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Wide-angle infrared metamaterial absorber with near-unity absorbance

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ABSTRACT

A wide-angle infrared perfect metamaterial absorber is experimentally verified. The perfect metamaterial absorber shows polarization-independent at normal incidence and displays high absorption rate at a large angle of incidence. The absorption property of the proposed metamaterial absorber is sensitive to the change of refractive index of environmental mediums. An absorption sensor scheme is proposed by combining the concept of the perfect metamaterial absorber and the variation of the refractive index of the environmental medium. Measured results indicate that the proposed absorption sensor scheme achieves high FOM values with different surrounding mediums (air, water, and glucose solution).

1. Introduction

he artificially preparation metamaterials consists of a variety of materials. Metamaterials have attracted considerable interesting due to their unique properties, such as superlensing, emitter, and cloaking [1,2]. The optical properties of artificially preparation metamaterial are usually the basis of actual applications, for exam-plechemical and biomedical sensing [3]. Many researchers focus on developing of optical properties of metamaterial, such as applications in sensors. This is because that the performance of metamaterial devices is easy to be disturbed due to the variation of the surrounding medium. For example, localized surface plasmon (LSP) resonance is always excited by the collective excitation of conduction electron in metal layer, which maybe lead to the incident electromagnetic wave signal interfere [4]. This physical phenomena limits the application of optical metamaterial sensors in practice. Some previous works indicate that the resonant characters of the localized surface plasmon is defined by the shape, size, and surrounding dielectric environment of the designed structure [5]. In particular, the surrounding dielectric environment of the designed structure shows an important effect on the practical application of optical metamaterial sensors. To date, many novel structure designs are proposed to optimize these metamaterial sensors to reduce the influence of the large spectral change in the surrounding dielectric environment (such as refractive index). These novel structure designs include nanoshells, nanostars, nanospheres, and nanorice [6,7]. On the other hand, the energy loss is inevitable in practical applications of optical metamaterial sensors. The energy loss is always performance by two forms, Ohmic loss and dielectric loss [8]. Many researchers pay large effort and propose different methods to reduce the loss of optical metamaterial sensors, such as using gain materials and optimizing structural geometries [9,10]. It is interesting that the energy loss of metamaterial structure is also noticed by researchers since the concept of perfect metamaterial absorber proposed. The energy loss becomes essential in designing perfect absorbers [11,12]. The absorption can be maximized through minimizing the reflectance and simultaneously eliminating the transmittance under the impedance matching conditions [8]. Moreover, the variation of the surrounding medium has an important influence on the performance of perfect absorbers. In this paper, a novel plasmonic metamaterial device is designed and manufactured based on combining the concept of perfect absorber and variation of the surrounding medium, which is named "absorption sensor" in this paper. The designed absorption sensor consists of three functional structure layers, a circular holes arrays gold layer, a middle dielectric absorption layer, and a bottom reflective gold layer. Measured results indicate that the manufactured absorption sensor demonstrates a high sensitivity to the variation of the surrounding medium. Moreover, the manufactured absorption sensor shows high absorption over a wide range incident angle in both transverse magnetic (TM) and transverse electric (TE) cases.

2. Mode and experiments

Fig. 1(a) and (b) shows the geometry design of the proposed matematerial device. The proposed absorber is fabricated as

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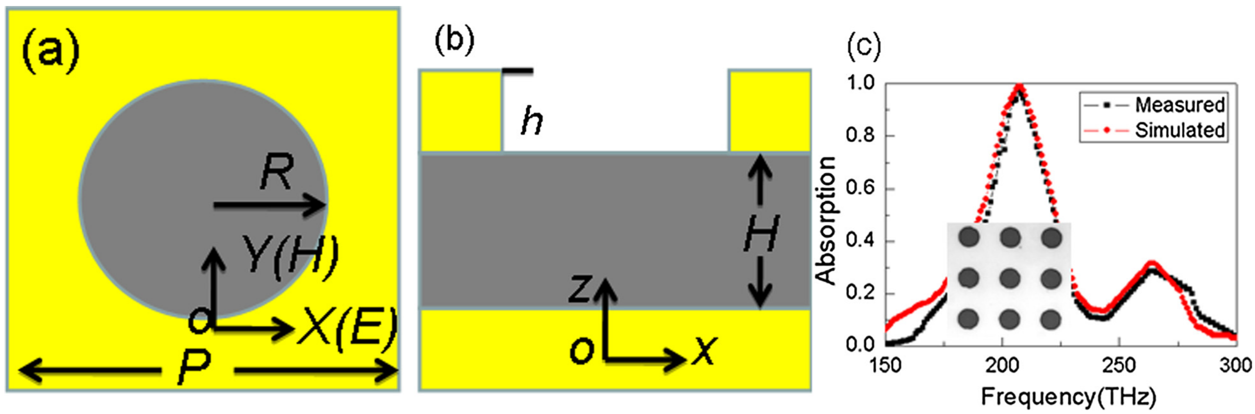

Fig. 1. (a) Top view of the designed structure on the xoy plane. (b) Side view of the designed structure on the xoz plane. The yellow part is gold layer, the gray part is MgF_2 layer, (c) The measured and simulated absorption spectra, the inset is photograph of samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Dimensional parameters of the designed absorber.

Parameter	P	R	H	h
Value (nm)	1600	500	300	55

follows: A thermally oxidized Si handle substrate is selected. A 200 nm-thick SU-8 layer is then spun on the Si substrate. A 55 nm-thick bottom gold layer is evaporated on the SU-8 layer at a rate of 1.8 Å s^{-1} under 56e−10 (atm) working pressure by electron beam evaporation (ZZL-U400H). Then a MgF_2 dielectric layer is then deposited onto the surface of the gold layer. Another 55 nm -thick top gold layer is evaporated on the MgF_2 dielectric layer (ZZL-U400H). The designed circular holes arrays are defined by regular electron-beam lithography (EBL) on the top gold layer. Finally, the fabricated SU-8/gold/MgF_2/gold structure temporary samples are subsequently removed from the Si substrate through using a buffered oxide etchant to etch the SU-8 layer away. The actively area of samples has a structure area of nm. The optical microscopy images of the samples are obtained by using Leica DM2700M. The measured absorption rate spectra are obtained by the Bruker Optics Equinox (BOE) 55 Fourier transform infrared spectrometer.

The designed structure consists of three functional layers. The top layer is a two-dimensional gold round air hole arrays. The middle layer is a MgF_2 dielectric spacer. The bottom layer is a thickness 55 nm gold layer, which is obviously larger than the skin depth of the electromagnetic wave in the working spectrum and hence prohibits transmission through the proposed structure. Therefore, the reflection which comes from the top layer of the designed structure is the only factor limiting the absorption: A = 1-R. The proposed absorber is designed to be polarization independent in y-direction and x-direction, respectively, at normal incidence (see Table 1).

To research the physical mechanism and optical resonant behavior of the designed sensor, numerical simulations are performed through using a full-waves electromagnetic solver (Ansoft 13.0). In all of simulations, two Floquet ports are adopted at the top and the bottom boundaries of the designed structure to simulate a normally-incident light. Two boundaries normal to the x-axis, two ideal magnetic conductor planes are adopted. Similar, two boundaries normal to the y-axis, two ideal electric conductor planes are adopted [13]. The frequency step is used 0.02 THz, and the thickness of the upper and lower air layers are 1000 nm and 400 nm, respectively. In this paper, the permittivity of the dielectric layer

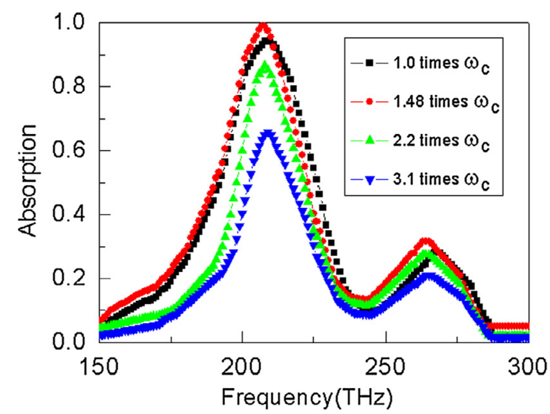

Fig. 2. Simulated absorption spectra in dependence on different damping constants of bulk gold.

(MgF_2) is given as 1.9 [14]. And the permittivity of bulk gold is described by the Drude model, two key parameters the damping constant $\omega_c = 4.08 \times 10^{13}\ s^{-1}$, and the plasma frequency $\omega_{pl} = 1.37 \times 10^{16}\ s^{-1}$ [15].

It should be noted that differences between the experimental results and simulation results are nature, especially the damping constant has an important effect on the optical property of the designed structure. Zhang et al. [16] indicate that the damping constant of bulk gold is likely lower than that of the gold film due to the grain boundary effect and the surface scattering in thin films. To obtain an optimization damping constant of the gold film in simulations, Fig. 2 shows the simulated absorption spectra as a function of damping constants of bulk gold. As shown in Fig. 2, different amplitudes of absorption peaks are achieved. For one times damping constant of bulk gold (see the black curve in Fig. 2), a resonance absorption peak with 65% absorbance rate is obtained. For 2.2 and 3.1 times damping constant of bulk gold (see the green and blue curve sin Fig. 2), the maximum absorbance rate is reduced to 87% and 65%, respectively. However, a strong resonant absorption peak with nearly 99.8% is achieved for 1.48 times damping constant of bulk gold (see the red curve in Fig. 2). The designed metamaterial absorber shows a high absorption band resonance with a damping constant equal to 1.48 times that of bulk gold. Consequently, a simple structure of perfect absorber is obtained. These results indicate that the perfect impedance matched condition is obtained between the top layer of the designed structure and the