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A perfect absorber design using a natural hyperbolic material for harvesting solar energy

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ABSTRACT

A perfect absorber design is proposed here that uses a periodic array of pyramidal nanostructures, made from a natural hyperbolic material bismuth telluride (Bi_2Te_3) on a substrate. A numerical study is carried out to investigate the absorption of solar radiation and to determine the suitable ranges of the geometric parameters for the proposed structure submerged in water. The results show that the proposed structure can achieve absorptance values greater than 99.9% in the wavelength range of 300–2400 nm, which covers most of the solar radiation spectrum. The underlying mechanisms are attributed to the combination of the slow-light effect and the gradient index effect. Optical properties of this type of absorber are affected by the geometry of the nanostructure (such as the height and the top and bottom widths of the pyramid), the distance between two adjacent pyramids, as well as the material and thickness of the substrate. Nevertheless, extremely high absorptance can be achieved even with some variations of these parameters. This study could open a route for effectively harvesting solar energy in photothermal conversion processes in water.

1. Introduction

Solar energy harvesting has attracted a great deal of interest in the past few decades in order to provide abundant clean and renewable energy (Meier et al., 2005). Solar energy can be used as energy sources for (i) photovoltaic process such as a solar cell to generate electricity (Todorov et al., 2010), (ii) photochemistry process such as photocatalysis (Asahi et al., 2001), and (iii) photothermal process such as vapor generation (Fang et al., 2013; Neumann et al., 2002, 2013; Polman, 2013), desalination (Narayan et al., 2010; Qiblawey and Banat, 2008; Shannon et al., 2008; Tiwari et al., 2003), sterilization (Bansal et al., 1988; Saitoh and El-Ghetany, 1999), and many other industrial processes (Mekhilef et al., 2011). One of the most significant challenges in these applications is the low energy harvesting efficiency of the incident solar energy, especially for photothermal conversion (Neumann et al., 2012, 2013; Polman, 2013).

During the past several decades, absorbers with high photothermal efficiency have been extensively studied for applications in various fields (Alaee et al., 2012; Hedayati et al., 2011; Tian et al., 2007). Most of these absorbers, however, show a strong absorption with nearly 100% absorptance only in a narrow band (Chen et al., 2012; Diem et al., 2009; Fang et al., 2012; Hao et al., 2011; Hendrickson et al., 2012; Wang et al., 2015). Recently, some broadband perfect absorbers have also been proposed by packing several resonators together (Chen et al., 2012; Diem et al., 2009; Hendrickson et al., 2012), employing phase change materials (Kats et al., 2012), or using nanowires for which the reflection suppression of arrays of nanowires can greatly enhance optical absorption (Liu et al., 2013; Roszkiewicz and Nasalski, 2012; Zhu et al., 2008). Based on the anti-reflection effect, nanocones can also broaden the absorption spectrum compared to nanowires (Han and Chen, 2010; Hsu et al., 2012; Raut et al., 2011; Wang et al., 2012; Zhu et al., 2008), because the gradual increase in the cross-sectional area enables a gradient index from the incident medium to the material. Most recently, two approaches for photothermal conversion with high efficiency have been proposed by Ni et al. (2016) and Zhou et al. (2016). Ni et al. (2016) found that steam could be generated from such a process under only one sun, although the solar absorptance was about 93%, which is much lower than that with vertically aligned carbon nanotube arrays that can achieve an absorptance greater than 99% (Wang et al., 2009). Subsequently, Zhou et al. (2016) fabricated self-assembled gold nanoparticles on a 3D porous alumina template to achieve efficient broadband absorber, taking advantages of the hybridization of localized surface plasmons and non-radiative plasmon decay. Due to the high absorptance (about 99%) of solar energy in the plasmonic structure and localized heating, their structures have high conversion efficiency and evaporation rate at increased illumination

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intensity.

Another way to realize a broadband perfect absorber is to use hyperbolic materials (Cui et al., 2012; Ferrari et al., 2015; Hu et al., 2013; Krishnamoorthy et al., 2012; Wu, 2016; Zhao and Zhang, 2017). These materials, with completely different dielectric functions (metallic and dielectric media) in two orthogonal directions, have anisotropic optical properties. When a tapered nanostructure is made from this kind of material, the group velocity of the waveguide mode decreases as the width (i.e., the cross section) of the structure increases. Consequently, the group velocity can become zero at certain location and negative at larger cross sections (i.e., deeper into the structure). The electromagnetic waves are localized in the region where the group velocity is zero and hence can be fully absorbed. This phenomenon is called the slow-light effect (Ferrari et al., 2015; Hu et al., 2013; Krishnamoorthy et al., 2012; Zhou et al., 2014; Zhao and Zhang, 2017), which allows the trapping of broadband light due to the gradual variation of the structure width. The shortwave light is trapped at small widths (near the incident medium), while the longwave light is absorbed at large widths (deep into the structure), resulting in a nearly completely absorption of the incident energy in a broader spectral range. Unlike the surface plasmon resonance which occurs close to the surface of the metallic nanostructures or nanoparticles, the resonance for the hyperbolic materials takes place inside the nanostructures. Some artificially constructed multilayer metamaterials show hyperbolic response with broadband light absorption when the nanostructure is made of specially designed shapes (e.g., trapezoid structure). Zhao and Zhang (2017) theoretically demonstrated perfect absorption in the mid-infrared with some natural hyperbolic materials. While most of the fabricated or naturally occurring hyperbolic materials are for the mid-infrared or terahertz frequency region, researchers have recently shown that certain materials can exhibit natural hyperbolic behavior in the visible and near-infrared range (Esslinger et al., 2014; Narimanov and Kildishev, 2015). However, their application to solar absorption enhancement has not yet been explored.

In the present study, a perfect light absorption structure is proposed that uses an array of pyramidal nanostructures made of Bi_2Te_3 (a natural hyperbolic material) over a thin substrate to absorb incident solar radiation, as shown in Fig. 1. The absorptance of this structure is numerically calculated by adjusting the geometric parameters of the nanostructure, as well as the substrate material and thickness, to achieve extremely high absorptance in the solar radiation spectral region. Moreover, the mechanisms involved in the broadband absorption of the proposed design are elucidated by using the power dissipation density distribution. This absorber, when submerged in water, may be used as a heat source for vapor generation under sunlight.

2. Optical properties of Bi_2Te_3 and mechanisms for perfect absorption

The proposed absorber structure consists of a 2D periodic array (with a period Λ) of pyramidal nanostructures made of Bi_2Te_3 on the top of a substrate as shown in Fig. 1. The geometry of the pyramid is defined by a width w_1 at the top, a width w_2 at the bottom, and a height H. The thickness of the substrate is h. The nanostructure is made of Bi_2Te_3, which exhibits optical anisotropy and is a natural hyperbolic material from ultraviolet to the near-infrared up to the wavelength $\lambda \approx 1000$ nm (throughout this paper, λ is the wavelength in vacuum). The light is incident in the positive z direction that is parallel to the axis of the pyramids. The optical properties of the material and the nanostructure are discussed next focusing on explaining the two key mechanisms that give rise to the perfect absorption, namely, the slow-light effect of the hyperbolic material and the gradient index effect of tapered nanostructures.

2.1. Slow-light effect

The dielectric function of a uniaxial medium whose optic axis is parallel to the z-direction can be expressed as (Bohren and Huffman, 1983):

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_x & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix} \quad (1)$$

The dielectric function is the same in the x and y directions (ε_x), but different in the z direction (ε_z). Note that ε_z is for the electric field parallel to the optic axis, as illustrated in the inset of Fig. 2(a). For a given direction, the dielectric function is a complex function, i.e., $\varepsilon = \varepsilon' + i\varepsilon'' = (n + ik)^2$, where n and k are the refractive index and extinction coefficient, respectively (subscripts x or z is omitted here for simplicity). The real and imaginary part of the dielectric functions for

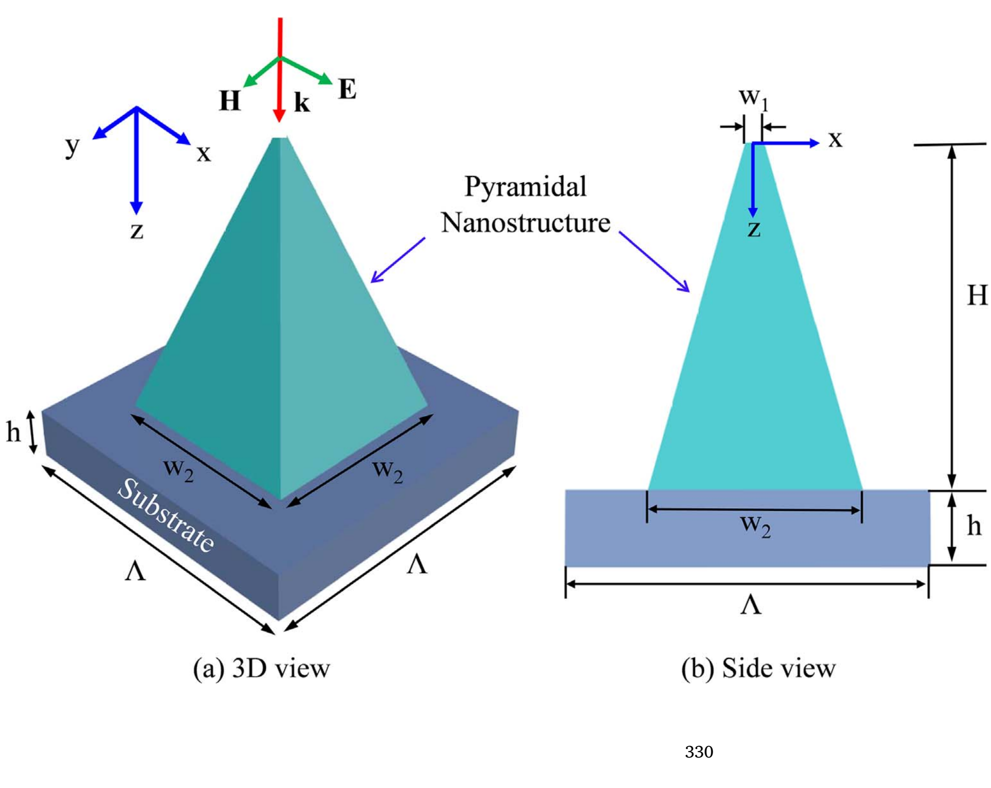

Fig. 1. Schematic of a unit cell of the periodic structure with Bi_2Te_3 pyramids on a thin film (substrate): (a) 3D view and (b) side view. The direction of the incident light is indicated by the wave vector **k**, which is parallel to the vertical axis of the pyramid or the z direction. Other geometric parameters and the electric and magnetic fields are also indicated. The structure is submerged in water (incident medium).