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Design and optical analyses of an arrayed microfluidic tunable prism panel for enhancing solar energy collection

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HIGHLIGHTS

- We present an arrayed tunable prism panel enabling wide tracking and high solar concentration.
- A microfluidic technology allows a low-cost, lightweight and precise solar tracking system.
- Our prism panel enables high solar concentration up to 2032× factor.
- Various liquid prism configurations (stacked prism arrays) and optical materials are considered.
- Their impacts on solar beam steering, reflection losses and beam concentration are studied.

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ABSTRACT

We present the design and optical analyses of an arrayed microfluidic tunable prism panel that enables wide solar tracking and high solar concentration while minimizing energy loss. Each of the liquid prism modules is implemented by a microfluidic (i.e. non-mechanical) technology based on electrowetting for adaptive solar beam steering. Therefore the proposed platform offers a low-cost, lightweight and precise solar tracking system while obviating the need for bulky and heavy mechanical moving parts essentially required for a conventional motor-driven solar tracker. In this paper, various liquid prism configurations in terms of design (single, double, triple and quad-stacked prism arrays) as well as optical materials are considered and their impact on optical performance aspects such as solar beam steering, reflection losses and beam concentration is studied. Our system is able to achieve a wide solar tracking covering the whole-day movement of the Sun and a reflection loss below 4.4% with a Rayleigh's film for a quad-stacked prism configuration. Furthermore, an arrayed prism panel is proposed to increase the aperture area and thus allows for the collection of large amounts of sunlight. Our simulation study based on the optical design software, ZEMAX, indicates that the prism panel is capable of high solar concentration up to 2032× factor even without conventional solar tracking devices. We also deal with dispersion characteristics of the materials and their corresponding effect on concentration factor. The proposed microfluidic platform has a potential for high solar energy harvesting and is not only economically viable, but also reliable and practical for various solar power applications.

1. Introduction

Climate change, lack of fossil fuel and rapid urbanization are demanding the need for cleaner and more sustainable energy solutions. Among various renewable energy sources, solar energy is expected to be one of the most promising means as future energy solutions. It is transferred to the earth in the form of electromagnetic radiation and usefully converted to thermal and electric energy forms through various solar power technologies such as photovoltaic (PV) [1–4], concentrated solar power (CSP) [5–8], solar thermal heating [9,10], solar daylighting [11,12] and solar thermo-chemical reaction [13–16].

With an ever-increasing interest in these solar power technologies, a key question has been how to effectively collect solar energy from the daily and seasonal movements of the Sun. A solar tracker is the most commonly used approach, which allows both receivers and collectors in an optimal position perpendicular to the solar irradiance and maximizes solar energy capture [17,18]. However, conventional solar tracking systems require bulky, heavy and complex mechanical moving parts such as motors and supporting hardware. Such mechanical complexity and heavy loading of the tracking systems increase installation and maintenance cost as

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well as consume large operational power up to 10% of the solar power generated [19]. In addition, a tracker's reliability is also a significant concern. In the field, more than 50% of the observed reliability issues with solar energy harvesting systems are caused due to malfunctioning of mechanical solar trackers [20]. Therefore, there is a critical need for optimizing solar energy collection through the usage of alternate tracking methodologies that obviate the requirement of bulky, power-hungry, expensive and complex mechanical moving parts.

To avoid such problems arising from current motor-driven mechanical solar trackers, our group recently presented the concept of electrowetting-based (i.e. non-mechanical) solar beam steering [21,22]. Electrowetting is a well-known microfluidic technology that enables to electronically modulate the surface tension of a liquid on a solid surface [23–27]. Recent works have used the electrowetting principle for adaptive beam steering in a liquid prism and showed potentials of free-space optical communication without bulky mechanical moving parts [28–30]. We proposed this microfluidic concept for potential concentrated photovoltaic (CPV) applications [21,22]. An arrayed prism panel increases the aperture area to collect a large amount of sunlight and focuses it onto a small CPV cell through concentrating optics without heavy and bulky mechanical moving parts, which is essentially required for conventional motor-driven solar tracking systems. However, none of the previous studies has been conducted for optimization of various prism configurations and their optical analyses, although these studies are critical in order to improve the prism capabilities for greatly enhancing solar energy collection. Most work to date only presents data for a single prism system which does not effectively consider the overall impact and potential of an arrayed prism panel towards solar energy collection and utilization [21,30]. In addition, the previous studies have not factored into consideration performance metrics such as wide solar beam steering, minimum reflection losses, high solar concentration and material selection.

In this paper, we present analytical studies of the arrayed microfluidic liquid prism panel in various configurations aiming to achieve wide solar tracking and high solar concentration, while minimizing reflection loss. For the beam steering study, four different prism configurations (single, double, triple and quad-stacked) are proposed and their optical performance is compared and further optimized. We report a whole-day solar tracking with the proposed microfluidic platform. Reflection loss and its dependence on prism layout as well as liquid materials were also studied to achieve minimum energy loss. The quad-stacked prism was further optimized with Rayleigh's films, which further reduced the loss to 4.4%. In addition, studies on solar concentration were conducted over various incident angles using the optical design software, ZEMAX, and showed the concentration factor as high as 2030× without mechanical solar tracking devices. Dispersion issues caused by the materials used were also investigated to optimize the concentration performance. The arrayed microfluidic prism panel offers several advantageous features, including (1) reduced installation and maintenance cost by removing heavy and bulky mechanical moving parts such as dual-axis trackers, motors, and other related components, (2) reliable solar tracking and high concentration enabled by microfluidic-based precise sunlight modulation, (3) extremely low power consumption for the operation in the range of ~mW and (4) convenient installation and quiet rooftop operation due to compact design of the system. This new tracking system when used in conjunction with concentrating optics can be revolutionary for rooftop solar applications and various other solar power technologies such as solar thermal heating, solar indoor lighting, concentrated photovoltaic (CPV), concentrated solar power (CSP), and solar thermo-chemical reactions.

2. A microfluidic solar energy collection system and its working principle

Fig. 1(a) shows a schematic of the basic liquid prism module. Each prism sidewall is fabricated with a hydrophobic dielectric layer coated on a conductive substrate. Four sidewalls are then assembled on a transparent base substrate to form the cuvette. Two immiscible liquids (e.g. water and oil) are filled and covered by another top transparent plate without air trapping. To achieve non-mechanical beam steering, the prism is operated by a microfluidic technology based on electrowetting, which refers to the modulation of the surface tension at the interface between a liquid and a solid electrode with an applied electric field [24,25,31]. The resultant contact angle modulation of the liquid can be estimated by the well-known Young–Lippmann theory [26]. The fluid–fluid interface initially forms a curved meniscus with the contact angle of θ_0 at the cuvette sidewalls. An electric bias is applied at the west and east sidewalls (V_W and V_E) and modifies the initial contact angle to θ_W and θ_E (see Fig. 1(a)). The Young–Lippmann equation can be re-written for the contact angles at the west and east sidewalls as [21,22,30]:

$$\theta_W = \cos^{-1}\left(\cos\theta_0 + \frac{1}{2\gamma}cV_W^2\right),\ \theta_E = \cos^{-1}\left(\cos\theta_0 + \frac{1}{2\gamma}cV_E^2\right) \quad (1)$$

where c is the capacitance per unit area of the dielectric layer deposited on the sidewall, and γ is the surface tension between two immiscible fluids. Proper adjustment of θ_W and θ_E allows the fluid–fluid interface to maintain a straight profile, which has been experimentally demonstrated in the previous works [21,28,30]. The apex angle, φ, of the prism (see Fig. 1(a)) defined as the angle made by the interface with respect to the horizontal is related to θ_W and θ_E by:

$$\begin{aligned} &\theta_W + \theta_E = 180^\circ \\ &\varphi = \theta_E - 90^\circ \quad \text{when } \theta_E > 90^\circ \\ &\varphi = 90^\circ - \theta_E \quad \text{when } \theta_E \leqslant 90^\circ \end{aligned} \quad (2)$$

Incoming sunlight with an incident angle of α_0 can then be steered at the interface of two different media with a refractive index contrast ($n_{air} \neq n_1 \neq n_2$). The applied electrical input varies to continuously regulate the apex angle of the prism and adaptively track the Sun's positions without bulky and heavy mechanical parts. By adjusting the contact angles at two and four sidewalls, various prism modulations are possible such as single- as well as dual-axis solar tracking as shown in Fig. 1(b).

To achieve wide solar tracking and high concentration, a basic prism module is arrayed, stacked up and integrated with concentrating optics, as shown in Fig. 1(c). Consequently, a large amount of sunlight is re-directed and focused onto solar receivers that can be potentially useful for various other solar power technologies such as solar thermal heating, CPV, CSP, and solar thermo-chemical reactions.

3. Performance analyses of various prism configurations

To enhance solar energy capture, each of the basic prism modules needs to be capable of wide solar tracking and minimized reflection loss. In this section, we analyze optical performance of various prism configurations (single, double, triple and quad-stacked) and the effect of liquid prism materials. Further optimization of these configurations was also conducted to meet the abovementioned requirements.