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Importance Of the Use of Natural Hyperbolic Material to Harvest Solar Energy

Manav Sinha [a], Pallavi Thakur [b]

[a] *Department of Petroleum Engineering, Krishna Institute of Technology, Visakhapatnam, India.*
[b] *Department of Petroleum Engineering, Krishna Institute of Technology, Visakhapatnam, India.*

Abstract

In this paper, we present a novel solar energy harvesting absorber using pyramidal nanostructures made of a naturally occurring hyperbolic substance. We begin by numerically studying regularly ordered anisotropic and naturally hyperbolic bismuth telluride (Bi2Te3) on a silver substrate, while the metamaterial is immersed in water. According to our research, this absorber exhibits a remarkable absorptance of more than 99.9% spanning the 300–2400 nm wavelength range. By analyzing the absorber's power dissipation density and electric field distribution, we explore the underlying mechanisms. It turns out that the gradient index effect in the longer wavelength range (1000–2400 nm) and the slow light effect in the type-II hyperbolic area (300–1000 nm) are essential for attaining complete solar energy absorption. These samples have an absorptance of up to 97.5%, with the lowest absorptance still surpassing 94% in the 380–1800 nm wavelength range. In order to verify the mechanics underlying the flawless absorption of solar energy, we also create and examine more samples. The findings of this work open the door to more efficient solar energy harvesting through the use of metamaterials with water-submerged nanostructures composed of naturally occurring hyperbolic materials.

Keywords: Hyperbolic Material, Harvest, Solar Energy.

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Introduction

The world is facing a predicted increase in energy demand of about 1GW per day, which is putting significant strain on our current energy systems. This looming challenge, coupled with the decline of traditional fossil fuel technologies and the urgent concerns about environmental changes—like the alarming rise in temperatures due to global warming and ozone depletion—highlights the need for advancements in sustainable energy solutions. We urgently require eco-friendly, low-pollution renewable energy strategies to lessen our environmental impact in the near future. Thankfully, there are various renewable energy methods available that are both clean and environmentally friendly [Liu, et al., 2020]. These sources don't emit CO2 or other harmful pollutants, and they don't rely on materials that take ages to form naturally. Renewable energy options include solar, wind, tidal, hydro, geothermal, and bio-energy production methods, all of which can potentially replace our current non-renewable systems [Yu, et al., 2020].

This sparked a growing interest among researchers to develop technology that is both sustainable and environmentally friendly, leading to the rise of solar energy. With copper (II) phthalocyanine (CuPc) as the donor and perylene tetracarboxylic derivative (PV) as the acceptor, Tang created a double-layered heterojunction cell in 1986 that had an efficiency of roughly 1% when illuminated. Generally, when sunlight strikes the solar cell, the active layer absorbs the incoming photons, forming what we call excitons—essentially pairs of electrons and holes [Simovski, et al, 2023]. The electric field produced at the layer contact subsequently separates these excitons.

Literature Review

Energy is a fundamental requirement for creating a better and more comfortable life for everyone. As the global population grows and technology advances, our energy consumption keeps rising. The industrial and transportation sectors are significant contributors to this demand. The key distinction between them is that non-concentrating collectors have the same size for both the aperture and the receiver area, while concentrating collectors feature a much smaller receiver area compared to the aperture. Non-concentrating solar collectors are typically used for low-temperature applications, such as producing domestic hot water and space heating, where temperatures are usually below 150 °C. On the other hand, concentrating solar collectors are more suited for industrial heating and power generation, capable of reaching temperatures up to 500 °C [Zhao & Zhang, 2017].

Incorporating solar energy is crucial for addressing challenges like climate change, rising energy demands, and the dwindling supply of fossil fuels. In fact, the total solar energy that hits the Earth's surface in just 84 minutes is enough to meet the global energy needs for an entire year. Incoming solar radiation is converted into heat energy by the solar thermal collector technology and into electrical energy by the photovoltaic panel technology. But the majority of the information that is now available tends to concentrate only on solar thermal collectors [Wang, et al, 2018]. While concentrating sun collectors can attain temperatures of up to 500°C, non-concentrating solar collectors can only reach a maximum of 150°C. The most well-known and important of them is the Parabolic Trough Collector (PTC), which has a higher thermal efficiency than other varieties and can normally deliver temperatures between 200 and 400°C. Numerous methods, including the use of nanofluids, cavity receivers, inserts, selective surface coatings on the absorber tube, optical adjustments, secondary reflectors to guarantee even heat flux distribution, and improvements in materials and structural geometry, can be used to improve a PTC's thermal performance. The PTC was investigated by Reddy et al. [Wang & Cheng, 2019] using porous fin inserts in square, trapezoidal, triangular, and circular geometries.

Methodology

Photovoltaic (PV) solar panels work by converting sunlight into electricity. Right now, this is the most popular method for harnessing solar energy. These panels consist of multiple PV cells arranged in a complex layout, and they can vary in size from just a few square centimeters to several square meters. It's pretty straightforward: the larger the surface area that captures sunlight, the more solar energy can be collected by the PV cells. The sun emits a variety of radiation wavelengths, including infrared radiation, which is effectively transferred as thermal energy to materials that can absorb it. Since black surfaces absorb all visible light wavelengths, materials that can efficiently soak up this thermal electromagnetic energy are known as "black bodies." An ideal black body can both emit and absorb all types of electromagnetic radiation across all wavelengths. This thorough investigation of the databases led to a comprehensive bibliographic portfolio that highlights the most significant research on solar energy harvesting [Wang, et al., 2020].

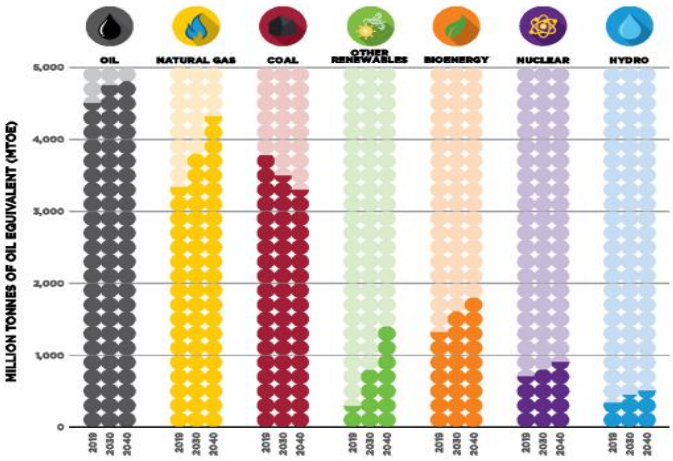

Fig. 1: World Energy Consumption

Fundamentally a type of solar energy, wind energy is the renewable energy source with the greatest rate of growth. However, wind potential is only available in select areas, and India boasts an enormous and seemingly endless supply of it. In fact, India ranks fourth in the world for wind power production. With the rising concerns of global warming, dwindling foreign exchange reserves, and the abundance of wind resources, the country's clean energy sector is on the rise. Thanks to advancements in wind energy technologies, the cost of generating electricity from wind has significantly decreased. Common models like Rayleigh distribution, Weibull, and the Markov chain are often used to forecast wind speed. It's crucial to closely monitor electrical parameters such as generator temperature, rotor rotation speed (rpm), and reactive power compensation to enhance the output power of wind turbines [Wang, et al., 2018]. The electricity generated is then transmitted to the grid through various interconnectors. The performance of the rotor's generator, the operational efficiency of the windmill, and power quality issues are all closely tied to the grid connection.

Results and Discussion

Heat transport using the trapezoidal-shaped porous inserts was improved by 13.8% as a result of their creation of a three-dimensional numerical model using CFD. Furthermore, a remarkable rise in the Nusselt number to roughly 64.3% was obtained from performance analysis with a porous disc receiver employing Thermion VP-1 as the heat transfer fluid (HTF). The vacuum shell setup works better than a non-evacuated receiver, but it doesn't outperform an evacuated receiver. One of the great things about the vacuum shell is its straightforward design and affordability.

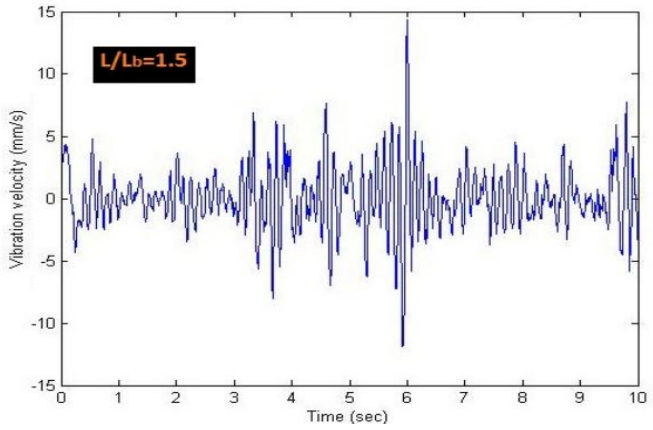

Fig. 2: Vibration Velocity

This also demonstrate how the optical characteristics of our suggested absorber are affected by the geometric parameters of the substrate and the nano-pyramids. To do a numerical analysis on a rough surface with sharp Bi2Te3 nanostructures. Further proceed to create samples with these nanostructures based on the simulation results from this rough Bi2Te3 surface, assessing their optical characteristics with a grating monochromator and an integrating sphere.

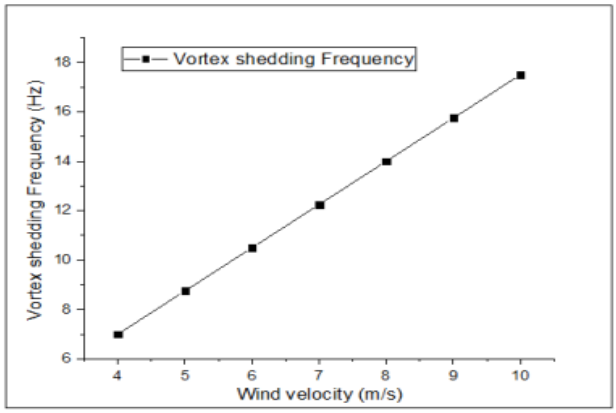

Fig. 3: Wind Velocity Vs. Strouhal Shedding Frequency

This article primarily highlights insights from global researchers regarding the different applications and how well each material fits those uses. Additionally, since each publication was assessed on its own, we included pertinent data about the energy generation methods discussed in each document. Ultimately, this review aims to enhance the methods we've explored and spark new ideas for applications in environmental engineering.

Conclusion

Solar absorbers and solar cells are often mixed up, but they serve different purposes. While solar cells convert sunlight into electricity, solar absorbers focus on turning that sunlight into heat. This heat can help cut down on the electricity needed to generate the same amount of heat, making them energy savers that fit into the broader category of energy conservation. Typically, the heat from these absorbers is transferred using a liquid, usually water. In central heating systems, copper pipes are used to circulate this water. If those copper pipes are left in the sun, they can absorb some energy and warm up the water inside. However, this method isn't the most efficient, which has led to efforts to enhance how well surfaces absorb heat. Ideally, we'd want a single material that can absorb visible light and convert it into heat effectively. Some materials, like hafnium carbide or tungsten, are wavelength selective, but none are perfect. They either transition from low to high reflectance too gradually or cut off the solar spectrum too early. On the simpler side, a common solution is to paint the surface with a dull black paint, which works better than a shiny metal surface. For a more advanced approach, optimizing absorptance is key. There are various strategies, such as using a combination of absorption and reflection, where the substrate reflects light back through the absorber for a second chance to capture it. Another method involves layering alternating dielectric and semi-transparent metallic materials. Alternatively, applying a heat mirror coating on a non-selective black substrate can also enhance performance.

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