Optics Communications 399 (2017) 28–33

Contents lists available at ScienceDirect

Optics Communications

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

Multiple-band perfect absorbers based on the combination of Fabry-Perot resonance and the gap plasmon resonance

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ARTICLE INFO

Keywords:
Perfect absorbers
Gap plasmon
Surface plasmon
Fabry Perot resonance
Grating

ABSTRACT

To realize multiple-band perfect absorption, a novel nanostructure consisting of subwavelength periodic metallic grating and a thick metallic substrate, separated by a thin dielectric spacer(MGDM), is proposed in this paper. Compared with the structures without the dielectric spacer, the designed MGDM nanostructure not only possesses the absorption peaks caused by the Fabry-Perot resonance in the grating slits, but also possesses additional absorption peaks. Numerical simulation results show that the additional absorption peaks are caused by the gap plasmon resonance in the dielectric spacer. Besides, the influence of structural parameters on the absorption properties of MGDM are also thoroughly investigated. The combination of Fabry-Perot resonance and the gap plasmon resonance in the proposed MGDM provide another route for designing multiple-band perfect absorber nanostructures, which have an extensive applications in photo-detecting, photo-conversion or photo-harvesting.

1. Introduction

Recently, metallic nanostructures-based perfect absorbers [1,2] have attracted widely attention and developed significantly due to their unique plasmonic and optical properties of large localized field enhancement [3], subwavelength scale light concentration [4], and near-perfect absorption [5], which enables a variety of applications such as bio-sensing [6], photo-thermal therapy [7], photovoltaic devices [8], hot electron collection [9–11] and photo-catalysis [12] etc. Through delicately designing, those perfect absorbers can not only possess near-unity absorption but also other unique optical properties, such as polarization dependent or independent absorption [13], variable angular dependent light absorption (both wide and narrow) [14,15], broad or narrow frequency band absorption [16–18], spatial dependent absorption [19], and dynamic absorption [20,21], which can satisfy different special application aspects. Based on the involved mechanisms, those plasmonic nanostructure-based perfect absorbers can be classified into three categories: the first kind utilizes the so-called light trapping via Fabry-Perot Resonance or localized surface plasmon resonance(LSPR), to achieve the near-perfect absorption. The reflection of those nanostructures extremely decreases due to the huge localized field concentration. With the delicate choice of the parameters of the structures, the absorbers can attain broadband or narrowband perfect absorption. For instance, Tiziana C. Bond and the colleagues [22] fabricated variable metallic nanopillar arrays which are tunable from ultra-violet to near infrared with the maximum absorbance strength over 95%. Yu-Lung Lo and the colleagues proposed a binary metallic sub-wavelength grating with the near-unity and polarization-insensitive absorbance [23]. The second kind takes advantage of the effect of magnetic plasmon resonance in the metallic-insulator-metallic (MIM) three layers nanostructure, such as metamaterials or metasurface nanostructures, to achieve the perfect absorption. In those MIM nanostructures, when the wavelength of the incident light is reasonable, the magnetic and the electric resonance can be excited simultaneously, which can arise the perfect absorption. The absorption spectrum can be adjust by change the geometric parameters or materials of the metallic and insulator. Qiu and the colleagues used the Au patch/Al_2O_3 spacer layer/Au substrate to realize the perfect absorption in the infrared region [14]. Liu and the colleagues designed the Au nanodisc/MgF2 spacer layer/Au substrate to realize the perfect absorption in the infrared region and investigated its application as plasmonic sensors [24]. Smith's group [25] proposed a simple method to create a metamaterial absorber by randomly adsorbing chemically synthesized silver nanocubes onto a nanoscale thick polymer spacer layer on a gold film and demonstrated that the film-coupled nanocubes provide a reflectance spectrum that can be tailored by varying the geometry(the size of the cubes and/or the thickness of the spacer).

The third kind is combining the above mechanisms together and

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http://dx.doi.org/10.1016/j.optcom.2017.04.041
Received 11 March 2017; Received in revised form 16 April 2017; Accepted 17 April 2017

then make it more practical to achieve the further enhancement of absorption and the large tunability of spectral responses. Crozier experimentally and theoretically investigated the coupling between the localized and propagating surface plasmons polariton (SPP) in the MIM nanostructure, and demonstrated this coupling can enhance the absorption strength and field enhancement factor [26]. Balci and his colleagues experimentally investigated the strong coupling effects between the LSPR of silver triangle nanoprism and the propagation SPP of the silver thin film. Liao designed a narrowband infrared absorber based on the hybridization of gap plasmon and Fabry-Perot resonance [16]. Zheng's group utilized Au bowtie nanoantenna arrays with metal-insulator-metal configuration in their research, and numerically demonstrated that coordinated designs and implementation of various optical coupling effects lead to both the improved tunability of spectral responses and the significant enhanced electromagnetic field [27].

Although there have been many research publications on the designed metallic nanostructures which aim to achieve perfect absorption mentioned above, there are few results related to the combination of the Fabry-Perot cavity resonance in the metallic slit grating and the gap plasmon resonance under the metallic grating in the research of the multiple-band perfect absorption. Most previous proposed MIM nanostructures only utilized the SPPs or localized surface Plasmon resonance properties of the periodic metallic grating, few results related to the Fabry-Perot modes in the grating slit.

In this paper, we propose the metallic grating/dielectric layer/metallic substrate (MGDM) structure to realize the multiple band near-unity absorption in the visible and near-infrared region. The designed MGDM structure not only possesses the absorption peak modes in the comparable traditional grating, but also possesses new absorption peak modes. Those new absorption modes are considered to be related to the combination of the Fabry-Perot resonance in the slits of the grating and the gap plasmon in the dielectric layer between the metallic grating and the metallic substrate. Besides, we specifically investigate the influences of the structural parameters, including slit width, grating thickness, thickness and refractive index of dielectric layer, on the absorption peaks and absorption factors.

2. Modeling and simulations

Fig. 1(a) and (b) show the schematics of the proposed MGDM nanostructure and the traditional periodic subwavelength metallic grating, respectively, where t, w, P, and h are the thickness of the dielectric spacer, the slit width, the grating period, and the grating height, respectively. More specifically, the MGDM nanostructure has a dielectric spacer layer between the metallic grating and the metallic substrate. In the simulations, transverse-magnetic (TM) polarization plane wave is normally incident onto the structures. Silver is chosen as the material of the grating layer and the substrate, and the refractive index of the dielectric spacer is n_d. The optical permittivity data are referred to Handbook of Optical Constants of Solids [28]. The reflection R and transmission T of the structure are numerically calculated by finite-difference time-domain (FDTD) method [29]. The periodic boundary condition is set in x direction and perfect match layer is used in ±z direction. The structure is assumed to be infinite long in y direction. All the simulation results have been normalized to the incident light power, and in case of the transmission T is nearly to zero, the absorbance can be attained with A=1−R.

3. Results and discussion

Fig. 1(c) shows the absorption spectra of the structures in Fig. 1(a) and (b) with P=500 nm, w=100 nm, h=600 nm, t=20 nm, n_d=1.5. As shown in Fig. 1(c), the designed MGDM absorber has five absorption peaks (from left to right: 514 nm, 561 nm, 660 nm, 819 nm and 1090 nm), while the comparable traditional metallic grating just has three absorption peaks (from left to right: 514 nm, 669 nm and 1089 nm). In the later section we will focus on the effect of the structure parameters on the three distinct peaks (660 nm, 819 nm and 1090 nm) and divide those absorption peaks into three groups (mode I, II, III). It is obviously that the model I and III are look like almost the same for the MGDM structure and the comparable grating, but the absorbance of the MGDM at this two peaks is larger, which is also one of the advantage of the proposed MGDM absorber.

To find the physical mechanism of the additional absorption peaks (i.e, 561 nm and 819 nm in Fig. 1(c)) compared to the structure without the dielectric spacer, we calculate the magnetic field distributions of the five absorption peaks of the MGDM in Fig. 2(c). Two unit cells of MGDM in the following are considered. The magnetic field of 514 nm is shown in Fig. 2(a), firstly, the magnetic field is found to be confined at the metal/air interface, demonstrating the clear SPP characteristics. Secondly, the Fabry-Perot cavity mode(third order) in the slits of metallic grating and the gap plasmon resonance in the spacer layer is also excited, but the magnetic intensity is very weak

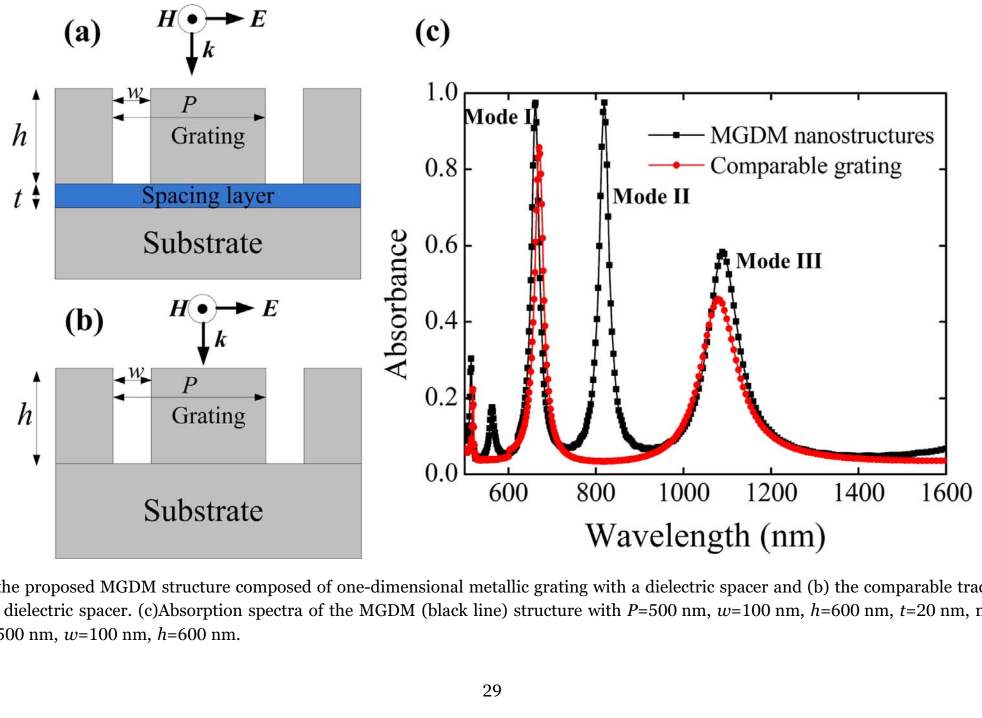

Fig. 1. Schematics of (a) the proposed MGDM structure composed of one-dimensional metallic grating with a dielectric spacer and (b) the comparable traditional metallic grating on metallic substrate without dielectric spacer. (c)Absorption spectra of the MGDM (black line) structure with P=500 nm, w=100 nm, h=600 nm, t=20 nm, n_d=1.5 and the comparable grating (red line) with P=500 nm, w=100 nm, h=600 nm.