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An ultra-narrowband absorber with a compound dielectric grating and metal substrate

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ABSTRACT

We propose an alternative method to achieve an ultra-narrowband absorber with a single-layer compound dielectric structure and metal substrate. The simulation results show that the absorption bandwidth is 1.3 nm and the absorption rate is more than 0.99 for TE polarization (electric field is parallel to grating grooves). The phase resonance plays an active role in the resonance absorption. Furthermore, the electric field is mainly distributed in the grating grooves. The figure of merit (FOM) is larger than 480 if this absorber is applied as a refractive index sensor.

1. Introduction

Absorption manipulation is a very important issue in electromagnetic research. Perfect absorbers with artificial structures have attracted great attentions because of their wide applications such as thermal emitters [1], solar cells [2], sensors [3], photodetectors [4] and filters [5]. The perfect absorbers typically consist of a metal-dielectric-metal tri-layer structures which generate strong electromagnetic resonance resulting in perfect absorption [6–11]. Generally, their absorption bandwidths are above tens of nanometers. The absorption bandwidth plays a critical role in some applications. For example, the broadband and ultra-broadband absorbers are proposed to efficiently absorb electromagnetic energy in a wide-wavelength range [12–17]. On the other hand, the ultra-narrowband absorbers with bandwidths less than ten nanometers are also expected in some applications. For example, an absorber with ultra-narrow bandwidth means high temporal coherence when a narrowband absorber is used as a thermal emitter [18]. In addition, a refractive index sensor based on perfect absorber with ultra-narrow bandwidth will have large FOM [3]. To realize ultra-narrowband absorption, several schemes have been reported. For example, Sharon et al. proposed an ultra-narrowband absorption scheme by exciting Rayleigh anomaly and guide-mode resonance [19]. In 2014, Meng et al. achieved an ultra-narrow absorption bandwidth by using the small radiative and resistive damping rates [20]. In the same year, Zhao et al. reported an ultra-narrow absorber with two cascaded cavities [21]. Very recently, our group reported a TE-polarized ultra-narrowband absorber based on the guide-mode resonance mechanism [22].

In this paper, we propose an alternative method to achieve an ultra-narrowband absorber with a single-layer compound dielectric structure and metal substrate. The ultra-narrowband absorption is originated from cavity resonance and phase resonance and metal loss. Furthermore, the electric field is mainly distributed in the grating grooves, and this ultra-narrowband absorber can be used as a refractive index sensor with high FOM.

2. Structure

Fig. 1 schematically shows a compound dielectric grating structure on a metal substrate. The compound dielectric grating consists of two slits (of widths a and b) in one period p, and other parameters can be depicted by ridge width w and height h. A TE-polarized plane wave is incident on this structure with an angle of θ ($90^0 > \theta \geq 0^0$). Gold (Au) is used as the metal substrate to efficiently reflect the incident light and dissipate the electromagnetic energy, the permittivity of gold at the infrared regime can be expressed with a Drude model:

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

where ω is the angular frequency of the light, $\omega_p = 1.32 \times 10^{16}$ rad/s, and $\omega_c = 1.2 \times 10^{14}$ rad/s. Aluminum oxide (Al_2O_3) is used as the material of grating ridges, and its refractive index is set as 1.75. The refractive index of the surrounding material is set as air. The absorption characteristics can be calculated with the rigorous coupled-wave

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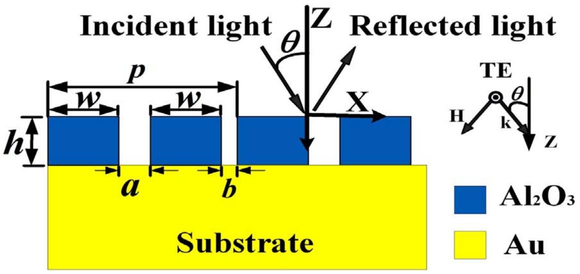

Fig. 1. Geometry of the absorber structure.

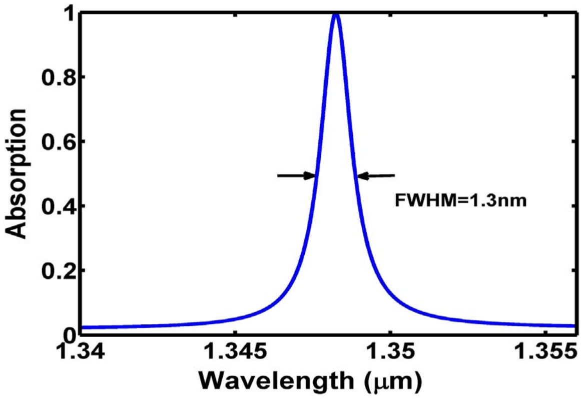

Fig. 2. Absorption as a function of wavelength.

analysis (RCWA) [23]. The incident light cannot penetrate through the gold substrate because the thickness of metal substrate is large enough. Thus, the absorption rate A can be attained with $A = 1 - R$, where R is the reflection calculated from the sum of reflected Fourier components in RCWA. Although the absorption characteristics of the flat metallic surface coated with dielectric grating have been extensively investigated [24,25], we pay more attention to the ultra-narrowband absorption with a dielectric microstructure on the metal surface in this paper.

3. Results and discussion

The simulated absorption spectrum for our proposed structure with normal incidence is shown in Fig. 2. In the simulation process, the optimized parameters of p=1.000 μm, w=0.400 μm, a=0.150 μm, b=0.050 μm, and h=0.740 μm. From Fig. 2, we can see an absorption peak with the absorption rate larger than 0.99 at the wavelength of 1.3482 μm for TE polarization. As seen in Fig. 2, the full width at half maximum (FWHM) of the absorption spectrum is 1.3 nm. Thus, we can get an ultra-narrowband absorber with a single-layer compound dielectric grating and metal substrate. Compared with the ultra-narrowband absorbers with metallic microstructures [20,21], our ultra-narrowband absorber has a potential advantage in fabrication cost because the proposed structure can be fabricated with nanoimprint lithography if the dielectric grating material is set as polymethyl methacrylate (PMMA) or SU-8 [26,27].

To reveal the physical mechanism of ultra-narrowband absorption, the electric field E_y distribution within one unit cell at 1.3482 μm is shown in Fig. 3(a). From Fig. 3(a), it can be seen that the electric field mainly distributes in the grating slits and the cavity resonance is excited. In addition, the E_y in the two slits is opposite. To further reveal the relation of the electric field in these two slits, we plot the phase distribution at the interface of $z = 0$ in Fig. 3(b). As shown in Fig. 3(b), the phase difference between the adjacent slits is π which means the so-called phase resonance. At this phase configuration, the electric field in these two slits will produce destructive interference in the far field so that the light which is reflected by the metal substrate will be completely reflected again if the energy in the two slits is equal. Such complete reflection in $-z$ direction makes the region of $z < 0$ act as a perfect cavity mirror. On the other hand, the metal substrate can be regarded as a non-perfect cavity mirror due to the inherent loss of metal material. And the light will be confined between these two cavity mirrors. If the power loss in a cavity decreases, the quality factor will increase and the bandwidth will become narrower. From Fig. 3(a), we can see that the electric field is almost zero in the metal substrate so that an ultra-narrow bandwidth can be attained because of the low power loss in the resonance process [22].

To verify the contribution of the phase resonance in our absorber with a compound dielectric grating, the absorption characteristics of a simple grating with one slit in a period will be simulated and discussed. To convert the compound grating into a simple grating, the widths of the slits are set as $a = b = 0.100$ μm. In addition, to attain the optimized absorption with a simple dielectric grating on the metal substrate, the absorption spectra with different grating height are simulated with normal incidence in Fig. 4(a). Other parameters are $p = 1.000$ μm, and $w = 0.400$ μm. As shown in Fig. 4(a), the maximum absorption is less than 0.05 which is much smaller than unity. To reveal the difference of absorption mechanism, we plot the electric field E_y distribution in Fig. 4(b) at the wavelength of 1.66 μm which is the absorption peak with grating height of 0.740 μm. From Fig. 4(b), we can see that the magnitude of electric field is identical along X direction, and the phase resonance mechanism is not found in a simple grating. From the difference between Figs. 3 and 4, we can conclude that the phase resonance in the compound grating plays an active role in the perfect absorption shown in Fig. 2.

Next, we investigate the influence of the height and refractive index

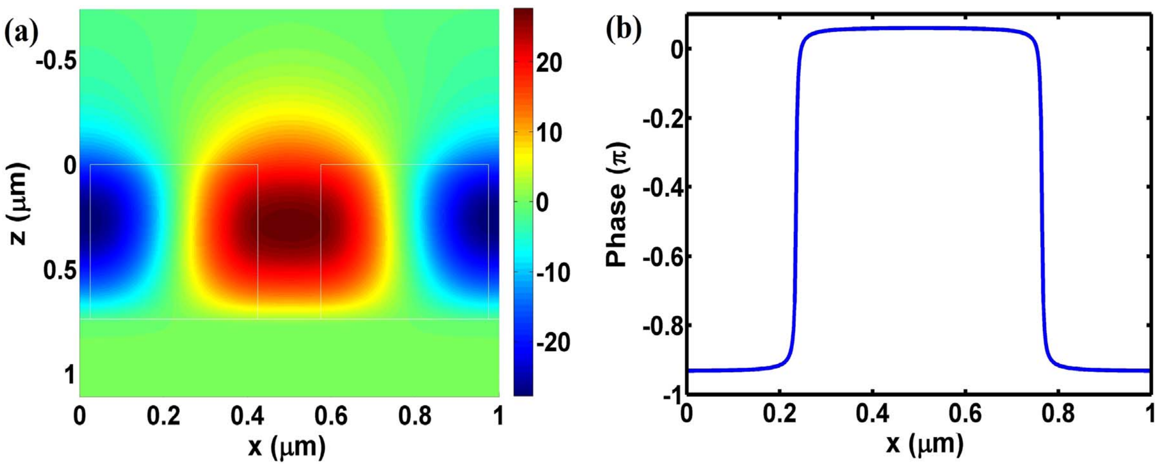

Fig. 3. (a) Electric field distribution for $\lambda = 1.3482$ μm, (b) phase distribution at the interface of $z = 0$.