Optics Communications 331 (2014) 310–315

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Multi-narrowband absorber based on subwavelength grating structure

Chenying Yang, Weidong Shen*, Yueguang Zhang, Ding Zhao, Xu Liu

State Key Laboratory of Modern Optical Instrumentation, Department of Optical Engineering, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form
13 June 2014
Accepted 22 June 2014
Available online 2 July 2014

Keywords:
Multi-narrowband
Absorber
Subwavelength grating

ABSTRACT

A near-infrared multi-narrowband absorber based on subwavelength metal-dielectric-metal grating structure was devised. The relationship between the parameters and the absorption performance was studied. By optimizing the geometrical parameters, a triple narrowband absorber with about 30-nm bandwidth was obtained. The electric and magnetic field distributions of the structure at the peak wavelength helped explain the nature of multi-narrowband absorption, which can be attributed to surface plasmon resonance and Fabry–Pérot resonance. The thickness of dielectric layer determines the absorption bands of the structure mostly due to Fabry–Pérot resonance. In addition, the absorber presents a satisfactory angular insensitive performance within 5° and can meet the demands for many applications.

1. Introduction

For recent years, plasmonic structures have attracted great interest for its potential application in many fields [1–15]. Perfect and tunable absorption of plasmonic structures has been investigated widely and developed in different aspects, which is always enhanced through the excitation of the surface plasmon resonance of structured metal material [5–14]. Among these proposed absorbers, the narrowband absorbers focused on the perfect absorption at only one or two specific wavelengths other than multi-wavelengths. Perchec et al. theoretically and experimentally presented that several nano-patched antennas assembled within a wavelength-scale region may constitute a tunable infrared multi-band photo-absorber [15]. However, the band of this multi-band absorber is not narrow, about hundreds of nanometers, limiting its further application. Besides, the arrangement of the antennas seems not expedient for design and fabrication. For many applications, e.g., isolating devices, sensing, and thermal imaging, the absorber is required to possess perfect absorption at multi-narrowband. Therefore, it is of essence to improve the absorption performance of the multi-band absorber. As far as we know, no such multi-narrowband absorber is reported before.

In this paper, we proposed a new multi-narrowband absorber in the near-infrared region using the metal of aluminum which is easier for fabrication and more stable than gold and silver. By optimizing the geometrical parameters, a triple narrowband absorber with about 30 nm bandwidth is obtained for the first time to our knowledge. We also analyzed the effect of the geometrical parameters on the absorption properties and provided a distinct relationship to design the desired multi-narrowband absorber conveniently. Through the analysis of the electric and magnetic fields of the structure, the physical origin of the phenomenon is verified that Fabry–Pérot resonance leads to the multi-narrowband absorption mostly. In addition, the absorber presents a satisfactory angular insensitive performance within 5° and meets the demands in many applications.

2. Structure and design

The structure of this multi-narrowband absorber is a two dimensional sub-wavelength metal-dielectric-metal grating. Fig. 1 depicts the schematic of our structure studied in this paper. It consists of a layer of aluminum grating and a layer of aluminum film with thickness larger than 100 nm, separated by a thick SiO_2 dielectric grating layer. The side lengths of square grating are denoted by a, the interval between the units is denoted by d and the period of the structure is denoted by p while the thicknesses of the top aluminum layer and the SiO_2 dielectric layer are represented by t_1 and t_2, respectively. A simple geometric relationship $p=a+2d$ could be obtained. The refractive index and extinction coefficient of aluminum come from the data in the book by Palik [16]. In our work, a plane wave illuminates the structure at normal incidence with TM polarization.

The finite-difference-time-domain (FDTD) method is used for reflectance/transmittance calculation and the electric/magnetic field distribution simulation. The FDTD method proposed by Kane in 1966 [17] is a powerful numerical analysis technique to compute

---

* Corresponding author.
E-mail address: adongszju@hotmail.com (W. Shen).

http://dx.doi.org/10.1016/j.optcom.2014.06.036
0030-4018/© 2014 Elsevier B.V. All rights reserved.

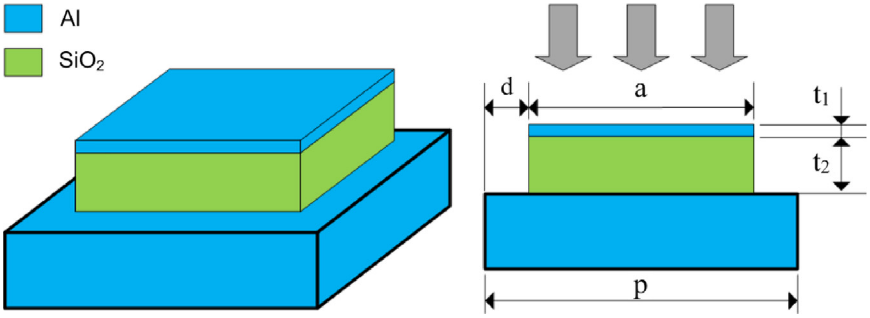

Fig. 1. Geometry of the proposed multi-narrowband absorber. The cross-sectional view is shown with the denoted geometrical parameters.

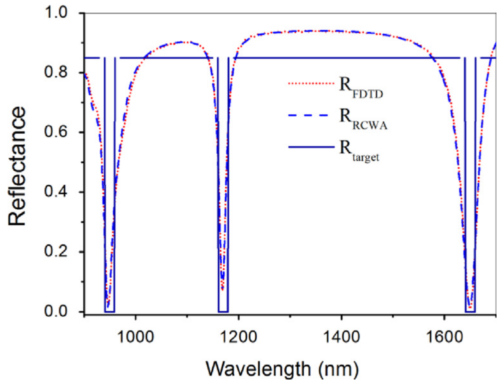

Fig. 2. The target reflectance and the calculated reflectance using the FDTD method and RCWA method of the optimal structure after optimization.

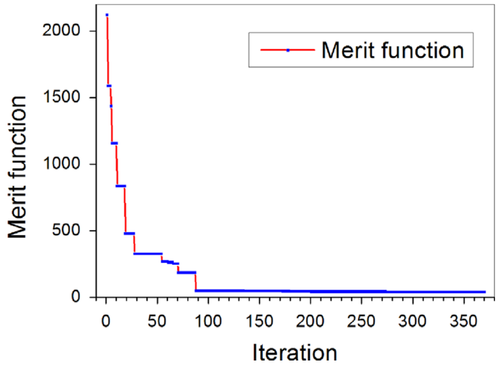

Fig. 3. The trend of the merit function during the optimization with the PSO method.

the electromagnetic field and through it a wide frequency range can be covered with a single simulation run. In our work, FDTD Solutions software from Lumerical, Inc. is used. The space interval is 5 nm along horizontal plane, 2 nm along the vertical direction and the time interval is 0.018 fs. A finer mesh of the space about 4 nm along horizontal plane is also calculated to ensure the validity of the computed results. There is no variation between the results with the space mesh mentioned above. Other steps to test convergence are examined as well [18]. Besides, the simulation results at these parameters agree well with those calculated by rigorous coupled-wave analysis (RCWA), shown in Fig. 2. In the RCWA model, the cutoff spatial harmonics order is set to 8 and the further increase of the cutoff orders does not affect the results. All of them confirm the validity of the computing results under these parameters.

To obtain the perfect absorption narrowbands at desired wavelengths, a particle swarm optimization (PSO) method is applied for the structure design owing to its advantage of fast convergence speed and less dependence on the initial parameters. PSO which is first developed by Eberhart et al. [19] roots in the social behavior of large number of birds or fish, with a simple but effective working schedule. The underlying rules of cooperation and competition within social swarms give it good capability for global optimization with the help of memory rather than a simple random search. In our case, flying particles search in a four-dimensional space built of four structural parameters mentioned above. The optimized variables are the side lengths of square grating a, the interval between the units d, the thickness of the top aluminum layer t_1 and the SiO_2 dielectric layer t_2 other than the period of the structure p, which can be received from a and d.

During the optimization procedure, merit function is of crucial importance for the convergence and the final results. Referring to the form of the merit function widely used in optical coating design processes, a similar merit function is adopted to design a desired multi-narrowband absorber. The merit function not only focuses on the high absorption at desired band, but also covers that non-absorptive region. In consideration of no transmission through the bottom aluminum film, the desired absorptance could be transformed into the desired reflectance. Upon the consideration above, the merit function in the optimization is defined as

$$\text{Merit} = \sum_{\lambda = 900\text{ nm}}^{\lambda = 1800\text{ nm}} W(\lambda)(R(\lambda) - R_{\text{target}}(\lambda))^2$$

where $R(\lambda)$ is the calculated reflectance at different wavelength and $R_{\text{target}}(\lambda)$ is the target reflectance of the multi-narrowband absorber specifying an ideal spectral response with perfect absorption. Taking an example of the multi-narrowband in this paper, the reflection characteristic with 20 nm bandwidth @950 nm @1170 nm @1650 nm respectively is required. And the target reflectance R_{target} is defined accordingly: $R_{\text{target}} > 80\%$@900–930 nm, $R_{\text{target}} = 0$@940–960 nm, $R_{\text{target}} > 80\%$@970–1150 nm, $R_{\text{target}} = 0$@1160–1180 nm, $R_{\text{target}} > 80\%$@1190–1630 nm, $R_{\text{target}} = 0$@1640–1660 nm and $R_{\text{target}} > 80\%$@1670–1700 nm, shown in Fig. 2. Thereinto, $R_{\text{target}} > 80\%$ at the non-absorptive region is adopted. If the reflectance R is larger than 80%, no contribution is made on the merit function at this wavelength, or the difference value is added to make effect on the optimization procedure. $W(\lambda)$ is the weighting functions. Generally, the properties in the absorption band are more important. So the weighting factors in this band are larger than those of non-absorptive region. As an example in this paper, W could be set: $W = 1$@900–930 nm, 970–1150 nm, 1190–1630 nm and 1670–1700 nm and $W = 300$@940–960 nm, 1160–1180 nm and 1640–1660 nm.

With the PSO method and the merit function given, the optimal multi-narrowband absorber is obtained by adjusting the weighting functions in the merit function, shown in Fig. 2. The