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Dual-band perfect metamaterial absorber for solar cell applications

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ABSTRACT

The efficiency of solar photovoltaic (PV) cells has been one of the major problems impeding its global adoption as one of the sustainable substitutes to fossil fuel based technologies. Metamaterial (MTM) based solar cells offer an opportunity towards increasing the system efficiency by enhancing the total absorbed solar radiation incident on this device. In this study, a nanostructure-based MTM perfect absorber has been designed and simulated. By adjusting geometrical parameters and MTM structure properties, nearly perfect dual-band absorptions have been obtained with 99.99% and 99.90% absorption at 543.75 THz and 663.75 THz, respectively. The proposed structure is simple and more flexible for scaling, which helps achievement of multiple-band absorption. Implementation of the intended MTM structure can effectively lead to the realization of more efficient PV solar cells.

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1. Introduction

Energy is a key issue for industrial and economic development of every country. Solar radiation is one of the best renewable energy resources proved to have potential for clean energy generation [1]. Solar PV cells, which are devices to convert solar radiation directly into electrical energy, are known as one of the best technological devices to harvest the solar radiation. Even though, PV cells contribute a tiny portion to the World's electricity; a sharp increase in its utilization over the last decades have shown its promising future development. Through technology improvement and governmental policies, the total installed PV system capacity increased by a factor of 27 at a rate of 40% since 2000, where installed capacity reached 39.5 GW in 2012 [2]. However, the lower efficiency of these devices hinders its utilization due to the fact that solar PV cells do not able to convert all received electromagnetic (EM) radiation into electricity. The high cost of electricity per square meter per kilowatt hour (cent/kWh m^2) has also been a challenge [3].

Currently, several research and development groups are working on this area to make PV cells more adaptive and to fine-tune the cost of material in order to make these devices available at inexpensive price. As known, the majority of PV cells are silicon based. Although, silicon is abundantly available in nature, it is extracted from silica (silicon dioxide SiO_2) which makes it expensive to get it in its pure form. The current technology of a thin film based PV cell tends to reduce the amount of silicon requirement per unit cell and hence there is a reduction in the cost of manufacturing these devices [4,5]. Nevertheless, although thin film solar cell technology reduces the amount of material requirement per unit cell (subsequently the total cost), this process has a disadvantage of reducing absorption properties of the structure. Therefore, light trapping structures are needed in order to increase the absorption of solar radiation in PV cells. The details for light trapping technique with the working principle and physics of PV cells are given in Refs. [6–9].

Currently, there has been a great deal of interest in creating thin film electromagnetic absorbers from a non-natural sub-wavelength material called "Metamaterial (MTM)". These man-made materials present unusual electromagnetic properties which can not be found in nature and are different from conventional materials. Such properties include, but are not limited to; negative electric permittivity, negative magnetic permeability and negative refraction index [10,11]. These special properties enable MTMs to be used in numerous applications like cloaking [11], super lens [12,13], chiral materials [15], and perfect absorbers (PAs) [16]. Among those applications, PAs attract many researchers' interest due to the fact that the materials can be manipulated to absorb most of the EM wave radiation.

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Landy et al. [14] designed a perfect MTM absorber with the manipulated parametric properties of the proposed MTM structure to obtain a near perfect absorption at resonant frequency. Presently, there are several studies on MTM absorbers for different ranges of EM spectrum. Dincer et al. [16], numerically and experimentally propose a polarization and incidence angle insensitive dual-band MTM absorber (which consists of an isotropic resonator) with two maximum absorption regions in the GHz frequency region. Additionally, Dincer et al. [17] also numerically and experimentally designed polarization angle independent perfect MTM absorbers for solar cell applications in the microwave, infrared, and visible frequencies. Viet et al. [18], proposed a MTM structure to provide a single perfect absorption peak and this structure was able to generate multiple peak absorptions when it is modified. Furthermore, Li et al. [19] designed a wide angle polarization insensitive ultra-thin MTM absorber with three resonant modes. Moreover, many researchers have been also focused on high frequency MTM based PAs for solar cell applications. For example, Wang et al. [20] presented a tunable broad-band PA by exciting multiple Plasmon resonances at optical frequency. Wu et al. [21] proposed a MTM-based integrated plasmonic absorber/emitter for solar thermo-photovoltaic systems. Akimov et al. [22] studied enhancement of optical absorption in thin-film solar cells through the excitation of higher-order nanoparticle Plasmon modes. Hashmi et al. [3] developed a theoretical model for MTM based solar cells, while, Liu et al. [23], also made a study of energy absorption on solar cells by using a MTM absorber. According to many researches and studies, development of MTM technology has brought huge solutions in the field of electrodynamics and more particularly, in the field of solar PV cells by improving their absorption properties [3, 23 25]. In general, MTM based solar PV cells are one of the promising technology to enhance the efficiency of these devices. Yet, the challenge is that most of the available MTM absorber designs have narrow and single-band frequency response.

In this paper, a new dual-band perfect MTM absorber for solar cell applications is proposed. The suggested design, offers two high peak absorption regions in the visible frequency regime. Parametric alteration in some dimensions of the proposed design, provides outstanding multiple bands of near perfect absorption in the Infrared (IR) and Ultraviolet (UV) frequency regions. Geometrical parameters and materials properties of the proposed design are manipulated in order to obtain dual-band nearly perfect absorption at the resonant frequencies.

2. Brief theory

When EM radiation strike solar cells, three different phenomena take place. Some of the radiation is reflected, some is absorbed while the rest is transmitted. The output power of a solar cell structure is strongly affected by these three phenomena. The scattering parameters can be defined as (Equation (1) and Equation (2)) [23]:

$$S_{11} = \frac{\int port1\left((E_c - E_1)\cdot E_1^*\right)dA1}{\int Port1\left(E_1 \cdot E_1^*\right)dA1} \tag{1}$$

$$S_{12} = \frac{\int \mathrm{port1}\left((\mathrm{E_c} - \mathrm{E_1})\cdot \mathrm{E_1^*}\right)\mathrm{dA1}}{\int \mathrm{Port2}\left(\mathrm{E_2}\cdot \mathrm{E_2^*}\right)\mathrm{dA2}} \tag{2}$$

where, E_c is the computed electric field on the port consists of the excitation plus the reflected field, E_1 and E_2 are the electric fields on ports 1 and port 2, respectively. The higher is the ability of a cell to absorb the radiations, the more power it gains. However, the reflection and transmission reduce the power gain as can be observed in the following equations (Equations (3)–(5)).

$$A(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{12}(\omega)|^2 \tag{3}$$

$$S_{11}(\omega) = \frac{\sqrt{\text{power reflected from port1}}}{\sqrt{\text{powerincident on port1}}} \tag{4}$$

$$S_{12}(\omega) = \frac{\sqrt{\text{power delivered to port2}}}{\sqrt{\text{powerincident on port1}}} \tag{5}$$

where $A(\omega)$ is the absorption, $S_{11}(\omega)$ and $S_{12}(\omega)$ are the scattering parameters which are directly related with the reflected and transmitted radiations. Therefore, in order to optimize the absorption; the reflected and transmitted radiations need to be minimized as much as possible. Fortunately, in the proposed design, there is no transmission due to the fact that the back metal substrate prevents transmission losses. As a result, Equation (5) is simplified to the following equation and Equation (6) will be used in the present study for the calculation of the absorption.

$$A(\omega) = 1 - |S_{11}(\omega)|^2 \tag{6}$$

3. Design and simulation

The proposed design consists of a solid structure as shown in Fig. 1. The bottom layer of the structure is selected to be gold plate for zero transmission. The dielectric material as substrate is selected to be lossy gallium arsenide (GaAs). On top of the substrate, there is a cylindrical metal (gold) layer filled with a dielectric material (GaAs) to be used as a resonator. Finally, a glass layer (Pyrex) is placed on the top of the cylindrical gold metal layer. The glass layer on the top is chosen due to its ability to transmit higher visible light and to resist heat expansion. The gold metal is chosen because of its appropriate absorption and reflection capability for EM waves and its ability to resist excessive heat [24]. The electric conductivity and thermal conductivity of gold are 4.56×107 S m^{-1}, and 314 W K^{-1} m^{-1}, respectively, while electric permittivity and loss tangent of dielectric spacer (GaAs) are $\varepsilon = 12.94$ and 0.006, respectively. Glass on the top layer has loss tangent and thermal conductivity of 0.0054 and 1.1 W K^{-1} m^{-1}, respectively.

The structure's geometrical parameters are: $x = 520$ nm, $z = 70$ nm, $t = 80$ nm, $n = 8.33$ nm (the thickness of Au layer on the top of GaAs spacer) and $l = 70$ nm. The geometric parametric of the resonator are: inner radius $a = 173.3$ nm, outer radius $b = 157.4$ nm and the height $k = 39$ nm.

The simulation was performed with a full wave EM simulator based on the finite integration technique. The structure is designed to work in visible frequencies ranging from 450 to 700 THz. EM radiation is polarized in a manner that the electric (E) and magnetic (H) fields are parallel with the design plane while the wave vector (k) is perpendicular to the structure's geometric plane. The boundary conditions are selected to be periodic while the simulation environment is designated to be vacuum.

4. Results and discussion

The structure provides two absorption peaks and the simulation results for visible frequency range (450 THz − 700 THz) is represented in Fig. 2. As can be observed, dual-band character with perfect (near unity) absorption is obtained at 543.75 THz and

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