A Brief Review of Solar Indoor Lighting System Integrated with Optofluidic Technologies

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Abstract

Indoor lighting system incorporating daylighting effectively provides potential energy savings as well as meaningful spatial and temporal variation in illuminance beneficial to human well-being and performance. Integration of the tunable liquid prisms driven by optofluidic technologies will further improve the solar indoor lighting systems to achieve better illumination performance and higher solar energy utilization efficiency. This paper provides an overview of the state-of-the-art investigations over different aspects of the solar indoor lighting system enhanced by optofluidic liquid prisms, including (1) theoretical background, design, fabrication, and operation of liquid prisms, (2) advances in solar collectors and solar trackers, and (3) major tools for indoor lighting simulation and ray-tracing simulation. These studies form a solid foundation for future solar indoor lighting systems integrated with optofluidic technologies. The prospective study will focus on laboratory and on-site testing of the integrated system.

Keywords: Solar; Electrowetting; Solar Lighting; Optofluid; Concentrator;

1. Introduction

Energy has become vital for the progression and survival of the modern world. To limit climate change, European Union and other 192 states have put in efforts in the form of the Paris Agreement to target an overall 2 °C rise in global temperature. This target will be achieved by replacing the use

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of fossil fuels with renewable energy resources [1-3]. However, under the current level of fossil fuel use [4, 5], a global temperature rise of 1.5 °C is expected [6, 7]. On the other hand, renewable energy production only shares 6.7% of the global energy needs [8]. Solar energy is only considered to be having enough potential to cover the current global energy demand among all renewable energy resources [9, 10]. Its easy availability also makes it the most suitable option to be target globally. There are two types of solar radiations, diffuse and beam. The diffuse radiations don't have any specific direction and are available throughout the day, even during cloudy periods. However, a significant portion of the solar energy is available as beam radiations, which are parallel rays hitting the earth's surface in a particular direction. Although its angle of incident is changing throughout the day, it can be tracked accurately.

A large portion of the global energy consumption is shared by indoor lighting. In developed countries like the USA, lighting accounts for 20-60% of a commercial building's electricity consumption [11]. Such electrical load of indoor lighting can be efficiently and easily covered by converting sunlight into high-grade electrical energy with the solar cell. However, although solar cells offer as high as 47.1% cell efficiency [12], converting solar energy into electricity and eventually converting it into light rays is not efficient due to the involvement of multiple conversion processes.

A significant portion of the solar spectrum consists of the visible region. Therefore, direct utilization of solar radiations for indoor lighting is the most efficient approach. Solar beam radiations can be captured onsite and delivered to the required destination with simple optics. Existing daylighting systems can be categorized into two types, i.e., light-guiding systems and light transport systems [13]. The former reflects light into the room using optical devices, while the latter can collect, transport, and redistribute light. Light-guiding systems are simple and cost-effective but have limited performance [14]. On the other hand, light transport systems have inferior performance with energy saving. However, they rely on mechanical systems e.g. adjustable baffles for illumination power control [15, 16]. Such mechanical systems require regular maintenance. Moreover, the light that is being obstructed by the baffles cannot be further used.

Recent advances in optofluidic technologies offer a promising solution to the issues of existing daylighting systems. The optofluidic liquid prisms, which work on electrowetting principles, allow flexible control of light transmission and reflection [17, 18]. Comparing with mechanical devices, the liquid prisms have high compactness, fast response, and low-cost design, making them appealing and competitive. By integrating the optofluidic liquid prisms into the daylighting systems, illumination power can be tuned with high flexibility [19]. Moreover, excess sunlight can also be

recovered for the other applications from such configuration [20], thereby further increasing the solar energy utilization efficiency.

Given these promising features, this review paper provides comprehensive knowledge on the solar indoor lighting system integrated with optofluidic liquid prisms. Firstly, three key components of the daylighting system are reviewed, i.e., liquid prism, solar collector, and solar tracker. Then, the analytical methodologies to evaluate system performances are presented, including indoor lighting simulation and ray-tracing simulation. The whole article is organized as follows. Section 2 provides a detailed description of the system's working principles where special focus is given to the optofluidic liquid prisms, a novel device for the solar indoor lighting system. Section 3 provides fundamental knowledge on the electrowetting phenomenon and the theoretical basis of the liquid prisms. Section 4 reviews recent advances in liquid prisms and their applications in solar systems. In Section 5 and Section 6, a brief review of solar collectors and solar trackers capable of the solar indoor lighting system is presented. Section 7 describes the tools and methods for indoor lighting simulation, followed by section 8, which discusses ray-tracing simulation. At last, conclusions are presented in Section 9.

2. System description

Figure 1 shows the schematic of a solar indoor lighting system integrated with tunable liquid prisms. It consists of solar concentrators, optical fibers, and liquid prisms. Solar concentrators collect sunlight and focus them on the optical fiber, which delivers the sunlight into the rooms. In each room, an array of liquid prisms are installed below the optical fiber. The relative amount of light transmitted through the prism or reflected into the fiber is controlled by changing the prism apex angle, thus allowing lighting power regulation. Excess sunlight that is not used for lighting can be directed to illuminate other rooms and other solar applications (e.g., photovoltaic or solar thermal).

Figure 1 A schematic of solar indoor lighting system integrated with optofluidic liquid prisms [20]

2.1 Solar collection and transportation

A solar collector tracks the sun's movement, collects sunlight, and directs them into the optical fiber. Figure 2(a) shows the schematic of the solar collection devices, consisting of a parabolic reflector, a hyperbolic reflector, and a homogenizer. The optical fibers, shown in Figure 2(b), are attached at the bottom of the homogenizer to receive the concentrated sunlight and transport it into the rooms. In each room, liquid prism arrays are attached below the optical fibers. At the prism-fiber interface, the clad material is removed, and the core material is attached below the working fluid of the prisms, as depicted in Figure 2(c). In this way, sunlight can escape from the fiber and enter the prism. The amount of light being directed into the room or returned to the prism is controlled by regulating the prisms' apex angle, which will be described in the following subsection. A diffuser is attached at the bottom of the prisms to distribute the light in the room space evenly. The sunlight that is reflected in the optical fiber is directed elsewhere for other uses.

Figure 2 Schematic of (a) the solar collector, (b) optical fiber bundles, and (c) prism arrays attached to optical fiber and diffusers [20]

2.2 Optofluidic liquid prisms

The tunable optofluidic liquid prism is a crucial component to improving the solar indoor lighting system's performance. It enables flexible control of illumination power, which allows for fast response to the fluctuation of solar intensity and sustains a constant illumination level inside the room. Also, the energy efficiency can be greatly improved since the excessive sunlight can be directed back into the fiber for further use. More importantly, the prisms are driven by micro-fluidic technologies and don't require bulky mechanical components.

The operation of optofluidic prisms is based on droplet manipulation, which can be achieved via different principles, such as molecular diffusion, heat conduction, centrifugation effect, light-matter interaction, and electrowetting-on-dielectric (EWOD) [21]. EWOD-driven prisms are most suitable for solar indoor lighting applications due to the fast response. EWOD is the phenomenon that the contact angle of a droplet on a dielectric surface changes when voltage is applied, as shown in Figure 3(a-b). The relationship of the initial and final contact angles follows the Young-Lippmann equation [22]

$$\cos\theta = \cos\theta_0 + \frac{1}{2\gamma_{LG}}cV^2 \quad (1)$$

where θ_0 and θ are the initial and final contact angles before and after applying the voltage, respectively. γ_{LG} is the interfacial tension between the droplet and the atmosphere, c is the coating layer's capacitance, and V is the bias-voltage across the dielectric layer [23].

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Figure 3 Working principle of (a-b) electrowetting on dielectric, and (c-d) liquid prisms. (a) electrowetting device with no voltage, (b) electrowetting device with bias-voltage applied, (c) liquid prism at natural state, and (d) liquid prism with different bias-voltages on the sidewalls [20]

A liquid prism is a rectangular cuvette with four sidewalls coated with dielectric materials. When voltages are applied, the contact angles at the sidewalls (θ_L and θ_R) also follow the Young-Lippmann equation:

$$\theta_L = \cos^{-1} \left(\cos \theta_0 + \frac{1}{2\gamma_{LG}} cV_L^2 \right) \quad (2)$$

$$\theta_R = \cos^{-1} \left(\cos \theta_0 + \frac{1}{2\gamma_{LG}} cV_R^2 \right) \quad (3)$$

A flat interface can be achieved by modulating θ_L and θ_R to $\theta_L + \theta_R = 180^\circ$, as shown in Figure 3(d). The corresponding prism apex angle (φ) is derived as

$$\varphi = \begin{cases} \theta_L - 90^\circ & \text{when } \theta_L > 90^\circ \\ 90^\circ - \theta_L & \text{when } \theta_L < 90^\circ \end{cases} \quad (4)$$

The amount of sunlight that transmits through a prism is directly correlated to the incidence angle (the angle between the sunlight and the interface), which is described by the Fresnel equations:

$$R_s = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 \quad (5)$$

$$R_p = \left| \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right|^2 \quad (6)$$

$$T_s = 1 - R_s \quad (7)$$

$$T_p = 1 - R_p \quad (8)$$

where R_s and R_p are the reflectance for s-polarized and p-polarized lights, respectively, while T_p and T_s are the transmittances. n_1 and n_2 represent the refractive index of the working fluids filled into the liquid prism. θ_i and θ_t are the incidence and transmittance angles, respectively.

Since sunlight is unpolarized, the overall amount of sunlight that is transmitted through the prism is calculated as

$$T = (T_p + T_s)/2 \quad (10)$$

For sunlight coming from a given direction, its incidence angle with respect to the prism interface (θ_i) can be simply controlled by regulating the prism apex angle, thus achieving illumination power control.

3. Electrowetting phenomenon

The electrowetting phenomenon is the basis for liquid prisms. Extensive research efforts have been conducted on electrowetting to increase angle modulation, simplify the fabrication process, and improve device stability.

Dielectric material. The performance of an electrowetting device, quantified by the contact angle change, is directly related to the dielectric material's capacitance, as revealed in Eq.1. Therefore, increasing the dielectric layer's capacitance is an effective way to achieve a larger angle modulation with lower voltages. Moon et al. [23] experimentally verified the efficacy of increasing the capacitance of the insulating layer, i.e. increasing the dielectric constant and reducing the thickness of the dielectric layer. To study the effect of dielectric layer thickness, three thicknesses (i.e., 1000 Å, 1 µm, and 12 µm) were tested for amorphous fluoropolymer (Teflon® AF, Dupont), silicon dioxide (SiO₂), and parylene. As for the effect of dielectric constant, SiO₂ ($\epsilon=3.8$) and barium strontium titanate (BST, $\epsilon=180$) with the same thickness were compared. The experimental results agreed with the expectation. When the thickness of SiO₂ was reduced from 1 µm to 1000 Å, the required voltage to induce 40 ° contact angle change reduced from 65 to 19 V, as shown in Figure 4(a). The voltage can be further reduced to 15 V when the BST was used as the dielectric material, as depicted in Figure 4(b).

Figure 4 (a) Contact angle with applied voltage for 1000 Å SiO₂ (circles), 1 μm SiO₂ (triangles) and 12 μm parylene (diamonds); (b) Contact angle change with applied voltage for 700 Å BST +200 Å fluoropolymer (solid squares), 1000 Å SiO₂ +200 Å fluoropolymer (solid circles) and 1200 Å fluoropolymer (open circles) [23]

Commonly used dielectric materials, including Parylene C, silicon dioxide (SiO₂), and aluminum oxide (Al₂O₃), are usually fabricated by conventional integrated circuit (IC) processes. These processes are typically time-consuming and expensive. Polydimethylsiloxane (PDMS) allows a simple spin-coating process, but its dielectric constant is low, and the corresponding contact angle change is limited. To simplify fabrication and improve angle modulation, Narasimhan and Park [24] demonstrated the use of a novel ion gel material as the dielectric layer for EWOD applications. Figure 5(a) shows the chemical structure of the ion gel, which consists of a copolymer, poly(vinylidene fluoride-co-hexafluoropropylene) [P(VDF-HFP)], and an ionic liquid, 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide [EMIM][TFSI]. It can be simply spin-coated or dip-coated, thus eliminating the need for IC processes. Moreover, it has a high capacitance of $c \approx 10 \mu\text{F}/\text{cm}^2$, several orders higher than that of conventional dielectric materials. Figure 5(b) compares the electrowetting performance among ion gel, Al₂O₃, SiO₂, and PDMS. Ion gel is able to achieve significantly larger angle modulation with lower voltage.

Figure 5 (a) Chemical structure of the ionic liquid; (b) comparison of contact angle modulation between ion gel and conventional dielectric materials. Reprinted with permission from [24].

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AC/DC electrowetting. For typical electrowetting studies, the liquid droplet is equivalently modelled as a resistor and a capacitor connected in parallel, while the dielectric layer underneath the droplet is equivalently assumed as a single capacitor [25, 26]. The equivalent electrical circuit diagram is illustrated in Figure 6(a). Under the DC signal, the droplet behaves like a resistor, as can be seen in Figure 6(b), and the most voltage drop occurs across the dielectric layer. Therefore, contact angle modulation is not affected by signal frequency. However, when a high-frequency AC bias voltage is applied, the droplet behaves in a capacitive manner, as shown in Figure 6(c), and the voltage drop across the droplet becomes considerable [25, 27]. Consequently, less energy is stored within the dielectric layer, leading to reduced contact angle modulation. Based on such understanding, Hong et al. [25] developed a mathematical model for AC electrowetting. The model prediction agreed well with experimental measurement.

Figure 6 (a) Equivalent circuit diagram for a typical electrowetting-on-dielectric device; (b) at low-frequency range droplet behaves as a resistor; (c) at high-frequency range droplet behaves as a capacitor [26]

Mugele et al. [28] conducted a fundamental study on electrowetting of saltwater droplets on Teflon AF. Saltwater (concentration = 0.2 mol/L, conductivity = ~ 20 mS/cm) and deionized water (conductivity = $3 \mu\text{S/cm}$) droplets were used in the experiments. Due to higher conductivity, the saltwater behaves as a perfect conductor, and its electrowetting behavior is not affected by the signal frequency as well as the position of the electrode. In contrast, the deionized water behaves as a capacitor, and the voltage drop across the droplet is not negligible. When the electrode is placed further from the substrate, its capacitance becomes smaller (due to a larger thickness), leading to less voltage drop at the droplet-dielectric interface. As a result, contact angle change becomes smaller.

Kumar et al. [29] further studied the AC electrowetting phenomenon for droplets with different conductivity. When fluid has low conductivity, contact angle modulation is weaker under a higher frequency, as shown in Figure 7 (a). The reason is that the droplet behaves in a capacitive manner, and more voltage drop occurs across the droplet when the frequency is higher. The effect of signal frequency becomes less significant when droplet conductivity is higher, as depicted in Figure 7 (b). When the droplet conductivity reaches $300 \mu\text{S/cm}$, the droplet behaves like a resistor, and contact angle change becomes independent of the signal frequency, as shown in Figure 7 (c).

Figure 7 Electrowetting response for under different AC frequencies for droplets with conductivities of (a) $5 \mu\text{S/cm}$, (b) $17 \mu\text{S/cm}$ (b) and (c) $300 \mu\text{S/cm}$. Signal frequencies from top to bottom are: 0, 0.5, 1, 5, 10, 20, 40, and 100 kHz [29]

Stability. Vallet, Berge and Vovelle [30] studied the stability of electrowetting by testing water and aqueous solutions on polyethylene terephthalate (PET) films. Contact angle change under a low voltage followed the Young-Lippmann equation (Eq.1). However, the electrowetting behavior deviated from the theory under a higher voltage. Firstly, the droplets' contact angle couldn't return to its initial value after the voltage was released. Secondly, the PET film along the droplet surface became hydrophilic. Thirdly, smaller droplets are expelled around the droplet contour. Such behavior can be attributed to dielectric layer damage under a higher voltage. The phenomenon is observed to be more severe when DC voltage is used [31]. In contrast, AC electrowetting is observed to have higher stability, decreased contact angle hysteresis, and delayed contact angle saturation [32, 33]. Nanayakkara et al. [34] compared DC and AC electrowetting behavior of ionic liquid. Electrowetting experiments were conducted on different ionic liquids (including mono-, di-, and tricationic varieties) under four frequencies: DC, 60 Hz, 1 kHz, and 10 kHz. Under AC signals, the contact angle was able to return to its initial value after the voltage is released, demonstrating better stability than DC electrowetting.

Droplet oscillation. Despite better device stability of AC electrowetting, droplets are unable to keep a stable shape under lower AC frequencies. The hydrodynamic eigenfrequency of the drops is in the range of a few tens of Hertz. Under such low frequencies, the shape of the droplets will follow the time-dependent electric forces. Mugele [35] studied droplet oscillation induced by AC electrowetting. Water-glycerol-NaCl mixture (viscosity 1-65 mPa-s) with a volume of 1-2 μL was placed on top of SiO_x substrate, and an AC voltage with frequencies of 0-10 kHz and amplitude of 0-75 V was applied. The droplets were observed to oscillate under a frequency between 10 and 125 Hz, and the contact angle changed periodically between 130° and 80°, as demonstrated in Figure 8.

Figure 8 Super-imposed image of droplet shapes at the initial state and maximum deformation [35]

Oh, Ko and Kang [36] conducted a more systematic study on droplet oscillation under AC electrowetting. Parylene-C and Teflon were coated on ITO substrates. An aqueous NaCl solution of 10^{-3} M was used for testing, and the electrical signal had an amplitude of 60-100 V and a frequency of 20-1000 Hz. Figure 9 is the super-imposed images of droplet shapes at different frequencies. Resonance occurred at frequencies of 33, 61, 100, 196, and 289 Hz, and the corresponding numbers

of node points are 2, 2, 4, 6, and 8, respectively.

Figure 9 Super-imposed image of droplet shapes at different frequencies, reprinted with permission from [36]. Copyright (2008) American Chemical Society.

For prism operation, a stable liquid-liquid interface is required. Thus, the frequency of the signal should be > 200 Hz to avoid oscillation. On the other hand, a higher frequency induces more voltage drop across the droplet, leading to smaller angle modulation. For optimal operation, the signal frequency is recommended to be 200-1000 Hz.

4. Optofluidic liquid prism

Fundamental study on the electrowetting phenomenon provides useful information for the design, fabrication, and operation of the optofluidic liquid prisms. Based on the findings of electrowetting study, liquid prisms are designed and tested using different dielectric materials and working fluids. Possible applications of liquid prisms in solar utilization are studied.

Prism operation. Smith et al. [37] fabricated an electrowetting micro-prism using SiO_2 as the dielectric material and Teflon AF as the hydrophobic insulator. A mixture of water, glycerin, and KCl (weight ratio 80:20:0.1, refractive index $n=1.359$) was filled into the prism as the working fluid. Continuous beam steering of $\pm 7^\circ$ was demonstrated by applying different bias-voltages on the sidewalls to modulate the apex angle (shown in Figure 10). The beam steering can be further increased to $\pm 15^\circ$ by using a liquid with a higher refractive index of $n=1.6$. The design can achieve high beam steering with a relatively small prism apex angle since the other working fluid is air, whose refractive index is lower than other fluid ($n=1$). However, the working fluid gradually evaporates due to direct exposure to air.

Figure 10 Liquid prisms under different bias-voltages [37]

To prevent evaporation, Cheng and Chen [17] developed a two-liquid prism using water and oil. Ti/Au was deposited on the ITO-glass substrate as the dielectric, which was then covered with a fluoropolymer (PFC1601V, Cytonix Corporation) layer. Coated substrates were assembled into prisms with an aperture size of $10\text{ mm} \times 10\text{ mm}$. Water and silicone oil were filled into the prism as the working fluid, as shown in Figure 11(a). The orientation of the water-oil interface was modulated between -26° and 26° , and the corresponding beam steering angle was $0-15^\circ$. Since silicone oil is not volatile, such a two-fluid design eliminates working fluid evaporation and allows long-term operation.

(a)

(b)

Figure 11 Water-oil interface of the liquid prism (a) under natural state and (b) with bias-voltages on the sidewalls [17]

Inspired by the promising electrowetting performance and simple fabrication of ion gel, Clement et al. [18] developed a liquid prism using the ion gel layer as the dielectric material. Unlike conventional dielectric materials, ion gel can be fabricated with a simple dip-coating or spin-coating method, which significantly simplified device fabrication. Using water ($n=1.33$) and 1-bromonaphthalene (1-BN, $n=1.65$) oil as the working fluid, prism angle modulation of 27° was

achieved, and the beam steering can be increased to 19° , as demonstrated in Figure 12. Both prism angle modulation and beam steering are larger than prisms using regular dielectric materials.

Figure 12 Steering of the green laser in the liquid prism [18]

Prism application. After concept demonstration, different applications of the liquid prisms have been reported. For each specific application, the prism design has been modified accordingly to meet the requirement. Cheng, Park, and Chen [31] proposed an optofluidic solar tracker consisting of linear prism arrays. As shown in Figure 13, a linear array of liquid prisms direct the sunlight to the Fresnel lens, concentrates the rays on the CPV cell. The liquid prism has a fast response, thus allowing precise solar tracking without any moving parts. Compared with conventional PV cells, the proposed system can increase power production by 70%, while the cost is reduced by 50%.

Figure 13 Stacked liquid prism modules for significant sunlight steering [31].

In addition to solar tracking, liquid prisms can also be used for solar concentration. Clement, Thio, and Park [38] proposed a linear array of liquid prisms to function as a tunable Fresnel lens. The analytical study revealed that focal length could be significantly reduced by increasing the prism angle. For experimental demonstration, a 3×1 liquid prism array was fabricated and tested. As

shown in Figure 14, spatial control was achieved for both longitudinal ($263 \text{ mm} \leq f_{\text{long}} \leq \infty$) and lateral ($0 \leq f_{\text{lat}} \leq 30 \text{ mm}$) directions.

Figure 14 Experimental demonstrations of spatial focal tuning. (a) $\beta_{a1} = \beta_{a2} = \beta_{a3} = 0^\circ$, no concentrating effect. (b) $\beta_{b1} = -3.2^\circ$, $\beta_{b2} = 0^\circ$, $\beta_{b3} = 3.3^\circ$, $f_b \approx 525 \text{ mm}$. (c) $\beta_{c1} = -6.2^\circ$, $\beta_{c2} = 0^\circ$, and $\beta_{c3} = 6.4^\circ$, $f_c \approx 263 \text{ mm}$. (d) $\beta_{d1} = -7.3^\circ$, $\beta_{d2} = -4.0^\circ$, $\beta_{d3} = 0^\circ$, $f_{\text{lat}} = 30 \text{ mm}$ [38].

Thio, Jiang and Park [39] employed liquid prisms to control lighting power in the solar indoor lighting system. Prisms are attached at the bottom of the optical fiber in each room, and lighting power is dynamically controlled by regulating the prism apex angle. Such a design helps to sustain a constant lighting power in response to the fluctuation of solar intensity. To demonstrate the concept, experimental tests were conducted for both the laser beam and white light source. For a single laser beam, lighting power can be modulated from 0 to 95% by modulating the prism apex angle between 0 – 10° . When it comes to the white light source, 40 prisms are required to achieve complete lighting power control (0 – 90%). The aspect ratio of the prism also impacts lighting power, with a smaller aspect ratio leading to a larger lighting power.

A higher level of beam steering is always desired for different prism applications. For such purpose, Narasimhan et al. [40] proposed and evaluated stacked prism configurations, including single, double, triple, and quad-stacked prism arrays, for application in solar tracking. Figure 15(a) shows the schematic and beam pathway of the quad-stacked prism arrays. It can steer the beam by $>90^\circ$ with a prism apex angle of 30° , as revealed in Figure 15(b). For solar tracking applications, it allows the prism-based tracker to track the whole-day movement of the sun. When it comes to solar concentration, the quad-stacked prisms can achieve a high solar concentration factor of up to $2032\times$.

(a)

(b)

Figure 15 (a) Schematic of a quad-stacked prism with beam pathway; (b) beam steering capability under different apex angles for various prism configurations [40]

Prism fabrication. Since the electrowetting phenomenon is only valid on a small scale, the prism dimension is usually limited (e.g., 10 mm × 10 mm). In actual applications, liquid prisms are assembled in an array to meet the dimension requirement. The fabrication of such a prism array is usually tedious. Figure 16 (a-b) shows the schematics of prism arrays' typical fabrication processes using the spin-coating method. Each sidewall has to be spin-coated with dielectric material before being assembled together. To fabricate a prism array with $n \times n$ prisms, the spin-coating process has to be repeated $4 \times n^2$ times, and the coating layers are prone to damage during fabrication.

To simplify the fabrication process, Clement et al. [41] proposed a dip-coating method. As shown in Figure 16(c-e), the desired structure is firstly assembled using the substrates. Then the assembled structure is dip-coated with ion gel and hydrophobic material. Such a single-step coating process significantly reduces the fabrication time and allows mass production of the prisms. Moreover, the risk of damaging or contaminating the dielectric layer can be eliminated, leading to better device stability and reliability.

Figure 16 **(a-b) Schematic of the conventional fabrication process of prism arrays:** (a) four sidewalls are spin-coated and assembled into a single prism; (b) prisms are assembled into an array. **(c-e) a single-step dip-coating process for prism array:** (c) substrates are assembled to get the desired 3D structure; (d) the assembled structure is dip-coated; (e) fully coated prism array [41].

Chen et al. [20] further optimize the design of the prism array. The prism array structure proposed in [41] integrated all prisms as one piece, as shown in Figure 17(a). Damage of any sidewall (which is common during electrowetting operation) will require the replacement of the whole prism array. To address this disadvantage, a new structure is proposed that allows each sidewall to be separated from the main structure, as shown in Figure 17(b). Any sidewall that is deranged during operation can be replaced individually without affecting other sidewalls.

Figure 17 (a) Prism array with integrated structure, and (b) modified structure that allows each sidewall to be detached and replaced [20]

5. Solar Radiations Collectors

The most common concentrator for solar application is the reflector-based design. The Cassegrain arrangement provides the best compact design for the solar lighting system, as shown in Figure 18 [42, 43]. The collimated solar radiations are concentrated in the opposite direction after being reflected by the primary parabolic reflector. However, the secondary hyperbolic reflector guides and focuses them in the original direction. The homogenizer element, placed at the second focal point of the Cassegrain concentrating assembly, accommodates any optical deviation or errors and uniformly guides rays towards the distribution section. As a result of the Cassegrain arrangement, the solar radiations are concentrated in the direction of the incident. The optical fiber connected at the outlet aperture of the homogenizer then guides the collected rays for further distribution to the point of application. The mini parabolic dishes provide a feasible solar radiation collection solution, as compared to the large conventional dishes. The main reason is that cost-effective manufacturing methods such as injection molding can be utilized to fabricate the reflectors. In addition, each reflector assembly can be dedicated to a single optical fiber, thereby reducing the optical loss and the need for a fiber bundle and distributor in the case of a large reflector dish.

The main advantage of using Cassegrain design is the reduced height of the concentrating module. As compared to a single reflector design, the rays are collected and concentrated with a height shorter than the focal point, as the secondary reflector intercepts and reflects them in the opposite direction. This results in an overall reduction in the size of the concentrating assembly. On the other hand, for reflective concentrators, the quality of reflective coating and material is essential to achieve high optical efficiency. Silver has the highest reflectance efficiency, followed by aluminum. However, silver is prone to oxidation when exposed to the moisture of ambient conditions, and special care is needed. Therefore, aluminum provides the most feasible solution for reflective concentrators.

Figure 18 Cassegrain arrangement of Reflective Solar Concentrating Assembly [42]

The conventional design of Cassegrain reflector provides a single outlet aperture for the collection of the concentrated solar radiations. On the other hand, the multi-leg homogenizer reflective concentrating assembly, as shown in Figure 19 [44, 45], not only provides the advantage of the reduced modular height but multiple outlet ports for a single set of reflectors. In addition, it can also benefit from the manufacturing methods of mini parabolic dishes.

The multi-leg homogenizer concentrating assembly utilizes two parabolic reflectors instead of a pair of parabolic and hyperbolic reflectors of the conventional Cassegrain design. Here, the secondary parabolic reflector makes the concentrated rays collimated again, which are being reflected by the primary parabolic reflector. Therefore, instead of point concentration, area concentration is achieved with concentrated collimated/parallel rays. The multi-leg homogenizer placed after the secondary parabolic reflector then splits and guides the rays towards four outlet apertures where four optical fibers can be connected directly. This configuration simplifies the overall system design and reduces the need for many reflectors for the collection of solar radiations.

Figure 19 Multi-leg Homogeniser Cassegrain Concentrating Assembly [44]

The Cassegrain arrangement of reflectors, as shown in the last two figures, has one limitation of shadow projected by the secondary reflector: the larger the size of the reflector, the larger is the shadow on the primary reflector, decreasing the effective area of the primary reflector [46]. Figure 20 shows the off-axis design of the parabolic reflector for the side concentration [47]. As a result, the reflector's total area represents the receiver's effective area without any shadow. Due to the large focal point [48] and to effectively utilize the space, two off-axis parabolic reflectors are combined as a set in a single concentrating assembly. Two optical fibers can be installed at the side focal points, which can further direct the rays towards the required lighting space. Although high reflective efficiency and shadow-free design can be achieved with such an off-axis reflector design, the side concentration can provide difficulty in the attachment and the distribution of the fiber optics network, which is relatively easy in Cassegrain arrangement when concentration is achieved in the direction of the incident of solar radiations.

Figure 20 Off-axis Design of Parabolic Reflector for Side Solar Concentration

Figure 21 Ring-Array Reflective Concentrator [49]

To achieve the concentration of rays in the incident direction with high reflectance efficiency, the ring array concentrator is shown in Figure 21 [49]. This design is also called a mirror Fresnel lens in which a series of reflective rings are arranged such that the incident parallel rays are directed to a single focal point. With the help of optical fiber installed at the point of focus, the concentrated rays can be guided towards any application point. Besides providing high optical reflective efficiency, the reflective concentrators relatively require more effort in fabrication and assembly. This increases the complexity of the system and the cost for large capacity units. To have an economical and simple design of solar concentration but with a slight compromise on the optical efficiency, the refractive concentration provides the best solution than reflective concentrators.

Figure 22 shows a simple design of Fresnel lens based single-stage concentration assembly [50, 51]. Fresnel lens is a compact form of the aspheric lens in which the curvature of the lens is split into multiple rings to have a single point concentration. By carefully designing the curvature of each refractive ring, spherical and chromatic aberrations can be avoided for fine focus. The homogenizer placed at the focal point also helps to accommodate such optical errors and angular deviations. The optical fiber can be attached at the homogenizer's outlet aperture to further guide the concentrated rays towards the required space. Although the single lens configuration provides the concentration in the direction of incident radiations, the larger focal length increases the module's overall height. The focal length or height of the module is proportional to the size of the lens. Therefore, for larger collector areas, module height will be proportionally larger, which can cause a problem during solar tracking operation.

Figure 22 Design of Fresnel lens based Single Stage Concentration Assembly [42]

Figure 23 Concentrator Assembly with Dual Fresnel lens and Compound Parabolic Concentrator (CPC) as Homogenizer [52]

Figure 23 Concentrator Assembly with Dual Fresnel lens and Compound Parabolic Concentrator (CPC) as Homogenizer [52] shows a concentrator assembly design with a dual Fresnel lens and compound parabolic concentrator (CPC) homogenizer [52]. The first lens converges the incoming solar radiations towards its focal point. However, the second Fresnel lens, which is placed in the

path of converging solar radiations, further increases their angle of convergence. As a result, the rays are focused with a reduced focal length that decreases the overall height of the concentrator module. Besides achieving reduced focal length with dual-lens, the sensitivity of the concentrator also increases for angular deviation of incident rays. Therefore, to increase its acceptance angle, CPC is used as a homogenizer, which collects focused rays and directs them towards its outlet aperture where optical fiber can be attached.

Figure 24 shows a compact form of Fresnel lens, a light guide in which incident solar radiations are directed toward the center of the lens where they are projected out as point concentration [53-55]. Unlike Fresnel lens, where incident rays are concentrated at a certain point on focal length, Sun Simba solar concentrator directs parallel rays towards its center where they are further refracted and become parallel to the concentrator axis. This design's significant advantage is the most compact concentrator design, like a plastic sheet's thickness. This eliminates the need of lens housing and provides smooth operation with practically zero height. Unlike the Fresnel lens, the size of the collector is not linked to the height of the module. The fiber optic can be directly fixed at the center of this light guide. Thus it will act as the inlet aperture of the optical fiber for the collection of rays, which will increase the receiving area of the optical fiber. Such kind of compact light guide can be installed as glass tiles to collect the solar radiations and deliver them at the point of application through fiber optics.

Figure 24 Compact Fresnel lens type Light guide – Sun Simba from Morgan Solar [54]

6. Solar Trackers for Concentrating Systems

For all of the solar concentrator applications, either reflective or refractive, solar tracking is essential as solar concentrators require parallel collimated rays for their operation. Therefore, solar trackers need to track solar movement throughout the day. This solar tracking requires a certain

level of accuracy, and if the tracking error goes beyond the concentrator's acceptance angle, the system's performance can fall to zero. That is why solar tracker is essential for the application of solar concentrators. In addition, this solar tracking solution should be accurate and economical as for larger applications, multiple units are needed to mount a larger number of concentrators. For higher accuracy, the hybrid tracking algorithm is used in which the movement of the solar tracker is controlled through passive calculations and active feedback. The passive movement is based upon well-defined solar geometry models that define the sun's position at any point on the earth and at any time of the day. However, these models are accurate within a certain error range. Thus, higher accuracy is ensured through active feedback obtained from the solar sensor's feedback, which provides information regarding the sun's current position.

Figure 25 Schematic of a Shadow based Comparative Solar Tracking Sensor

Figure 25 shows a typical shadow based comparative solar tracking sensor, which is used for simple solar tracking applications. The sensor is comprised of four photosensors and a column rod as a shadow element. When the tracker is accurately facing the sun, the solar radiations shine equally on all four photo sensors with the same output. When the sun goes towards the right side of the tracking sensor, the incident solar radiations do not remain parallel to its central axis, and as a result, a shadow appears on the left photosensor, which gives lower output than the right sensor. By analyzing the feedback signal, the tracker's movement is adjusted such that all four sensors provide equal output. Such configuration provides a simple and cost-effective solution; however, it is not suitable for high accuracy tracking application as in solar concentrators. A very tall shadow element

is needed to achieve higher accuracy, which makes this design unsuitable for solar tracking. For 0.1° tracking accuracy, a 2.25m shadow element is required.

Figure 26 shows the only available commercial solar tracking sensor for solar concentrators. In this configuration, a highly accurate position sensitive diode (PSD) is used, which is attached to a pinhole light collimator [56]. When the solar tracker is accurately facing the sun, the collimated light ray falls at the center of the PSD. With the error in solar tracking, the light rays from the pinhole collimator do not remain parallel to its axis, and as a result, it does not fall at the center of the PSD. As per the point of the incident on PSD, the feedback signal is analyzed such that the tracker is moved to bring the collimated light ray back at the center of the PSD. Such kind of solar tracking sensor is not economical for the larger number of units, which can increase the overall cost of the system.

Figure 26 Position Sensitive Diode (PSD) and Pin Hole Light Collimator based Solar Tracking Sensor

Figure 27 CMOS camera and Baader film based Solar Tracking Sensor with Real Sky Images [57]

Figure 27 shows another solar tracking sensor based upon CMOS camera and Baader film [56], which works by capturing the real-time image of the sky. Instead of collimated light, as in the case of PSD based configuration, the CMOS camera captures the sky's image by using Baader film as a ray filter; the Baader film blocks almost 98% of the incoming rays. Therefore, in the sky's image captured by the CMOS camera, the sun appears as the bright spot. When the tracker is accurately facing the sun, the bright spot appears at the CMOS camera's center pixel. When the error appears in the solar tracking, the bright spot deviates from its center position, and the tracker is then adjusted again to bring it back in the center pixel of the CMOS camera. Such configuration provides a wide-angle view, which increases the acceptance angle and error range of the tracker. However, it is not suitable for concentrating assemblies with high accuracy requirements, such as a Cassegrain reflector. Because the accuracy of the sensor depends upon many parameters such as pixel density, camera lenses, quality of image, and light filtration by the film. On the other hand, this configuration is also not suitable for a cost-effective solution for large scale system and the reliability of the CMOS sensor is unknown for the harsh conditions in real field.

Figure 28 Double lens Collimator based Accurate and Economical Solar Tracking Sensor [58]

The most economical form of solar tracking sensor is shown in Figure 28, in which instead of expensive photosensitive material, optical elements are used to achieve high sensitivity in the detection of the deviation in the incident radiations [58, 59]. A double lens based collimator provides concentrated collimated rays that hit in the middle of the photosensor array. As long as the concentrated collimated rays hit in the middle of the photosensor array, the tracker is assumed to be working within acceptable tracking accuracy. The idea of using concentrated light in the sensor is to

eliminate any possibility of non-uniformity in the output of the photosensors. The concentrated rays intensity is higher than the saturated limit of the photosensor. Therefore, the photosensors operate in the binary mode of 0 or 1 (high or low). The moment concentrated collimated rays hit any of the photosensor arrays, a high signal is received, and the tracker position is adjusted to bring it back into the middle of the sensor array to get a low signal from all of the sensors. Like such binary operations, ordinary photosensors can be utilized for highly accurate solar tracking applications. This configuration can provide the most cost-effective solution for tracking solar concentrators in a large scale system with multiple units. However, due to high accuracy and resolution, this sensor provides a low acceptance angle and tracking error range. Therefore, the solar trackers with mechanical drives, which are prone to the high backlash in long term operation, are not suitable to be used with such tracking sensors.

Thus, due to the large scale application of the solar system, the solar tracking system should be cost-effective with high tracking accuracy and error range. Moreover, low-cost manufacturing techniques such as plastic molding should be explored for the fabrication of the solar trackers as a conventional bulky system are not suitable for the simple and economical operation of the daylighting system.

7. Indoor lighting simulation

Radiance is a sophisticated indoor lighting visualization simulation software, which is developed by the lighting research team at the US National Lawrence Berkeley Laboratory (LBL) and has been used in the Architecture Department at the University of California at Berkeley since 1987 [60]. Radiance algorithm is principally based on the Backwards Ray-tracing Technique, which means it trace the light ray in the opposite direction to the direction the ray travels in order to predict the light source from which the light ray is created.

Figure 29 Flowchart of indoor lighting simulation [61]

Figure 29 shows the indoor lighting simulation procedure, which involves three steps of computational modeling, namely CAD modeling, Raytracing simulation, and Radiance simulation. The first step is to design and model an indoor lighting system and an interior space with CAD design software. Detailed mesh structures are required to conduct photorealistic ray tracing in the next step. The second step is to generate IES files by ray-tracing simulation (Tracepro, Photopia, etc.). IES stands for the Illuminating Engineering Society. IES files include detailed information such as luminous intensity and distribution angle to allow for realistic indoor lighting simulation. Once IES files are created, they are imported by Radiance to conduct a photometric analysis of the daylighting system. The photometric results are typically provided with illuminance and luminance images.

Figure 30 Illuminance images of the classroom for different daylighting systems simulation at various solar altitudes: (a) Illuminance distribution for a dish concentrator and a light pipe, (b) Illuminance distribution (plan view of the room) for the different schemes of daylighting [61]

Figure 30 shows the Radiance simulated images of the classroom for different daylighting systems at various solar altitude angles. The isolux curves in the figures help one to compare the effectiveness of the different daylighting systems at various solar altitudes. The distribution angle of the light pipe begins to decrease as the solar altitude angle increase, whereas the dish concentrator with fiber optics generate a constant distribution angle regardless of solar altitude angles. Figure 30 (b) shows the effect of the daylighting system on the dimly lit space of a classroom. Although more light enters through windows as time elapses, the opposite space (wall side) is maintained dimly lit, showing insufficient illuminance levels of 300 ~500 lux on the desk even at noon. The daylighting systems, however, provide sufficient illuminance levels as shown in the figures. It is worthy to note that the solar concentrator system is more suitable for indoor lighting system because it creates constant illuminance distribution regardless of solar altitudes. It can be observed that the daylighting systems also enhance the uniformity of the classroom.

Figure 31 Radiance images of illuminance delivered (a) daylighting by window only, and (b) daylighting by the window, side lighting, and top lighting [62]

Figure 31 shows indoor lighting simulation results for different daylighting schemes, namely daylighting by window only and side lighting and top lighting, which is conducted by Radiance. For the second daylighting scheme, the sunlight is first collected by a primary mirror that tracks the sun inside the Coelostst. The collected sunlight is then reflected by a secondary mirror and delivered through a tunnel that is located at the center of the building. Finally, the sunlight is distributed by either the side lighting method or the top lighting method. It can be observed in Figure 31 (a) that most part of the space is dimly lit except for the area in the vicinity of the windows. When the side lighting and top lighting systems are installed in the space, on the other hand, it can be seen that most of the space is sufficiently illuminated with the level of 450 ~650 lux.

8. Ray tracing simulation

Ray tracing is of technical importance to analyze daylighting systems' optical performance, such as a solar concentrator, a light tube, and fiber optics. The ray-tracing algorithm is basically based on the Monte Carlo method to predict the behavior of light, such as refraction, reflection, and absorption.

TracePro is a ray-tracing simulation software developed by Lambda Research Corporation of Littleton. Under a NASA grant, it is a ray-tracing program for designing and analyzing optical and

illumination systems. It provides GUI (Graphical User Interface) in which 3-dimensional modeling can be drawn by simply entering values [63]

Figure 32 Ray tracing simulation of a concentrator module in Tracepro: (a) The geometrical modelling of a concentrator module, (b) Ray tracing result

Figure 32 (a) shows the 3-dimensional modeling of each component of the solar concentrator module. There is a perfect absorber plate to count the number of rays exiting from the homogenizer. The absorbed rays are then compared to rays generated from the source to compute the efficiency. The ray source can be defined as either a uniform ray or a solar ray. For the uniform ray, each ray is perpendicular to the ray source plane, and each ray has the same intensity while the solar ray has an angular profile that is equal to the real sunlight. The accuracy of ray tracing depends on the number of rays that are generated from the ray source. However, higher accuracy requires large computational resources. As a result of ray racing (see Figure 33 (b)), it can be observed that the primary dish first concentrates all rays generated from the grid source, and then they are reflected by the secondary mirror to enter into the homogenizer.

Figure 34 shows the total irradiance map for the flux absorbed by the absorber at the bottom of the homogenizer. As shown in Figure 34(a), it can be easily observed that the uniform ray is more efficient, generating the total output flux is 69.497 W at the bottom with a collection efficiency of 0.98. The concentration ratios are 614 suns and 456 suns for uniform rays and solar rays, respectively.

Figure 34 Irradiance map for absorbed flux absorbed by absorber at the bottom of the homogenizer:
(a) uniform ray, (b) solar ray

Figure 35 shows two different types of solar concentrators and their performance as tracking error increases. It is observed that the performance is largely affected by the accuracy of the solar tracker. It is also observed that a solar concentrator with a high focal point requires more precise solar tracking with a deviation less than 0.6° whereas the one with a lower focal point requires less precise solar tracking.

Figure 35 Irradiance map for absorbed flux of two different types of concentrator: (a) a paraboloid dish, (b) hyperboloidal reflector [57]

Photopia is a simulation program that is able to predict and analyze the candela distribution curves of luminaires. Photopia algorithm is based on the probabilistic ray-tracing method, which uses optical data such as reflectance and transmittance of luminaire materials. It is also possible to design and simulate the sun and sky model for daylighting simulation. The sun and sky model are generated in Photopia using IESNA RP-21 equations by which the illuminance and luminance from both the sun and sky can be calculated at various altitude angles and various sky conditions such as a sunny sky and a cloudy sky.

Figure 36 The modeling for daylight simulation in Photopia, showing sun and sky components, light tube and illuminance work plane

Figure 36 shows one of the complete modelings in photopia in which there are a light tube with a diameter of 0.6m and a length of 0.5m, a 70° solar model, a clear skydome model with an aperture of 0.6m, and the illuminance work plan of 8m×8m. The distance between the base of the light tube and the illuminance work plane is 2.25m. This means the illuminance work plane is 0.75m above the floor of the reference room, which is a standard value for measuring the illuminance in office buildings.

Figure 37 Design and mesh generation of daylighting systems: (a) dish concentrator (b) light tube
[61]

Figure 37 shows the 3D design and the mesh structures of a dish concentrator and a light tube. Each daylighting system is simplified in Photopia to enhance simulation performance, reducing less important information such as the thickness of the element and the backside of the reflectors. Different color indicates different components and properties, which is pre-defined in Photopia. The dish concentrator consists of a small convex mirror with a diameter of 3 cm (yellow), a primary dish with a diameter (30cm), a homogenizer with a length of 17.5cm(green). At the bottom of the homogenizer, a distributor is placed, either a convex or a concave lens, to distribute the sunlight delivered by the homogenizer.

Figure 38 shows the candela distribution curves of different daylighting systems, namely the dish concentrator system and the light tube at various solar altitude angles. It is observed that the dish concentrator system produces a uniform distribution angle regardless of the solar altitude angle while the distribution curves of the light tube vary with the solar altitude angle. For the dish concentrator, only the intensity of light varies with maintaining the distribution angle, which makes the dish concentrator more feasible for indoor lighting.

Figure 38 Candela distribution curve of the dish concentrator system (left) and the light tube(right) at various solar altitude angles: (a)10°, (b)30°, (c)50°, (d)70°, (e)90°[61]

9. Conclusions

This paper presents a comprehensive review of the solar indoor lighting system integrated with optofluidic liquid prisms. Both theoretical and practical aspects of the system are described in detail, including fundamentals of electrowetting theory, fabrication and operation of liquid prisms, design, and optimization of solar collectors and solar trackers, and major methods for indoor lighting simulation and ray-tracing simulations. Key findings are summarized as follows:

- Electrowetting is the theoretical basis of liquid prisms, a critical device that promotes solar indoor systems' energy efficiency. Understanding the electrowetting phenomenon is essential for optimal design and operation of the liquid prisms to reduce their power input and increase device stability. Improved design and fabrication of the liquid prisms to achieve better beam steering capability while allowing easier scalability is also critical for the practical application of prisms in the solar indoor lighting system.
- The solar radiation collection system is the driving force for the indoor lighting system, and it must have a compact, cost-effective, and efficient design. The efficient solar collector will ensure maximum solar light being delivered to the required space; otherwise, it can be compensated with an increased number of the collector but with a higher total cost. Besides, compact collectors are effective for solar tracking as the bulky unit can cause complexities during extreme wind weather conditions, and compact design can be achieved through

multi-stage reflection or refraction and light guide. Although modern solar trackers can achieve high accuracy, collectors' high acceptance angles can decrease the tracking steps and the system's power consumption.

- Computer simulations for physically based ray tracing and rendering are vital to predict the performances of daylighting systems such as a light guide and fiber optics. Radiance is a validated rendering engine that focuses more on scientific results than the exact same output as measured by a physical optical sensor. Photopia and Trace pro are powerful raytracing simulation tools that can generate accurate light behaviors by tracing every single beam of light traveling through any materials. It was demonstrated that such simulations provide satisfactory and meaningful results to analyze the daylighting system's performance.

Although the solar indoor lighting system integrated with optofluidic liquid prisms has a high potential for efficiency improvement and energy-saving, existing studies have only achieved laboratory testing of prototype components: prisms, solar collectors, solar trackers, and optical fibers. The integrated system itself has not been demonstrated so far, and it will be the focus of the next phase of the study.

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This paper provides an overview of the state-of-the-art investigations over different aspects of the solar indoor lighting system enhanced by optofluidic liquid prisms, including (1) theoretical background, design, fabrication, and operation of liquid prisms, (2) advances in solar collectors and solar trackers, and (3) major tools for indoor lighting simulation and ray-tracing simulation.