Electrowetting Solar Cell

David Reilly
Faculty Mentor: Jianguo Cheng
Department of Mechanical and Energy Engineering

1. Abstract

A solar concentrator was developed using a novel optofluidic system. With two immiscible fluids (water and silicone oil) in a transparent cell of aperture size 10mm x 10mm, we can actively control the contact angle along the fluid-fluid-solid tri-junction line and hence the orientation of the fluid-fluid interface via electrowetting. With 1 wt% KCl and 1 wt% SDS (Sodium Dodecyl Sulfate) added into DI water, the orientation of the water-silicone oil interface can be successfully modulated between 0° and 26°, deflecting sunlight within the incidence angle of 0°-15°. Without any mechanical moving parts, this dynamic liquid prism allows the device to adaptively track both the daily and seasonal changes of the Sun’s orbit, i.e., dual-axis tracking. This invention reduces capital costs for concentrating photovoltaics (CPV) and increases operational efficiency by eliminating the power consumption of mechanical tracking. Most importantly, the elimination of bulky tracking hardware and quiet operation will allow extensive residential deployment of concentrated solar power.

In comparison with traditional silicon-based PV solar cells, the electrowetting-based self-tracking technology will generate ~70% more green energy with a 50% cost reduction. The success of this program has huge market impacts and will enable a paradigm shift in the role of concentrating photovoltaics in the U.S. energy market.

2. Background

The electrowetting-on-dielectric (EWOD) principle, first discovered by G. Lippman in 1875 (Smith, 2009), is the basis of an approach to solar concentration which could significantly impact renewable energy use in the U.S. An integrated solar concentrator and dual-axis tracker can be constructed from an optofluidic beam deflector for unpolarized light in combination with a fixed optical condenser (Fresnel lens). The beam deflector consists of liquid prism arrays whose orientations can be varied via EWOD by applying a DC or AC electrical field. The applied electrical field modifies the orientation of the individual prisms in order to keep direction of the deflected beam fixed as the incident beam shifts. When the liquid beam deflector is used with the fixed concentrator, the position of the focus remains fixed on a CPV cell as the Sun moves. The main innovation is the ability to track the sun without large, heavy mechanical moving structures. This R&D project demonstrates the feasibility of the EWOD technology for solar concentration.

The Electrowetting-on-Dielectric Mechanism

As a surface-tension-control technique, EWOD has become a promising method for manipulating liquids on a surface. The EWOD effect is the change in contact angle between an electrolyte and a solid surface as a result of an applied potential difference between them (Fig. 1). The contact angle change of a liquid by EWOD is described by Lippman-Young’s

Figure 1. Electrowetting-controlled fluid-fluid interface.
equation: \( \cos \theta = \cos \theta_r + \frac{\varepsilon \varepsilon_0 V^2}{2 \gamma} \) where \( \theta \)

is the contact angle at electric potential \( V \), \( \theta_r \) is the contact angle with no electric

potential, \( \gamma \) the liquid-liquid interfacial tension, \( \varepsilon_0 \) the permittivity of vacuum, \( \varepsilon \)

dielectric constant of the insulator layer

and \( d \) the thickness of the dielectric insulation layer. For example, electrowetting in one of our studies produced a saline contact angle change of \( 35^\circ < \theta < 170^\circ \) (Fig. 2). Changes in the contact angle can give rise to continuous variations of the fluid-fluid interface curvature and shape. Therefore, the meniscus interface can function as a liquid prism (light deflector) or as a tunable optical lens. The concepts of the EWOD-based liquid prism deflector are discussed below and illustrate the mechanism of morphing fluid-fluid interfaces for solar concentration purposes.

3. Hypotheses

Our plan to manufacture EWOD cells is shown in Fig. 3. We will evaporate a thin layer of transparent electrode (ITO) onto the sidewalls of glass cuvettes of square cross section (10 mm x 10 mm) and cover the electrode with a layer of dielectric insulator. The top and bottom surfaces

will be coated to be anti-reflective. Then we will fill the cell with two fluids (e.g., water and a nonpolar oil). By applying different voltages to each wall, we can modify the wettability of the walls and change the orientation of the fluid-fluid interface.

Figure 4 shows a liquid electro-optical prism formed in the EWOD cell by tilting the interface via electrowetting. For a liquid prism, gravity-induced deformation and stability are a concern, especially at tilted orientations (Cheng & Chen, 2011). We can overcome the deformation by synthesizing two fluids of equal density but with differing refractive indices. Thus, the prism can be maintained independent of its orientation and will be rather insensitive to external vibration and shock. A liquid prism usually ranges in cross section from 0.5 cm x 0.5 cm to 2 cm x 2 cm. But with higher stability, the prism diameter can be even larger (perhaps to 4 cm x 4 cm).
Since the two fluids have different refractive indices, sunlight passing through the EWOD cell will be deflected in a specific direction controlled by the applied voltages. It can be seen in Fig. 4 that the sunlight is collimated without the need for additional focus operations. We can arrange an array of electro-optical cells on a large panel to form a beam steering sheet. Two or more beam steering sheets can be stacked to achieve a large steering angle (>30°). The steered beam will be concentrated on a relatively small CPV cell (several mm) with a commercial concentrator. The solar panel will use a non-reflective-coated optical acrylic Fresnel lens to capture the steered light from an area >1000 times that of the CPV cell and focus it onto a triple junction CPV cell. Each hexagon-shaped Fresnel lens (segment) is about 5.5 inches (13.9 cm) long on each side with the solar cell located about 7.9 inches (200 mm) beneath the lens. Each segment is identical, so there is no scaling of this component required between various configurations. The device can track the sun by simply changing the steering direction of each electro-optical prism without any mechanical moving parts.

4. Methodology
We followed several steps in the fabrication of the glass cuvette. First, we used a diamond-tipped glass cutter to dice the indium tin oxide (ITO) glass into four pieces of 10 mm × 20 mm each. These ITO slides work as the module sidewalls. Next, four copper wires were silver epoxied (TRA-DUCT 2902) to the ITO glass sidewalls. Silver epoxy was chosen to ensure electrical conductance for the control input between the copper wire and the ITO glass. With all the wires secured, UV epoxy (Norland Electronic Adhesive 123) was applied to assemble the glass sheets into an open channel as shown in Fig. 5. The open channel was cleaned with acetone to remove any residue left from the adhesion process. An ohmmeter demonstrated that the four side walls were isolated (i.e., infinite resistance). Subsequently, 1.7-μm-thick paralayne C (εr = 2.8) was conformally coated on the channel surface. The open channel was dip coated with a fluoropolymer (PFC1601V, Cytonix Corporation) and baked at 145 °C for five hours. During the baking process, the rate of temperature increase did not exceed 1 °C/min in order to preserve the dielectric layer. The coated channel was attached to an ITO glass substrate using UV epoxy to form a transparent cuvette. Finally, the cuvette was sealed by attaching another glass slide on the top.

**Figure 4.** An electro-optical prism formed in a cube via EWOD.

**Figure 5.** Open channel
5. Conclusions

Driven by square-wave AC voltages, the liquid prism module is capable of fulfilling continuous modulation and achieving numerous switching cycles. Through the application of Snell’s law, we can accurately predict the path of the deflected beam as it travels to a Fresnel lens with a concentrating photovoltaic (CPV) at its focus. Therefore, this liquid prism can work as an electrowetting solar cell for solar tracking. Without any mechanical moving parts, this dynamic liquid prism allows the device to adaptively track both the daily and seasonal changes of the Sun’s orbit, i.e., dual-axis tracking. This approach can potentially reduce capital costs for CPV and increases operational efficiency by eliminating the power consumption of mechanical tracking.

6. References