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Study of A Perfect Absorber Design Using Metamaterials for Harvesting Solar Energy

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Abstract:

Solar energy has attracted a lot of attention during recent years due to its availability, effectiveness for application and the usage being harmless for the environment. The following paper gives a brief review on two solar harvesting processes i.e. Photothermal and Photovoltaic. For these conversions, use of metamaterials are discussed with various parameters like the material that can be used for a particular process, its effectiveness, absorption efficiencies within a particular bandwidth, the methodology used for its application etc. It basically aims in designing a particular absorber using these metamaterials as the use of these materials aims in perfect absorption of the sunlight incident on it. Thus by using metamaterials in the solar harnessing units may ultimately aim to absorb maximum incident light on it.

Keywords: Slow-light, gradient-index, resonance, dielectric, concentrator.

Introduction:

Metamaterials are the materials that are made from assemblies of multiple elements fashioned from composites arranged in a specific pattern which ultimately helps to achieve benefits beyond conventional materials. A numerical study is carried out to investigate various metamaterials and their absorption efficiencies, advantages and disadvantages when applied to a solar cell. Optical properties of this type of absorber are affected by the geometry of the nanostructure, the material and thickness of the substrate. Thus, very high absorptance can be achieved by making some variations of these parameters. This study could open a route for effectively harvesting solar energy in photothermal and photovoltaic conversion processes of solar energy.

Solar Harnessing processes may involve photovoltaic conversion such as used in a solar cell for generation of electricity, photothermal conversion such as generation of vapour using heat from solar radiation and other processes like photochemistry which includes sterilization and photocatalysis etc. Many concentrators and absorbers are being designed for such harnessing processes which show perfect absorption in a particular bandwidth. Thus the review paper basically focuses on understanding various parameters of these absorbers such as metamaterials used, methodology followed, working conditions and dependency parameters, drawbacks and the desired outcomes. The paper involves a comparative study of these absorbers which will help in building the device with optimum output. In case of photothermal conversion, the metamaterial used is Bi_2Te_3 on the top of the substrate (1) and exhibits optical anisotropy and works as a natural hyperbolic material within ultraviolet to near infrared wavelength. Conversion happens with the help of two mechanisms i.e. slow light effect and gradient refractive index effect.

Another case of photothermal conversion (2) and (3), the metamaterials used are i. an array of silver particles separated by dielectric medium i.e. quartz kept on the top of a silver film and ii. Patterned graphene micro-ribbons. It involves designing an absorber working similar to a black body in which maximum absorption is achieved. The process involves restricting the transmission and reflection of incident rays, resulting in maximum absorption due to excitation of localized electromagnetic resonances. For photovoltaic conversion, (4) and (5), the metamaterials used are two plates separated by a dielectric medium, such that the thickness of the plates and dielectric combined are less than the wavelength of the incident light. Applying the electric and magnetic fields as boundary conditions, the models are numerically simulated using full wave Electromagnetic solver. For designing of photovoltaic concentrators and absorbers (6), arbitrary geometries are simulated using full wave EM solver and the results are analysed for absorption efficiencies.

Material and Methodology:

For photothermal conversions as in (1), the metamaterial used is Bismuth Telluride (Bi_2Te_3). These nanostructures are fabricated in periodic array of pyramidal shapes placed on a substrate. The mechanism of maximum absorption involves combined effect of slow light effect and gradient refractive index effect. Absorption efficiency is then calculated numerically by changing various parameters of the absorber as well as the thickness of the substrate. The absorber when placed under water will thereby help in effective vapour generation.

The material used in (2) consists of three layers of metamaterial absorber. Top layer consists of small or medium sized arrays of silver particles, while the bottom layer is made of silver film. These two layers are separated by a dielectric layer whose thickness is varied to resemble Fabry-Perot model and is assembled on a quartz substrate. The physical mechanism works by excitation of localized electromagnetic resonances. If we can minimize the reflection and transmission of incident rays, and if the impedances in free space match the structural impedance, optical resonance will be achieved. This resonance will further help in complete absorption by trapping the light and provide sufficient time to harness the energy by ohmic or dielectric losses, i.e. conversion to heat. Numerical computation is done further to understand the relation of absorption with the dimensions.

According to Rasoul Alaee et al (3), the material used consists of patterned grapheme micro-ribbons which are placed on a thick dielectric layer mounted on reflecting metal substrate. To simplify the calculations part and to give physical explanation, one must consider as symmetric Fabry-Perot cavity model resembling two mirrors; a graphene micro-ribbon array as the top mirror and the metallic grounded plate acts as the bottom mirror. Thus for perfect absorption Reflection (cancelled due to destructive interference occurring at desired frequencies) and Transmission (cancelled using sufficiently thick ground plate) channels are completely suppressed. The Fourier Modal Method (FMM) is used to solve Maxwell's equations for the periodic structure.

For photovoltaic conversion as in (4), a square-shaped resonator with gaps on the top and the metal plate (silver for microwave and copper for infrared and visible regime) on the bottom layer are separated by the dielectric substrate (Quartz fused for infrared-250nm and visible-200nm, and 1.6mm FR4 for microwave regime) are used. Initially the structure is simulated with full wave EM solver which uses finite integration technique. Boundary conditions used in the

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simulations are periodic and open add space. The microwave measurement is carried out by using a vector network analyser (VNA).In order to verify the physical mechanism of the operation principle of the solar cell based on MTM at resonances, investigations at resonant frequencies are made of the the electric field and surface current distributions. Hence overall absorption behaviour can be studied.

According to (5), the structure consists of an aluminium plate placed at the bottom (to prevent transmission), on which GaAs plate is placed which acts as a dielectric material. To prevent reflection two aluminium strips are embedded in the dielectric plate. The thickness of Al and GaAs plate is less than the wavelength of the incident light. The two strips inserted causes generation of localized surface plasmon polaritons, causing collective oscillations of electrons within the metal and dielectric layer which helps in perfect absorption. Simulation was carried out using a full wave EM solver for finding the optical and electrical properties of the absorber. The X and Y axis are electric and magnetic layers and absorber is considered as an infinite slab within these boundaries. Further parametric study is carried out for comparing output with change in dimensions.

In case of (6), two-dimensional (2D) metamaterial-assisted electromagnetic concentrators with arbitrary geometries are derived based on transformation-optical approach. It actually works on the phenomenon of field concentration of light for harnessing solar energy. Initially the structures with arbitrary geometries are designed for 2D concentrators and are validated using numerical simulation. It provides great flexibility as arbitrary geometries can be easily obtained using contour equations. This physical model is then confirmed by full-wave simulation based on finite element software COMSOL Multiphysics.

Results and Discussion:

In his paper (1), Zhaolong Wang et al. reported that the maximum efficiency can be achieved within the visible spectral wavelengths using Bi_2Te_3 mounted on a substrate(may be Au, Ag, Al_2O_3, etc. used to reflect back the unabsorbed light back to the pyramidal structure). In case of short wavelengths slow light effect (major cause) combined with reflection suppression effect with gradient index refractive effect (minor cause) causes perfect absorption. For long wavelength region, the gradient refractive index effect (major cause), and reflection/absorption by substrate, ensures perfect absorption. Thus optimum dimensions of the pyramid like top and bottom width and height is decided (< 20nm, 200-500nm, 3000-5000nm resp.).

As in case of (2), Maximum efficiency of absorption is achieved by creating optical resonance and eliminating the transmission and reflection of light thus causing excitation of fundamental resonant mode and is independent of angle of incidence. By changing the thickness of dielectric layer, perfect absorption is achieved but it is sensitive to the angle of incidence. Thus by numerical computation it is found that the absorption can be controlled by adjusting the geometrical dimensions of the absorber structure.

The results obtained through (3) mentions that complete absorption is obtained in far-infrared regimes of light using graphene micro ribbons. This is done by supressing the transmission and reflection phenomena upon incidence of light, thus facilitating maximum absorption by the structure. The structure also shows absorption which is independent of incidence angle, thus demonstrating versatility of graphene.

For (4), experimentally achieved results (calculated for microwave regimes) are very close to those achieved numerically; also the design is simple and thus can be practically used. The simulated and observed values of absorptance are close to unity, which means it has perfect absorber design for wide range of frequencies. Also it is concluded that the results of absorption are independent of polarization angle considering daytime application.

B. Mulla and C. Sabah reported in their study that the result obtained displays maximum efficiency of absorption (99.9%) is achieved at approx. 403.5 THz frequency by changing geometrical dimensions of absorber (5). The results obtained from EM solver also displays that the absorber is insensitive towards the polarization angle which in turn is a benefit. Also the simulations were done on the basis of incidence angle and it was found that it varies marginally from 99.9% thus making it insensitive towards incidence angle too. Thus the absorber offers perfect absorption at a particular bandwidth.

According to Jingjing Yang, 2D concentrators with arbitrary geometries are developed and tested (6). All the theoretical and numerical results validate effectiveness of concentrator for harnessing solar energy. Also the metamaterial loss is very less compared to the power flow distribution of concentrator which gives very high efficiency of the concentrator. Thus the concentrator can help in concentrating solar energy at very high intensities with very high effectiveness.

Conclusion:

The above review suggests various metamaterials that can be used for harvesting solar energy, their geometries and the specific bandwidth in which maximum efficiency is achieved. The absorption efficiencies are numerically simulated and the results are compared for finding the optimum absorber properties. The above results display that the pyramidal geometry Bismuth Telluride can be used for photothermal conversion with absorption efficiency of 99.9%, while some other metamaterials like grapheme micro-ribbons or silver layers separated by dielectric layer can give extremely high efficiency at a particular bandwidth by restricting reflection and transmission of incident rays. Thus the paper helps in overall design of the solar harnessing units and various parameters related to these units. Hence metamaterials will play a vital role in building solar harnessing units which will have maximum absorption rate.

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