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Polarization-independent broadband absorber based on pyramidal metal-dielectric grating structure

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ABSTRACT

An infrared broadband polarization-independent metamaterial absorber is designed and investigated. It consists of a pyramidal metal-dielectric multilayered rectangle grating structure. The absorber exhibits near-unit absorption at multiple adjacent wavelengths overlapping with each other, which results in a high absorption over a wide wavelength range. The absorbance at normal incidence is higher than 90% in a wavelength range of 2321 nm–4631 nm, and the broadband absorption performance can be maintained over a large incident angle range. Furthermore, the mechanism of such broadband absorption are investigated by illustrating the electric field distributions for TE polarization and magnetic field distributions for TM polarization at the resonant wavelengths. It is believed that the conclusions can be applied for developing polarization-independent broadband absorber.

1. Introduction

Metamaterials are artificial materials with particular arrangement of metallic and dielectric subwavelength structures in one unit, can provide fascinating physical properties unattainable in nature [1,2]. Due to their potential applications in the fields of perfect lens [3] and cloaks [4], and so on, they have already attracted much attentions in recent years. To realize such exotic electromagnetic properties, it generally requires a low optical losses at the desired frequency range. However, this is usually limited by the materials loss employed. Conversely, for many other applications, such as perfect absorber [5], it would be desirable to take advantage of the intrinsic materials loss. Due to their wide applications in narrowband absorber/emitter [6,7], thermal imaging devices [8], detectors [9], IR cloaking [10] and solar power harvesting [11], metamaterials absorbers have been investigated in a wide frequency range from radio frequency to visible [12–22].

To obtain near-unit absorption, a resonance is generally employed, which usually leads to a narrow absorption bandwidth [6–9,12,13,15,17,19,20,22]. However, for applications in the areas of IR cloaking [10] and solar power harvesting [11], the broadband absorption is desirable. A simple and effective method to extend the bandwidth of absorption is to employ multiple resonant structures in one unit cell with overlapping resonance wavelengths [14,23–26]. However, the bandwidth is still limitation due to the limited number of resonators which can be blended in a subwavelength unit. To further broaden the bandwidth, the concept of anisotropic metamaterials has been proposed and experimentally demonstrated [27–31]. Cui et al. reported a sawtooth anisotropic metamaterial slab absorber for TM polarization with the absorbance above 95% covering a waveband ranging from 3 to 5.5 μm and a FWHM of 86% at normal incidence [27]. Ji et al. experimentally realized a patterned hyperbolic metafilm with engineered and freely tunable absorption band from near-IR to mid-IR spectral regions based on multilayered metal/dielectric films [28]. Zhou et al. realized a tunable TM polarization broadband absorber in the visible and IR range based on the tapered metal–dielectric multilayered structure [29]. However, the broadband absorbers based on one-dimensional anisotropic metamaterials proposed above suffer from a common disadvantage of sensitive to the polarization state of the incident light, which greatly limit their potential applications. Ding et al. proposed and fabricated a microwave ultra-broadband absorber based on a periodic array of metal-dielectric multilayered quadrangular frustum pyramids, which achieves polarization-independent nearly unity absorption from 8 GHz to 14 GHz over a wide angular range [30]. Liang et al. designed a two-dimensional pyramidal shape metamaterial-based polarization-insensitive absorber, which performs excellently at full infrared waveband [31]. However, the polarized-independent broadband

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absorbers based on two-dimensional anisotropic metamaterials proposed above are rather difficult to fabricate, which also limit their potential applications.

In our previous paper, a polarization-insensitive broadband infrared absorber with a tapered metal-dielectric multilayered grating structure is proposed [32]. The designed absorber exhibits great optical performance. However, the tapered multilayered grating structure used increases the challenge of fabrication. In this paper, a broadband polarization-independent metamaterial absorber for the infrared frequency is designed and investigated. It is composed of alternating metallic and dielectric one-dimensional multilayered rectangle grating structures. The absorber possesses perfect absorption at multiple wavelengths close to one another, which leads to a broadband absorption. Moreover, the broadband absorption performance can be maintained for the incident angle up to 60°. Lastly, to better understand the physical origin of such broadband absorption effect, the electric field and magnetic field distributions at several selected wavelengths are illustrated.

2. Design and results

As shown in Fig. 1, the polarization-independent broadband absorber considered here is comprised of a metallic-dielectric multilayered grating structures backed with a gold film and a dielectric substrate. The thickness of gold film is selected as 200 nm so as to block all light transmission. The dielectric substrate is quartz (SiO_2) with a refractive of 1.45. The metal grating are made of gold (Au) with a thickness of $h_1 = 6$ nm and the refractive index (n_m) taken from ref. [33]. The dielectric grating is Germanium (Ge) with a thickness of $h_2 = 258$ nm and a refractive index of $n_d = 4$. The total number of metal/dielectric grating pairs is $N = 15$. The period of the absorber is $d = 1643$ nm. The widths (duty cycles) of the bottom grating and the top grating are w_b ($f_b = w_b/d$) and w_t ($f_t = w_t/d$), respectively. The widths or the duty cycles change randomly from w_b (f_b) at the bottom to w_t (f_t) at the top. A TE polarization (electric field is parallel to grating grooves) and a TM polarization (magnetic field is parallel to grating grooves) monochromatic plane waves are incident from the air with an incident angle θ.

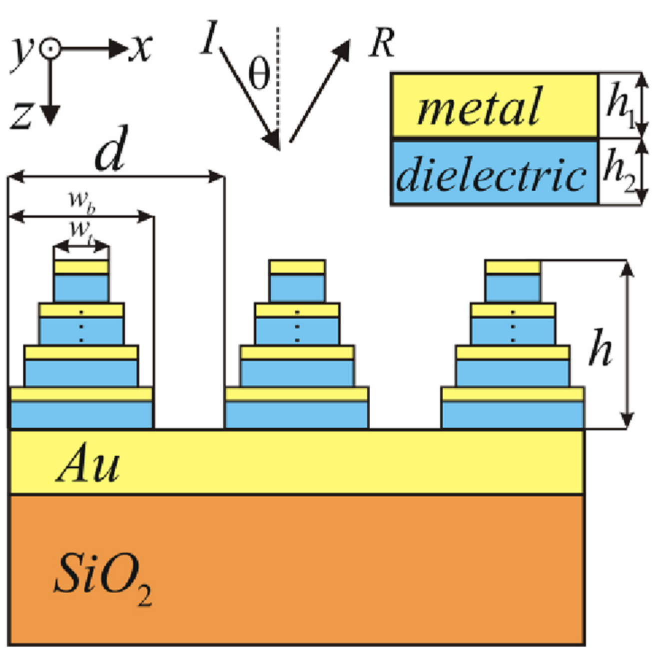

Fig. 1. Schematic of the polarization-independent broadband absorbers based on pyramidal metallic-dielectric multilayered grating structure.

To obtain the optimized structure parameters in the desired wavelength ranges, the simulated annealing (SA) algorithm [34] is employed, where the cost function is:

$$\phi = sum\left((A_{TM}(\lambda) - 1)^2\right) + sum\left((A_{TE}(\lambda) - 1)^2\right) \quad (1)$$

where, $A_{TM}(\lambda)$ and $A_{TE}(\lambda)$ are the absorption spectrums of TM and TE polarizations, respectively. The objective is to minimize ϕ by selecting suitable geometric parameters. At first, the duty cycles are optimized with a linear change from f_b at the bottom to f_t at the top, i.e. the difference of duty cycle between two adjacent dielectric or metallic grating is a constant. Next the duty cycles are changed randomly so as to further improve the broadband absorption performance. After some numerically optimization efforts, we obtain the optimized structure parameters as follows: $d = 1643$ nm, $h_1 = 6$ nm, $h_2 = 258$ nm, $N = 15$ and the duty cycles from top to the bottom are 0.0629, 0.0856, 0.142, 0.193, 0.277, 0.356, 0.409, 0.468, 0.504, 0.637, 0.658, 0.712, 0.797, 0.820, 0.975.

By use of the rigorous coupled wave analysis (RCWA) method [35], we obtain the absorption spectrums under normal incidence for both TE and TM polarizations, which are shown in Fig. 2. The wavelength-dependent absorbance are calculated by $A(\lambda) = 1 - T(\lambda) - R(\lambda)$, where $T(\lambda)$ and $R(\lambda)$ are the transmittance and reflectance, respectively. As can be seen from Fig. 2, the polarization-independent absorption is above 90% in a wavelength range of 2321 nm–4631 nm, which shows an excellent polarization-independent absorption performance. It is worth noting that the absorption performance is better for TE polarization at short wavelengths, where it is better for TM polarization at long wavelengths. The broadband absorption for TM polarization can be extended to wavelengths longer than 4700 nm, though not plotted in this figure. However, the absorbance for TE polarization decreases quickly at the long wavelengths. In general, the broadband absorption performance under normal incidence for TM polarization is better than that for TE polarization.

Next, the dependence of absorption on the incident angle is investigated. For a practical broadband absorber, the broadband absorption should be robust for non-normal incidence. In Fig. 3 we show the absorption and reflection as a function of wavelength and the angle of incidence for both TE and TM polarizations. As can be seen from Fig. 3(a), the absorbance remains above 90% (70%) in the wavelength range of 2500 nm–4404 nm (2259 nm–4413 nm) when the incident is below 30° (52°). The absorbance decreases

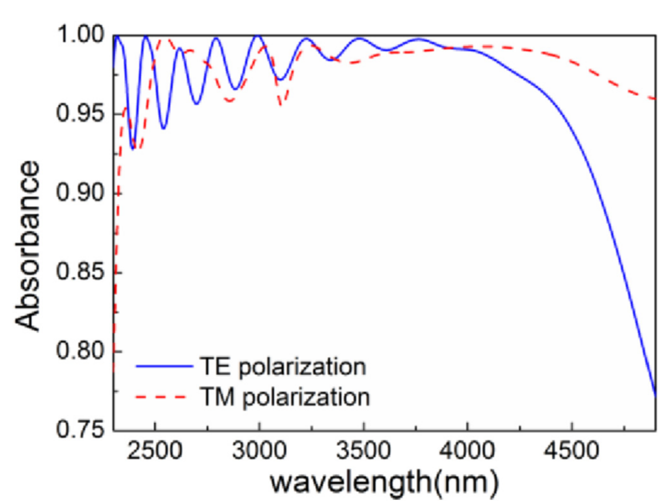

Fig. 2. Absorption spectrums under normal incidence for both TE and TM polarizations.