the incident wavelength, n is the particle refractive index, and d is the particle diameter [15, 16]. Such optical devices, including solar cells [16] and filters [17], require a high absorption, which is necessary for high energy transformations and the removal of unnecessary signals.

In this paper, we propose a perfect absorber based on an array of silicon (Si) nanoparticles above a metal substrate that exhibits two high absorbance peaks in the visible range resulting from Mie resonances. The wavelengths of these peaks depend heavily on the diameter of the Si nanoparticles. The absorbance of the silicon particles is enhanced using destructive interference between the Mie scattering and reflections from the metal mirror, which was confirmed by investigating the effects of the air gap. Optical properties of proposed structure are simulated by using a three-dimensional finite-difference time-domain (FDTD) method. We simulated full three-dimensional structure with a mesh size of 2.5 nm. Monochromatic plane waves propagate along the z direction where the wavelength increases from 400 nm to 700 nm with an increment of 5 nm. Also, we measured the absorbance, reflectance, and transmittance of silicon particles.

## II. BASIC CONCEPT

Our structure consists of a silver substrate and a Si

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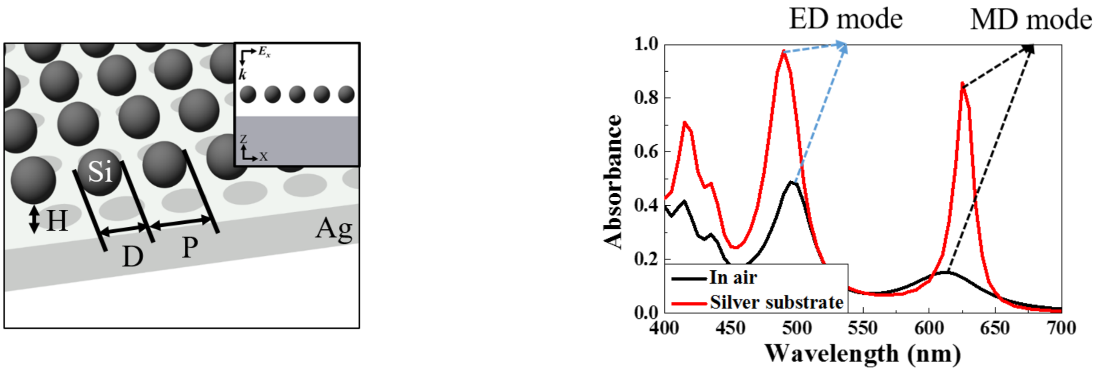


(a) (b)

FIG. 1. (a) Schematic of the silicon particle array on a silver substrate with diameter (D), period (P), and height (H). The inset depicts light scattering due to the particle array on the silver substrate. (b) Absorption spectra of the Si particle array on the silver substrate and the non-substrate.

particle array with an air gap, as shown in Fig. 1. The Si particles above the sliver substrate have a particle size of D and are arranged with a period of P and height of H. We considered ranges of D from 100 - 200 nm, P from 210 - 270 nm and H from 10 - 210, which result in resonant modes in the visible range. In this experiment, the silver substrate was used as a mirror. We measured the absorbance of Si particles after applying incident light, assuming the particular structure with D = 160 nm, P = 250 nm and H = 50 nm. The absorption of the silver substrate is negligible.

Figure 1(b) shows the absorbance of the Si particles for the silver substrate (red line) and the non-substrate (black line), which both have ED and MD modes at around 490 nm and 625 nm, respectively. The absorbance of the Si particles with a silver substrate have a larger absorbance than the non-substrate.

Figure 2 shows the normalized electric field intensity distribution for the ED (490 nm) and MD (625 nm) modes in the XZ plane. The ED mode profile exhibits a central, strong local electric field, while the MD mode profile clearly takes the form of a loop induced by the driving field [18]. The ED and MD mode shapes for Si nanoparticles on a silver substrate with an air gap are almost similar to those of single nanoparticles in air. The ED mode is generated from the incident electric field, and the MD mode of the dielectric particles originates from the circular displacement currents excited inside the particle by the incident wave. We calculated the filling factor as based on the structure with the highest absorbance, resulting in a filling factor of 0.332. The structure used in this study has a high absorbance of 97% and 83% at 490 nm (ED) and 625 nm (MD), respectively.

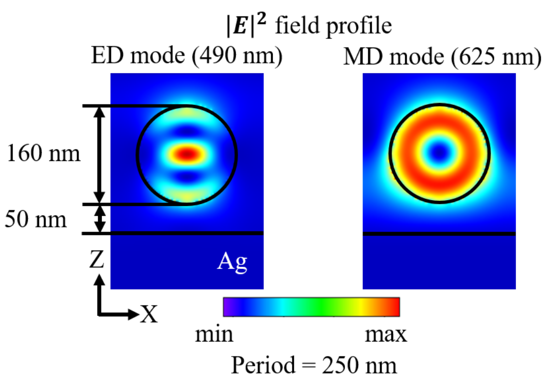


FIG. 2. ED and MD mode profiles at wavelengths of 490 nm and 625 nm. Here, D = 160 nm, P = 250 nm and H = 50 nm.

## III. RESULTS

First, in order to control the wavelengths of the absorption peaks, we changed the size of the Si particles. Mie resonance strongly depends on the size and shape of the dielectric nanoparticle [19]. Therefore, the absorption peak from Mie resonances depends on the structure parameters of the nanosphere array. As the diameter (D) increases from 100 nm to 180 nm, the ED and MD resonant peaks shift from 400 nm to 460 nm and 525 nm to 685 nm, respectively. The period (P) and height (H) are fixed at 250 nm and 50 nm. Figure 3(b) shows the wavelengths of two absorption peaks (ED and MD modes) as functions of the Si sphere diameter. As the diameter increases from 100 nm to 200 nm, the wavelengths of the ED and MD modes increase from 400 nm to 550 nm and 460 nm to 750 nm, respectively. The absorption peaks linearly depend on the diameter and can cover the entire visible wavelength range for D between 100 nm and 200 nm.

We investigated the effects of the period (P) on the absorbance for the range of 250 nm to 400 nm. The diameter and the air gap are fixed at 160 nm and 50 nm, respectively, and Fig. 4 shows the absorption peaks for the periods of 250 nm, 350 nm and 400 nm. As the period increases, the peaks red-shift slightly. However, the absorbances of the MD peak (625 nm) significantly decrease

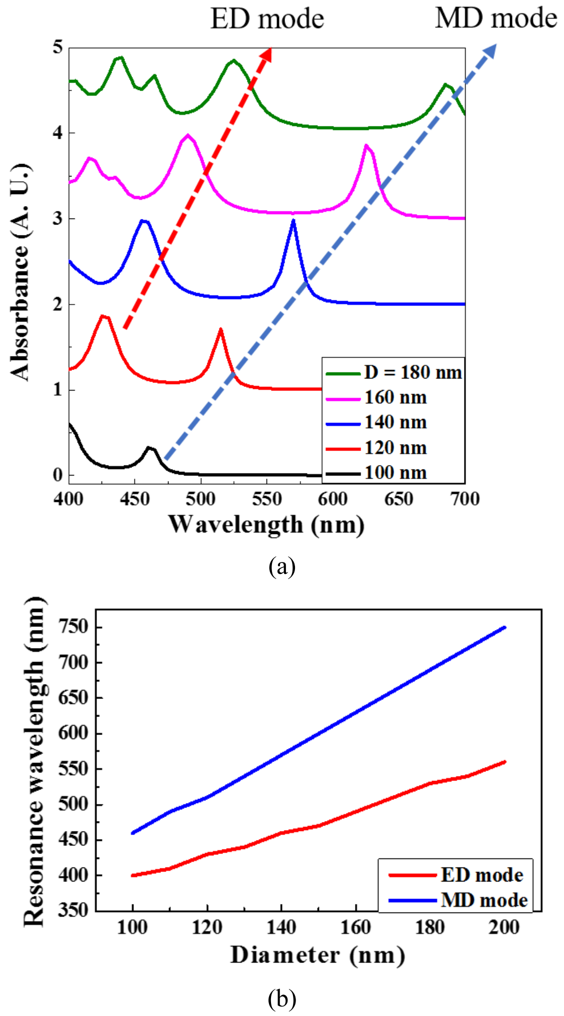


FIG. 3. (a) Absorbance spectrum with D ranging from 100 - 180 nm, while P and H are fixed at 250 nm and 50 nm, respectively. (b) The ED (block line) and MD (red line) absorption peaks as functions of the diameter for D between 100 and 200 nm.

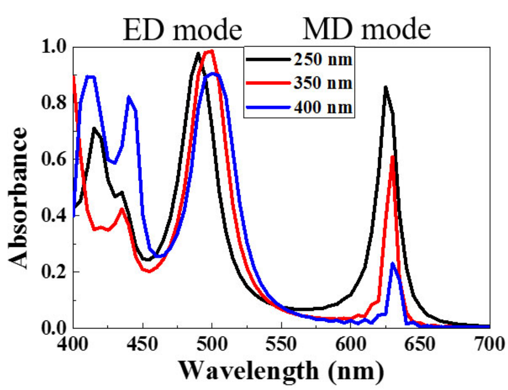


FIG. 4. Absorbance spectra of the Si particles on the metal substrate for different periods, P = 250, 350 and 400 nm, with the diameter and the air gap set to 160 nm and 50 nm, respectively.

from 0.8 to 0.2 as the filling factor of the Si spheres on the surface decreases from 0.332 to 0.126.

The shifts of the peak wavelengths appear when the period becomes larger than 450 nm [20]. However, the absorbance of Si particles becomes very weak, and therefore we did not consider structures with P > 450 nm.

The absorbance of Si particles strongly depends on the air gap because of the interference between Mie scattering and reflections from the silver substrate. Figure 5(a) shows the absorbance spectra for different air gaps (H) between the silicon particles and the silver substrate of 10 nm, 50 nm and 90 nm. Here, the diameter (D) and the period (P) are fixed at 160 nm and 250 nm, respectively. The absorbance of the ED mode changes from 1.0 to 0.8, while the MD mode exhibits large changes from 0.1 to 0.8; these changes are due to the strong interference between Mie scattering and reflections from the mirror. Destructive interference induces a high absorption for the Si particles for particular air gap heights. For Example, in Fig. 5(b), as the air gap increases from 10 nm to 210 nm, high absorbances for the MD mode (red line) and ED mode (black line) can be observed for gap sizes of 30 nm and 70 nm, respectively. We confirm that a high absorption for Si particles can result from destructive interference at single particles [21]. Figures 5(c) and (d) show the ED and MD mode profiles from a single particle with a silver substrate; the size of the air gap differs between (c) and (d), the gap is selected based on the high absorptions of single Si particles for the ED and MD modes. For example, in Fig. 5(c), the single Si particles have a high absorption at the ED mode (490 nm), while Fig. 5(d) shows a high absorption at the MD mode. Notice that in Figs. 5(c) and (d), there are two different field patterns. The emissions from the field at Si single particles are reduced at the ED mode in Fig. 5(c), but the field at the MD mode resulted in stronger emissions at the single particle. In contrast, in Fig. 5(d), the ED mode did not change as a result of the field, while the field at the MD mode is reduced. Figures 5(c) and (d) demonstrate similar results to those in Figures 5(a) and (b). Reduction of the field occurs due to interference resulting from the phase delay between scattering at individual particles and reflections from the silver mirror, but only for particular air gap heights. When energy is not being emitted, the absorption of the Si particles increases. The air gap can be replaced by a low index dielectric medium like glass for the mechanical robustness. The large absorption properties of the proposed nanoparticle array structure due to ED and MD modes is maintained while the spectral positions of the absorption peaks, gap size dependences, and the maximum value of the absorption can be changed slightly.

Our structure can be used as visible reflector-type color filters which can work as high resolution color pixels of display operating under external light since the absorption spectra can be tuned to red, green, and blue colors.

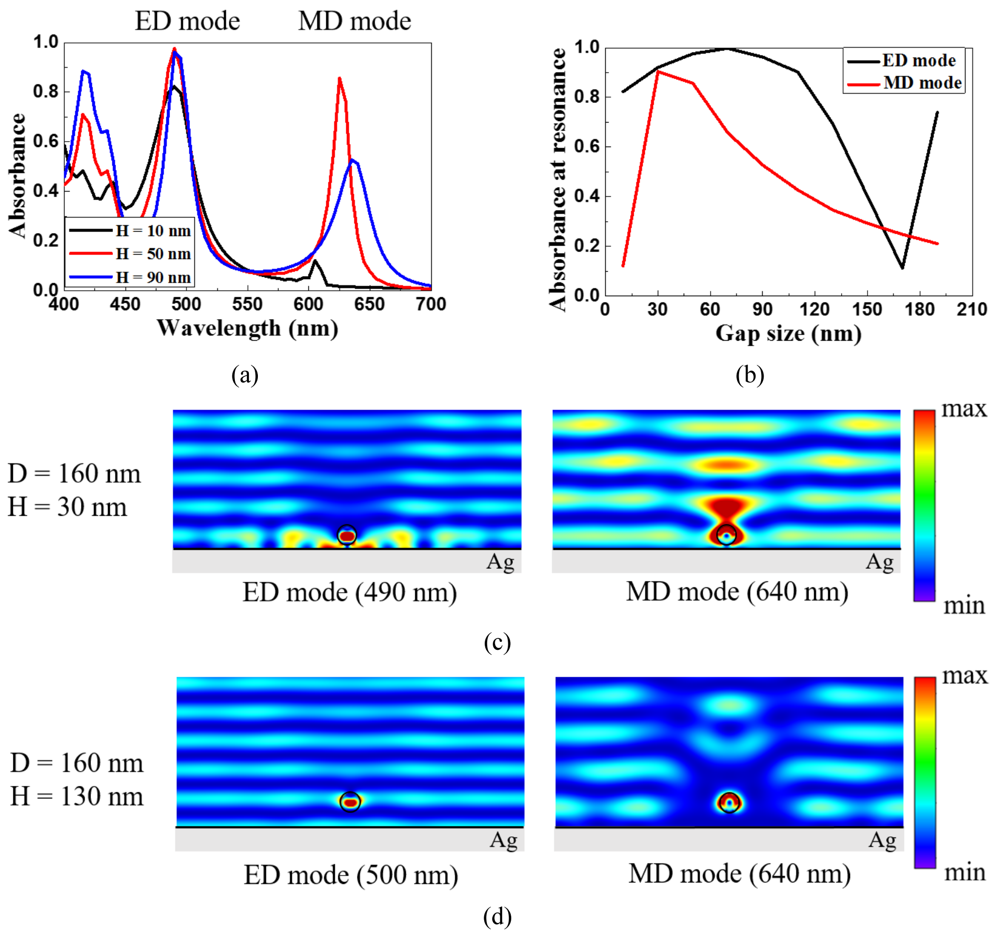


FIG. 5. (a) Absorbance spectrum of the Si particles for different heights (H). The diameter (D) and period (P) are both fixed at 160 nm and 250 nm, respectively. (b) The absorbance for the ED mode (black line) and MD mode (red line) as a function of the air gap. (c, d) The ED and MD mode profiles at single particles on the silver substrate, where (c) and (d) are for H = 30 nm and 130 nm, respectively, with D = 160 nm.

## IV. CONCLUSION

We proposed a dielectric perfect absorber consisting of a Si particle array above a silver substrate. Our structure has two narrow high absorbance peaks at nearly 100% in the visible range due to electric dipoles and magnetic dipoles. The Mie scattering linearly depends on the diameter and period of the Si particles. Also, the absorbance of Si particles can be changed by varying the air gap height between the Si particles and the silver substrate. The strong absorptions of the ED and MD modes are generated by the destructive interference between Mie scattering and reflections from the mirror. We believe that our dielectric perfect absorber can be used to control the absorbance in the visible range according to the diameter, period and air gap.

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