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Polarization-dependent and -independent spectrum selective absorption based on a metallic grating structure

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ABSTRACT

The absorption effect in grating-based devices is theoretically investigated. Three kinds of spectrum selective absorbers (TE polarization, TM polarization and polarization-independent) exhibiting near-unity absorption at the resonant wavelength are studied at visible frequencies. The optimized parameters of absorbers are all obtained by use of rigorous coupled-wave analysis and the simulated annealing algorithm. The underlying physics understanding of such perfect absorption effects is illustrated by investigating the field distributions and power loss density in these absorbers. The enhancement of absorption is attributed to the hybridization of cavity mode and guide mode resonance for TE polarization absorber, and attributed to the surface plasmon resonance for TM polarization absorber with ultra-thin grating structure. The relationship between the absorption spectrum and the geometric parameters of the structures is studied. In order to achieve perfect absorption, the grating should have large thickness for TE polarization, while it has not strict restriction for TM polarization. The conclusions should be useful for designing a polarization-dependent or -independent selective absorber based on a metallic grating structure in the visible region.

1. Introduction

In recent years, enhancement of absorption in subwavelength structures becomes a hot subject due to their potential wide application [1–19]. There are two kinds of perfect absorbers: broadband absorber (with broad spectrum) and spectrum selective absorber (with narrow band spectrum), which are both important devices. The former possesses blackbody-like behaviors and can find application in solar power harvesting [1]. The latter has near-unity absorbance at the resonant wavelength, which is useful for developing sensitive detectors, thermal imaging devices and narrowband absorber/thermal emitters for thermo-photovoltaics [2,3].

Various methods have been proposed to achieve enhanced absorption, such as metallic nanoparticles [4,5], metamaterials [6–19], etc. Among these, grating-based metamaterials are important and simple devices for effective enhancement of absorption. Compared with other metamaterials with complex structures [6–13], the advantages of grating-based metamaterials are that they can be designed and fabricated more easily. Through optimization, the grating-based metamaterials can offer the near-unity absorption at the resonant wavelength. The basic idea is to minimize the transmittance and simultaneously to minimize the reflectance by use of impedance matching.

Wu et al. [14] proposed a simple design for an ultra-thin, wide-angle perfect absorber for infrared frequencies. It is shown to exhibit nearly 100% absorption at the resonant wavelength. The absorption remained above 95% in P-polarization and 90% in S-polarization (in the orthogonal incidence plane, not as usual TE polarization) for the incidence angles up to 45°. Wu et al. [15] also introduced and experimentally demonstrated a simple metamaterial-based wide-angle plasmonic absorber, which can be utilized for subdiffraction-scale infrared pixels exhibiting spectrum selective absorption/emissivity. Mason et al. [16] designed and characterized a thin-film mid-IR metamaterials with strong absorption resonances, which is shown to be highly selective and largely independent of emission angles from normal to 45°. Cui et al. [17] experimentally demonstrated an infrared broadband absorber based on an array of nanostrip antennas of several different sizes, the broadband properties was due to the collective effect of magnetic responses excited by nanoantennas at distinct wavelengths. Diem et al. [18] designed a perfect absorber/thermal emitter exhibiting an absorption peak of 99.99%, and the high absorption can be maintained for large angles with a minimal shift in the center frequency. Lin et al. [19] investigated the polarization-independent broadband absorbers in the visible regime. Enhanced absorption in the structure was attained over a broad range of wavelength for both TE and TM polarizations.

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However, up to now, the selective absorbers based on grating-based metamaterials are mainly for TM polarization and work in infrared region. This is because they can achieve perfect selection absorption with ultra-thin grating structure for TM polarization. The ultra-thin grating structure has the advantage of less dependence on the angle, especially in the infrared region (due to strongly subwavelength dimensions in the longer wavelengths). Meantime, the perfect selection absorption in the infrared region can be fully explained by the theory of metamaterials.

In this paper, we investigate three kinds of spectrum selective absorbers exhibiting near-unity absorption for visible frequencies: TE polarization selective absorber, TM polarization selective absorber and polarization-independent selective absorber. The absorbers are three-layered structures consisting of a silver grating on top of a dielectric layer and a silver film at the bottom. The optimized parameters of absorbers are obtained by use of rigorous coupled-wave analysis (RCWA) [20,21] and the simulated annealing (SA) [22,23] algorithm. We also illustrate the underlying physics of such perfect absorption effects by investigating the field distributions and power loss density in these absorbers. At last, the relationship between the absorption spectrum and the geometric parameters of the structures is studied, which can be used for guiding the design of a spectrum selective absorber based on a metallic grating structure for visible frequencies. The designed absorber can be used in high quality detectors, thermal emitters and sensors.

2. Absorber in the visible region

Fig. 1 shows the structure of an absorber. The absorber consists of a subwavelength grating and a spacer layer deposited on a metal film. The material of the top-layer grating and the bottom metal film is silver (Ag), and the central-layer dielectric is quartz (SiO_2). The structure is assumed to be fabricated on a quartz substrate. The refraction indexes of silver at the visible regime are obtained from Ref. [24]. The refraction index of SiO_2 is 1.46. For TM polarization, the magnetic field is parallel to grating grooves, i.e. along the y axis; for TE polarization, the electric field is parallel to grating grooves. A monochromatic plane wave is incident from the air with an incident angle θ.

We select the appropriate structure parameters as the initial data and adopt the simulated annealing (SA) algorithm for optimization. The cost function is

(1) for polarization-independent absorber:

$$\phi(d,f,h_1,h_2) = -(A_{TE\_max} + A_{TM\_opt}) \tag{1}$$

where, $A_{TE\_max} = \max(A_{TE}(\lambda)) = A_{TE}(\lambda_m)$, $A_{TM\_opt} = A_{TM}(\lambda_m)$, A_{TE_max} means the maximum absorbance for TE polarization at wavelength λ_m, and A_{TM_opt} is the corresponding absorbance for TM polarization at this wavelength λ_m. $A_{TE}(\lambda)$ and $A_{TM}(\lambda)$ are the absorption spectrum for TE and TM polarizations, respectively. The optimization process is to find appropriate structure parameters so that $A_{TE}(\lambda)$ and $A_{TM}(\lambda)$ are maximum at the wavelength λ_m simultaneously.

(2) for TE polarization absorber:

$$\phi(d,f,h_1,h_2) = -A_{TE\_max} \tag{2}$$

(3) for TM polarization absorber:

$$\phi(d,f,h_1,h_2) = -A_{TM\_max} \tag{3}$$

where, $A_{TM\_max} = max(A_{TM}(\lambda))$, A_{TM_max} means the maximum absorbance for TM polarization.

The objective is to minimize $\phi(d, f, h_1, h_2)$ by selecting suitable grating parameters. After optimization, the optimized structure parameters can be obtained.

The ground silver film is thick enough (200 nm in this paper) so as to avoid transmission through the structure. Thus, it can block all light transmission ($T=0$), the absorption (A) can be calculated by its reflectance (R): $A\equiv1-R$. The absorption of energy is attributed to the power loss in the device. In the case of nonmagnetic dispersive medium, the time-averaged power loss density is given by [8,25]:

$$\frac{dP_{loss}}{dV} = \frac{1}{2}\varepsilon_0\omega \mathrm{Im}\varepsilon(\omega)\left|E\right|^2 \tag{4}$$

where, ε_0 is the permittivity of vacuum, ε denotes the relative dielectric permittivity of the material, ω is the angular frequency and E denotes the electric field. As can be seen from Eq. (4), the enhancement of absorption can be achieved by employing high-loss materials and large electric field intensity.

2.1. TE polarization selective absorber

The simulated absorption spectrums at normal incidence for the TE polarization selective absorber are shown in Fig. 2. A strong resonance with light absorption about 99.97% is achieved at the wavelength of 561 nm for TE polarization. The absorption peak is very narrow. It is found that there are three absorption peaks for TM polarization in the 400–800 nm wavelength range, though the optimized parameters are obtained for TE polarization. The relationship between the absorption spectrum and the geometric parameters of the structures will be investigated in Section 3.

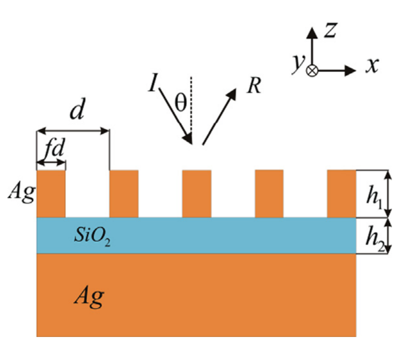

Fig. 1. Schematic of the absorber based on a metallic grating structure. d is the grating period, h_1 is the grating depth, h_2 is the thickness of spacer and f is the duty cycle.

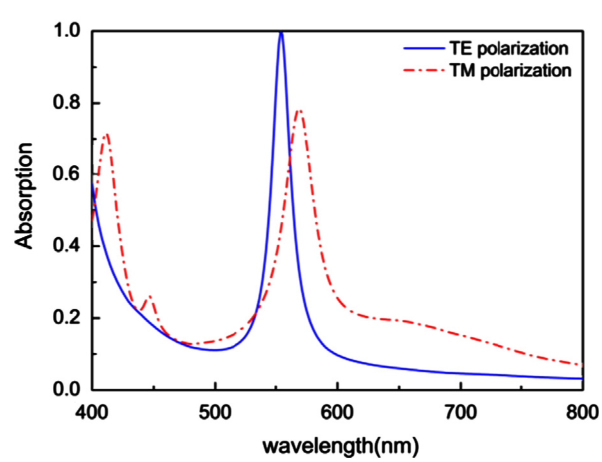

Fig. 2. Absorption spectrums for the TE polarization selective absorber with operating wavelength at 561 nm. The structure parameters are: $f=0.36$, $d=312$ nm, $h_1=218$ nm, $h_2=105$ nm.