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Design and measuring of a tunable hybrid metamaterial absorber for terahertz frequencies

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A tunable hybrid metamaterial absorber is designed and experimentally produced in THz band. The hybrid metamaterial absorber contains two dielectric layers: SU-8 and VO_2 layers. An absorption peak reaching to 83.5% is achieved at 1.04 THz. The hybrid metamaterial absorber exhibits high absorption when the incident angle reaches to 45°. Measured results indicate that the absorption amplitude and peak frequency of the hybrid metamaterial absorber is tunable in experiments. It is due to the insulator-to-metal phase transition is achieved when the measured temperature reaches to 68 °C. Moreover, the hybrid metamaterial absorber reveals high figure of merit (FOM) value when the measured temperature reaches to 68 °C.

1. Introduction

The metamaterial absorber is interesting functional equipment. The first experimentally confirmed metamaterial absorber is reported by Landy et al. in 2008, which achieves an 88% measured absorption peak [1]. The metamaterial absorber is widely used in industrial applications, such as thermal emitters, photovoltaic cells, and optical imaging devices [2–4]. Metamaterial absorbers with different properties are developed and experimentally validated. For example, a single-band wide-angle polarization independent absorber is designed and experimentally measured by Cheng-Wen Cheng et al. in 2012 [5]. In 2011, Pei Ding et al. simulated a dual-band perfect metamaterial absorber and modulated the interaction between different resonance modes to enhance the absorption [6]. Moreover, a triple-band metamaterial absorber is also reported by Xiaopeng Shen et al. in 2011 [7]. Many researchers modulate the properties of absorbers in different ways, such as innovative structural design strategy, optimizing the structure, stacking different dielectric layers, or stacking a large number of dielectric layers. For example, Donghao Zheng et al. proposed a flower-shaped structure metamaterial absorber [8]. Tao Wang et al. optimized the structural design to extend perfect absorbance bandwidth in the microwave frequency range [9]. Nan Zhang et al. designed and experimentally prepared a dual-band metamaterial absorber based on two distinct dielectric spacing layers [10]. In our previous work, a double circular-patterned metal–dielectric stacks metamaterial absorber is proposed, which contains three dielectric layers (SU-8 layer, Al_2O_3 layer, and ZnSe layer) [11]. X. Zhao et al. proposed and produced a nonlinear metamaterial perfect absorber in terahertz based on the GaAs layer [12]. X. Zhao et al. also designed another tunable metamaterial perfect absorber based on using flexible substrate [13]. Moreover, Fei Ding et al. proposed a metamaterial absorber based on many of metal and dielectric layers alternately stacking, and achieved 20 absorption peaks in 1–10 GHz band [14]. With further research, different types of dielectric layers have been used in the development of absorbers. Boyang Zhang et al. designed and measured a metamaterial absorber based on adopting the MgF_2 dielectric layer [15]. Hua Cheng et al. manufactured a polarization insensitive and wide-angle metamaterial absorber through using an Al_2O_3 dielectric layer [16]. The SiO_2 dielectric layer can be used in metamaterial absorber [17]. These dielectric layers have a common characteristic that their properties are stable and less susceptible to the change in external conditions. This characteristic hinders the metamaterial absorber responses to the change in external conditions in application process, for example the change in environment temperature. Therefore, taking advantage of the property modifiable dielectric layer to design a tunable metamaterial absorber is interesting to researchers. For example, the VO_2 layer is a kind of property modifiable dielectric layer. The conductivity of the VO_2 dielectric layer shows its dynamic insulator-to-metal phase transition when the measured temperature reaches to 68 °C [18].

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Therefore, development of a property adjustable absorber based on the VO_2 layer is worth studying.

In this paper, a single-band metamaterial absorber is proposed and experimentally produced. The proposed absorber contains a SU-8 layer and a VO_2 layer. A circular holes array is patterned on the top metal layer, which can be conveniently production in many methods. Maximum absorption rate and resonant frequency of the proposed absorber can be modulated through increased the measured temperature. The figure of merit (FOM) value indicates that the proposed absorber is highly sensitive to the measured temperature change.

2. Structural design and experimentation

The designed metamaterial absorber is shown in Fig. 1(a–b). The top metal layer is defined by a circular holes array. The optimized structure parameters are $P = 10$ μm, $w = 8.4$ μm, $d1 = 5.0$ μm, $d2 = 0.2$ μm, $H1 = 0.2$ μm, $H2 = 0.45$ μm. Simulations are achieved by the software HFSS 12. In simulations, the dispersion behavior of the silver layer can be described through the Drude mode:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma_D} \tag{1}$$

Here, $\omega_p = 1.37 \times 10^{16}\ \mathrm{s}^{-1}$ is the plasma frequency, $\gamma_D = 9 \times 10^{13}\ \mathrm{s}^{-1}$ is the collision frequency [19]. Boundary condition settings are consistent with the literature [20]. The dielectric layer SU-8 consistent with the literature [21]. The VO_2 layer will be described by the Bruggeman–Drude model [22]:

$$\varepsilon_{VO2} = \varepsilon_2 + \frac{(1-\varphi)^2\left[\left({\varepsilon_2}/{\varepsilon_1}\right) - 1\right]^2}{2}\varepsilon_1 - \varepsilon_1\left[\left({\varepsilon_2}/{\varepsilon_1}\right) - 1\right] \times \sqrt{(1-\varphi)^2\left[\left({\varepsilon_2}/{\varepsilon_1}\right) - 1\right]^2 \Big/ 4 + (1-\varphi)^2\left({\varepsilon_2}/{\varepsilon_1}\right)} \tag{2}$$

The production method of measured samples is as following: first, a 0.35 μm-thick silver layer will be evaporated on the silicon wafer substrate (at a rate of 2.0 Å s^{-1} and the working pressure is 58e-10 (atm)). Then the 0.2 μm-thick VO_2 layer will be evaporated on the silver layer. The 5.0 μm-thick SU-8 layer is spun on the VO_2 layer and bake for 4 min. Finally, a 0.1 μm-thick silver layer will be evaporated on the SU-8 layer. The holes array will be etched on the top silver layer using electron-beam lithography (CABL-9000C), which is consistent with our previous work [23]. The samples area is 4 mm × 3.5 mm. The absorption spectrum is obtained by the Bruker Optics Equinox spectrometer. The photo is obtained by Leica DM2700M.

3. Results and discussion

3.1. Simulated results and measured results

In HFSS simulations, the transmission is zero across the whole proposed metamaterial absorber, the absorption can be given as:

$$A(f) = 1 - R(f) \tag{3}$$

Here, the $R(f)$ is the simulated reflectance. The simulated absorption spectrum is shown in Fig. 2(a). An absorption peak (92%) is achieved at 1.04 THz. The measured absorption spectrum is shown in Fig. 2(b). A measured absorption peak reaches to 83.5% at 1.04 THz, which is slightly lower than the simulated results. Resonance frequencies of simulated absorption peaks are consistent with that of measured absorption peaks. The simulated result is agreed well with the measured result, which indicates that the simulation settings are effective.

The physical mechanism of the absorption peak can be reveal through calculated effective parameters in HFSS simulations. The S parameter extracted method is applied in simulations [24,25]. The extracted effective permittivity and permeability are shown in Fig. 3(a–b). The real part of permittivity (ε) is increased from negative value to positive value, and cross the zero at the absorption peak resonance frequency 1.04 THz. However, the real part of μ shows a reverse resonance behavior, which is reduced from a positive value to a negative value around the resonance frequency, as shown in Fig. 3(a). The real part of the ε and μ show opposite resonance behaviors around the resonance frequency 1.04 THz, as shown in Fig. 3(a–b). However, they are both cross zero at the resonance frequency 1.04 THz. The impedance matching condition $Z(\omega) = \sqrt{\mu(\omega)/\varepsilon(\omega)}$ [26] is achieved between the absorber and free space at the resonance frequency 1.04 THz, which results in the perfect absorption peak in Fig. 2. Similar resonance behaviors are reported in many literature. For example, Xianliang Liu et al. designed and manufactured a metamaterial perfect absorber in the infrared regime. The real part of the ε and μ also cross zero at the resonance frequency of the perfect absorption peak [26]. Moreover, Yong Ma et al. proposed and measured a dual band metamaterial absorber in the terahertz range. Both perfect absorption peaks are achieved based on the real part of the ε and μ of the reported

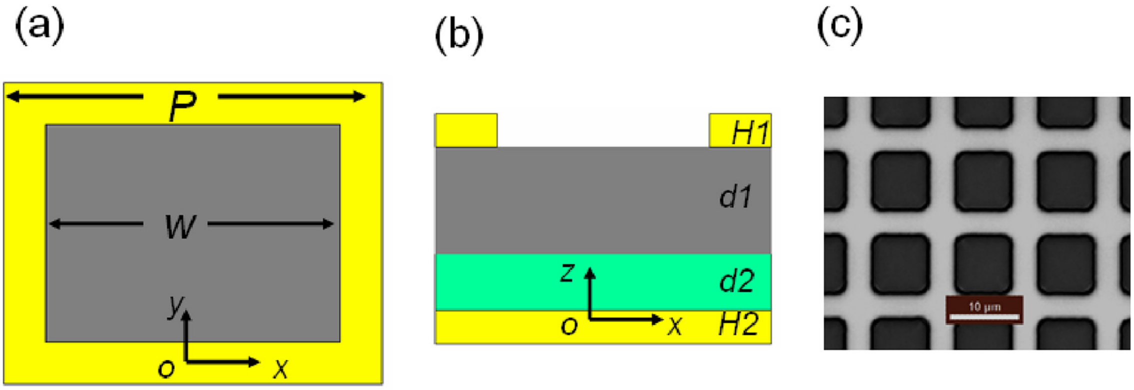

Fig. 1. (a) Top view on the xoy plane. (b) Cross section on the xoz plane with $y = 5.0$ μm. The yellow part is silver layer, the gray part is SU-8 layer, the green part is VO_2 layer. (c) the photograph of samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)