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Research paper

Scalable fabrication of high performance absorber based on colloid sphere lithography technology

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ABSTRACT

The perfect absorbers have attracted many attentions in recent years for their unusual property in absorbing the incident light, and own many potential applications in many fields, such as the selective thermal emitters, spectrally sensitive detectors and sensors. In this paper, we report a simple, low-cost and highly-efficient method for the fabrication of large area (>1 cm^2) high-performance absorber working in visible and near-infrared region based on the colloid sphere lithography technology. The absorber reported here is composed of glass substrate, silver triangle nanoparticle array, dielectric layer and silver slab. The theoretical analysis based the finite difference time domain method (FDTD) indicates that an ideal absorption efficiency of about 100% can be achieved at any desired wavelength. In experiment, a perfect absorber working at 752 nm has been fabricated. The measured results meet well with the simulations, and demonstrate the high performance of the proposed absorber. The low-cost, high-efficiency fabrication method and the high performance pave the way for the application of the absorber proposed in this paper.

1. Introduction

Metamaterials is a kind of artificial electromagnetic materials with unusual properties that cannot be found from the nature materials [1], such as negative refractive index [2], inverse Doppler effect [3], superlensing [4], and electromagnetic wave cloaking [5]. Metamaterials usually consist of well-arranged artificial structure unit as building blocks, and their properties mainly depends on the geometrical morphology, size and the arrangement mode of the building blocks. The permittivity and magnetic permeability of metamaterials can be well adjusted as desired by designing these building blocks and their arrangement mode [6,7]. This is a very powerful way to control the polarization state and propagation track of light, and will find potential applications in many fields, such as nanophotonics and military. With advances in micro/nano-engineering technology and electromagnetic simulation methods, a great number of devices with special electromagnetic properties have been demonstrated in experiments based on these metamaterials, such as super-lens [8], two dimensional invisible cloak, and broadband circular polarizer [9]. Absorber is one of the device with special absorption performance, and the whole energy of the incident electromagnetic wave can be absorbed by this device, leading to no reflection and transmission in specific wavelength or waveband [10]. This unusual property is very useful in many fields, such as selective thermal emitters [11], spectrally sensitive detectors, solar cells and sensors [12].

To date, a lot of absorber devices working at different waveband have been demonstrated, such as absorbers working in the THz and near-infrared wavebands [13–15]. Some basic design principles have been proposed and successfully used in the design and fabrication of absorber devices. One is using two metal resonators, which can couple separately to the electric and magnetic fields and absorb all of the incident electromagnetic energy within one single unit cell. This design principle is similar to that for the left-hand metamaterials [13]. Based on this principle, Landy et al. have demonstrated an absorber with absorption coefficient of 96% in theory and 88% in experiment [14]. The perfectly impedance matched principle is another design method for absorbers. It is demonstrated that by using two layers of cut wires to achieve the impedance matched to air, a near infrared absorber with absorptivity of 90% can be achieved at 1.5 μm in theory [15]. The destructive interference principle is the third effective method for designing perfect absorbers. Wang et al. report a kind of large-area perfect absorber designed by using this principle. This absorber is comprised of gold nanocubes and a gold plane, where the magnetic and electric dipole can both be excited between the nanocubes and the gold plane, leading to a destructive interference for the reflect electromagnetic wave and near 100% absorption efficiency at 800 nm [16]. These design principles pave the way for the achievement of perfect absorber. However, the fabrication of these prefer absorbers remains a challenge, especially for the

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device working in visible region, which usually require the plasmonic building blocks with size of order compared to the wavelength. In fact, the fabrication of perfect absorber working at visible region usually requires some expensive and inefficient techniques, such as the electron beam lithography (EBL) and the ion beam direct writing method. This limits the research of the perfect absorbers and the related applications.

Colloid sphere lithography technology (CSL) is a low-cost, large-area, high-throughput, and materials general nanofabrication technique. By using techniques of self-assembly, such as self-assembly at an air/water interface, microspheres could be assembled into wafer-scale polystyrene (PS) sphere monolayer [17]. Through effectively combining the polystyrene(PS) sphere self-assembly technology and vacuum vapor deposition technology, colloid sphere lithography technology has been widely used for fabrication of two- and three-dimensional nanostructures [18], such as the crescent shape structures [19], nano-cups [20], and the shell-like chiral nanostructures [21]. Especially for the two dimensional nanostructures, CSL is demonstrated to be an effective method for the fabrication of arbitrary planar nanostructures. In this paper, we employ this high efficiency for the fabrication of a kind of high-performance absorber working in visible region, which consists of a glass substrate, triangle nanoparticle array, dielectric layer and a gold slab. In theory, all of the incident electromagnetic wave at specific wavelength can be absorbed by this absorber, and the absorption peak can be adjusted in the whole visible and near infrared regions by well optimizing the structure parameters In experiment, the colloid sphere lithography technology has been used to fabricate the optimized absorber working at 752 nm, and the area of the absorber device can reach to wafer scale, indicating it's potential application prospect in the actual situation. In addition, the method proposed here is also suitable for the fabrication of absorbers with any nanostructures that can be fabricated by CSL. This will provide a great number of absorbers for different requirements.

2. Design and fabrication of high performance absorber device

The high performance absorber designed in this paper is composed of three parts as shown in Fig. 1(a), i.e. the top triangle nanoparticle array, the middle dielectric layer and the bottom silver slab. The transparent glass substrate on the top surface of triangle nanoparticle array is used to support the whole absorber device. For an ideal absorber, there should be no reflection and transmission from the device. For the absorber designed in this paper, we use a thick silver slab to prevent the transmission light from this device, and a triangle silver nanoparticle array to couple strongly with the incident light and reduce the reflection. In this case, all of the incident light can be effectively trapped in the absorber, leading to a 100% absorption efficiency. In this work, we design a perfect absorber working at 752 nm by optimizing the absorber parameters, and the detail information of the device structure is glass substrate/430 nm-period, 30 nm-height triangle nanoparticle array/100 nm-thick dielectric layer with refractive index of 1.698/200 nm-thick silver slab. Fig. 1(b) shows the reflectance, absorbance and transmittance spectra of this optimal device. The maximum absorbance can reach to about 100% at 752 nm, indicating the potential application prospect of this device. Certainly, this absorption peak can be continuously adjusted in the whole visible and near infrared regions by optimizing the related device parameters.

To verify the performance of the designed absorber device, the CSL, morphology and spectral characterization techniques have been used to achieve the fabrication and characterization of the designed absorber device. And the detail fabrication process is shown as below:

First is the glass substrate cleaning. The glass substrate was immerged in the 3:1 H_2SO_4/30%–H_2O_2 mixed solution at 80 °C for 1 h, and then, the substrate was washed with deionized water for several times to remove the particulate matter. To enhance the surface hydrophilic, the clean glass substrate was immerged in the 5:1:1 H_2O/30%–H_2O_2/NH_4OH mixed solution for 1 h [22], then the substrate was moved out and washed with deionized water for several times again. After these process, the glass substrates were ready for use.

Second is the PS sphere self-assembled on glass substrate. The 10% PS sphere colloid solution was purchased from DUKE company, and the diameter used in this paper was 430 nm. The PS sphere assembled process started with adding two or three drops of PS sphere colloid solution on the top surface of the substrate, and then the substrate was span at 1500 r/min for 40 s with the help of the spin coater. Then, the samples were dried in drying oven at 70 °C for one hour. After these steps, a layer of closely-packed PS sphere array with hexagonal lattice was successfully formed on the glass substrate, as shown in Fig. 3(a).

Third is the fabrication of triangle nanoparticle array. The silver deposition process was performed in a vacuum thermal evaporation system. The base pressure, deposition rate and temperature are $4 * 10^{-4}$ Pa, 0.1 nm/s and 30 °C, respectively. The deposition thickness could be accurately controlled by the deposition time. After material deposition, the Polydimethylsiloxane (PDMS) stamp was put on the top surface of the silver coated PS sphere array with a uniform pressure of 500 g/cm^2 for 1 min. Then the PDMS stamp was peeled off carefully. Due to the larger Van der Waals force when compared with that from the glass substrate, the PS sphere array was removed with the PDMS stamp. And the triangle nanoparticle array was successfully formed on the glass substrate, as shown in Fig. 3(b).

Fourth is the dielectric layer and silver slab coating. The 100 nm-thick dielectric layer was spin-coated onto the surface of the triangle nanoparticle coated glass substrate, as shown in Fig. 2(e). Then a

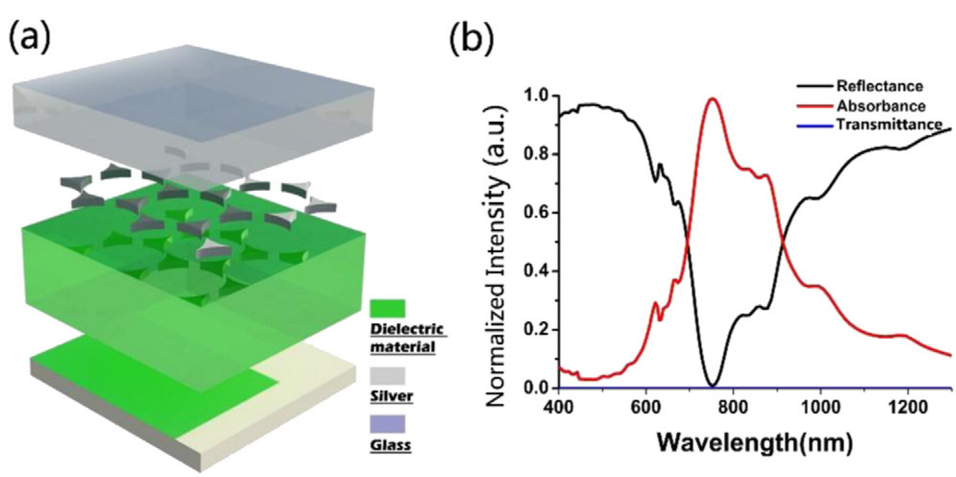

Fig. 1. (a) The 3D schematic of the designed absorber device. (b) Simulated results displaying reflectance (black), absorbance(red), and transmittance (blue) of the optimal absorber device.