Optical Materials 84 (2018) 195–198

Contents lists available at ScienceDirect

Optical Materials

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

Light absorption enhancement in tri-layered composite metasurface absorber for solar cell applications

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ARTICLE INFO

Keywords:
Metasurface
Broadband
Perfect absorber
Polarization-sensitive
Solar cells

ABSTRACT

Novel metasurface absorber based on crossed shaped resonator placed at the top surface is proposed to exhibit enhanced absorption resonances in the entire solar spectrum. Different cases of the absorber are discussed with special emphasis on large spectral width and peak amplitude. It is found that the absorption resonances and their corresponding spectral widths can be significantly modified and widened by adding extra nanorods to the crossed shaped structure at different locations. Furthermore, the weighted absorption under the AM1.5 solar spectrum ($A_{AM1.5}$) of the solar cell is also evaluated by varying the structural parameters, which reaches to ~ 86.35%. Such high value of $A_{AM1.5}$ indicates that the proposed design is highly suitable for solar cell application because it greatly enhance the conversion efficiency.

1. Introduction

Two dimensional metamaterials, sometimes termed as metasurfaces, have been greatly analyzed for different applications such as slow light [1], switching [2], and sensors [3,4]. Recently, such metasurfaces when used as top layer in the absorber structure have attracted considerable attention because of their extensive applications in thermal emitters [5], photo-detectors [6], and solar cells [7]. Metasurface absorbers mainly contain three layers: the top layer, which is composed of periodic arrays of metasurface, accountable for the electric response of the absorber, the middle dielectric spacer layer, which act as a cavity to trap or absorb the incident light, and the bottom metallic ground plane whose thickness should be chosen larger than the penetration depth of the incident electromagnetic wave to get rid of any transmission. To achieve near perfect absorption of the incident electromagnetic wave at specific frequencies, it is desirable to tailor metasurface shape, size, inter-particle distance, and the local dielectric medium, so that the effective permeability μ and permittivity ε can be tuned, which will cause an impedance match to free space.

The solar energy reaches the earth contain nearly 48% visible, 43% infrared, and 7.5% ultraviolet radiations [8]. Since, the contribution of visible and infrared radiations is more, so for solar cells application, it is appropriate to absorb such frequencies to get maximum current at the output. Any loss of light will reduce the conversion efficiency of the solar cell. The loss of light could be due to small transmission of radiations at the top layer containing array of metasurfaces and minimum reflections from the bottom metallic layer, which contain a metal foil. These losses highly limit the performance of solar cells. Therefore, several absorber structures were carefully designed by the researchers to absorb as much photons as possible. However, most of the existing absorbers cover only some portion of the visible or infrared region, which is not suitable for solar cell applications. K. Aydin et al., have designed plasmonic absorber using crossed trapezoid array geometry and capture electromagnetic energy from 400 nm to 700 nm with absorption level of about 71% [9]. Due to low absorption efficiency and narrow band such structure is not appropriate for solar cell applications. B. Zhang et al., have reported a metamaterial absorber composed of array of elliptical gold nanodisks at the top surface and trapped electromagnetic energy from 1200 nm to 1900 nm [10]. Since, their absorber structure do not cover visible regime, which contain most of the electromagnetic energy, so it cannot be utilized for solar cell application. X. Chen et al., have formed array of nanorods dispersed on a gold film separated by a thin dielectric layer [11]. They obtained broadband absorption form 900 nm–1600 nm with high absorption efficiency. Again, the structure does not support any absorption bands in the visible range, so it cannot be useful for solar cells. P. Rufangura et al., have designed an absorber for solar cell application, which support dual absorption bands with high efficiency from a wavelength range of 400 nm–660 nm [12]. However, due to capturing only a portion of visible radiations, such structure is also not appropriate for solar

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https://doi.org/10.1016/j.optmat.2018.07.009
Received 24 February 2018; Received in revised form 1 July 2018; Accepted 4 July 2018
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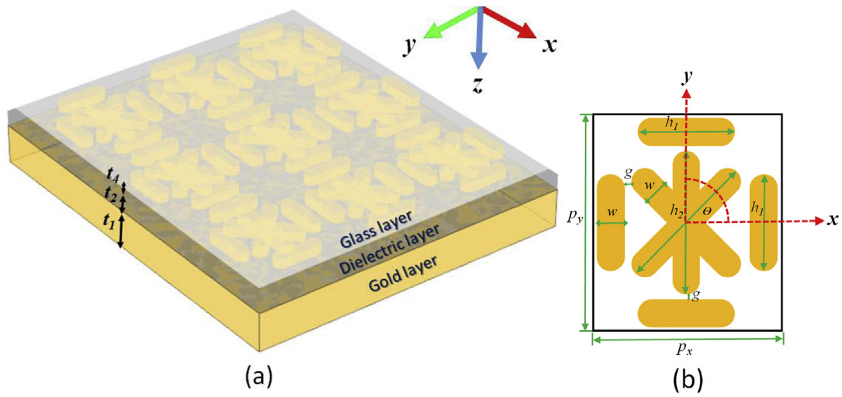

Fig. 1. (a) Schematic of tri-layer metasurface absorber. (b) Unit cell of the resonator.

cells. N. Areed et al., have reported a plasmonic absorber, which is comprised of regularly stacked and embedded cylindrical layers made of aluminum and silicon dioxide, offer high efficiency absorption in the visible spectrum [13]. However, their structure only supports absorption resonances in the visible range. Similarly, H. Ullah et al., have demonstrated plasmonic absorber based on layered split ring arrays, which also exhibit high absorption bands in the visible range [14].

In this paper, we suggest a crossed shaped metasurface absorber for solar cell applications. The proposed design offer high absorption peaks in a broad frequency range. Adding extra gold bars at different positions with the crossed shaped structure, provides several outstanding absorption bands in the visible and infrared frequency regime. Such results are highly suitable for solar cell applications.

2. Metamaterial absorber model

An array of tri-layer metasurface absorber is shown in Fig. 1(a), where the bottom layer is made of gold, the middle layer is a dielectric layer with permittivity of 2.5, and the top layer is made of an array of cross shaped metasurface along with gold nanobars at different locations. A Pyrex glass layer at the top of the metasurface is also placed to transmit maximum light into the absorber structure and resist heat expansion [12]. Fig. 1(b) shows the unit cell of the proposed resonator, where periodic boundary conditions are used to make a 2D array (along x- and y-directions). The period of the unit cell along x-direction is $p_x = 550$ nm and along y-direction is $p_y = 610$ nm, respectively. The geometric parameters of the absorber are: thickness of bottom gold layer $t_1 = 200$ nm, thickness of dielectric layer $t_2 = 80$ nm, thickness of resonator $t_3 = 50$ nm, and thickness of glass layer $t_4 = 20$ nm. The parameters of the resonator are: the length of the nanobars at different positions is $h_1 = 250$ nm, the length of the bars of the cross shaped structure is $h_2 = 370$ nm, the cross shaped is obtained by setting $\theta = 45^\circ$, the width of each nanobar is $w = 70$ nm, and the gap between the cross shaped structure and the nanobars is $g = 20$ nm. The dielectric constant of the gold is taken from Johnson & Christy data model [15]. Electromagnetic plane wave with frequency range of 100–1000 THz is incident upon the metasurface absorber in the z-direction. The simulations are performed in COMSOL Multiphysics software and the environment is selected as air.

3. Results and discussion

In order to better understand the absorption enhancement in metasurface absorber, the top metallic resonator is considered first for analysis. The absorption properties of five different cases are studied as shown in Fig. 2. For every case, one extra nanorod is added to cross shaped resonator at different position. There are two main advantages of the proposed resonator: 1) exhibit multiple resonances, 2) provide resonances in ultraviolet, visible, and infrared regime. Both these properties are highly suitable for solar cell application. Fig. 2(a) shows the absorption spectra of Type – I resonator. Since, the proposed structure is polarization dependent, therefore, analysis are performed for both the x- and y-polarized light. Multiple sharp absorption modes for both the polarizations are obtained. These multiple resonances appear because every nanorod are placed in close proximity with each other, therefore, the modes supported by each rod will couple efficiently. Also, two rods are placed at $\theta = 45^\circ$, due to which the rotational symmetry of the structure is also broken and more modes are excited in the spectrum [16]. So, all these modes significantly couples and induces multiple complex resonances in the absorption spectrum. In Type – I resonator, the maximum absorption level achieved is approximately 43%, which may be enhanced by constructing a complete absorber.

Fig. 2(b) shows the absorption spectra of Type – II resonator, where a single nanorod is placed vertically with the crossed shaped structure. In this case also, multiple absorbance resonances are obtained for both kinds of polarizations. Here, the modes supported by vertical nanorod essentially couple with the cross shaped structure's modes due to which constructive and destructive interference takes place and new modes engender in the spectrum. The highest absorption is achieved in the infrared range for y-polarized incident light, which is around 47%. Similarly, by adding more extra layers at different locations, different resonances of the composite structure couples and induce distinct absorption modes as shown in Fig. 2(c–e). The additional nanorods will also slightly enhance the absorption of light in the visible range. In this case, Type – IV & V resonators support absorption level of about 55%.

To enhance the light absorption, a perfect absorber has been constructed as shown in Fig. 1. Here, the modes supported by the top surface interfere destructively with the modes of the bottom surface due to which large amount of light can be trapped in the middle dielectric layer [14,17,18]. Fig. 3 shows the absorption properties of all the types which are discussed in Fig. 2. For Type – I metasurface absorber (Fig. 3(a)), multiple absorption bands with high levels are achieved in the whole spectrum. By comparing with standalone resonator (Fig. 2(a)), here absorption level reaches approximately to unity in the visible region. Furthermore, for y-polarized incident wave, four absorption bands are obtained above 70% absorption in the visible range. In the infrared region, the metasurface absorber does not provide any significant resonance modes. The region of interest is the broadband mode (680 THz) with spectral width of approximately 202 THz above 70% absorption level because here most of the light is concentrated. The large spectral width and high absorption level is suitable for solar cell application.

Fig. 3(b) shows the absorption spectra of Type – II metasurface absorber, where four absorption bands are achieved above 70% absorption in the visible and infrared region for y-polarized light. The absorption levels of two resonance modes around 229 and 449 THz reaches approximately to unity. In this case, dual broadband modes are

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