

Enhancement of photovoltaic cell response due to high-refractive-index encapsulants

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This study compares the electrical output of photovoltaic (PV) cells encapsulated with silicones having different refractive indices to unencapsulated PV cells. It is demonstrated that the optical concentration ratio of dome-shaped concentrator PV systems can be increased by using a higher refractive-index encapsulant. The short-circuit photocurrent of the PV cell having high-refractive-index encapsulation ($n=1.57$) is 71% higher than that of the PV cell having a low-refractive-index encapsulation ($n=1.41$), and 316% higher than that of the unencapsulated PV cell. These experimental concentration-ratio enhancements are consistent with the theoretical estimates of concentration ratio dependence on the refractive index of the PV concentrator. © 2010 American Institute of Physics. [doi:10.1063/1.3466980]

Photovoltaic (PV) technologies that convert sunlight directly into electricity hold great promise as a sustainable, environmentally friendly energy source for the 21st century.^{1,2} In particular, concentrator PV (CPV) technologies promise to achieve widespread deployment in renewable energy systems by combining high performance with low costs.³ By trading expensive PV semiconductor materials for cheaper plastic lenses and/or metal mirrors, CPV systems can in principle improve performance and reduce overall PV module costs. While a variety of different approaches to CPV design are being pursued, all CPV systems suffer from a fundamental trade-off between field-of-view and concentration ratio.^{4–8} Moreover, thermodynamic limits dictate that the maximum concentration ratio depends upon the half-acceptance angle ($\pm\theta_a$) and the refractive index (n) of the concentrator material that encapsulates the PV cell. That is, the maximum geometric concentration (C_{\max}) is given by⁵

$$C_{\max} = \frac{n^2}{\sin^2 \theta_a}. \quad (1)$$

Obviously, the refractive index of the concentrator material is of great importance to increase the maximum concentration ratio. In Fig. 1, the theoretical maximum concentration ratio, calculated from Eq. (1), is shown as a function of the refractive index of the concentrator material for half-acceptance angles of 45°, 60°, and 90°. The figure clearly shows that the concentration ratio increases not only as the half-acceptance angle decreases, but also as the refractive index of the concentrator material increases. Since the concentration follows an n^2 -dependency, the concentration ratio can increase four times when the refractive index of the concentrator material changes from 1 to 2. Therefore, the use of

a high-refractive-index material in a CPV system will enable increased concentration ratios while maintaining a wide field-of-view. In this work, we propose and demonstrate an improved CPV system by encapsulating the PV cells with transparent, high-refractive-index silicones. In order to investigate the effect of the refractive index of the encapsulant on the concentration ratio, we have fabricated CPV systems with several encapsulant materials having different refractive indices; we compare the performance of the encapsulated PV cells to the unencapsulated PV cell. The photocurrent is measured for the encapsulated and unencapsulated PV cells under different angles of illumination.

Figure 2 shows a schematic drawing of the CPV system employed in this work. To focus light onto the PV cell, it is encapsulated with materials having different refractive indices. Our PV cell is located in an encapsulant that is shaped into a dome-like lens. The dome is an approximate hemisphere with a radius of 2.5 mm. Light enters the dome and is

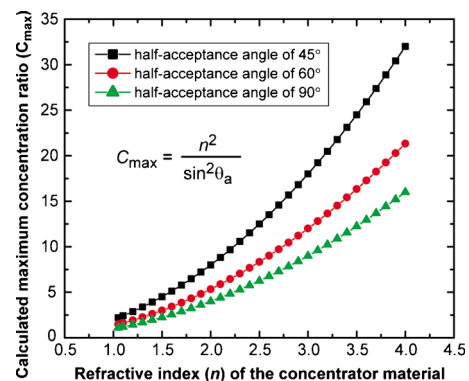


FIG. 1. (Color online) Theoretical maximum of concentration ratio as a function of the refractive index for CPV systems having half acceptance angles (θ_a) of 45°, 60°, and 90°.

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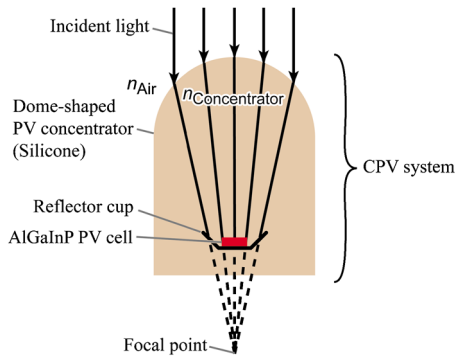


FIG. 2. (Color online) Schematic diagram of a simple CPV system consisting of a PV cell and a dome-shaped PV concentrator.

refracted toward the PV cell. According to Snell's law, a PV concentrator encapsulated with a higher refractive index will focus the object (the sun) onto a smaller area. (In this case, the concentration ratio is equal to the aperture area divided by the image area.) Thus, when a higher refractive-index material is used as the PV concentrator, more light is concentrated onto the PV cell, which means a higher concentration ratio. Another characteristic of our PV concentrator is that the dome acts as a variable entrance aperture in that different portions of the encapsulant surface are used at different incident angles.

To verify the effect of the refractive index of the concentrator material, we fabricated PV concentrators by using an encapsulation process that is known in light-emitting diode lamp fabrication. PV cells used in our experiments have an AlGaInP active region that absorbs wavelengths shorter than 615 nm; the AlGaInP chip area is $0.6 \times 0.6 \text{ mm}^2$. After the AlGaInP chip was die-bonded to an Al-coated lead frame, the PV chips were encapsulated with silicones having two different refractive indices ($n=1.41$ and 1.57) using a 5-mm-round-top molding cup. Both of the silicones are specified by the manufacturer to have a transparency higher than 99% at wavelengths ranging from 500 to 800 nm. In addition, we fabricated an unencapsulated PV cell (without an encapsulant material). A solar simulator (350~2500 nm) with a Xenon-discharge lamp is incident upon the concentrators via a liquid waveguide and a lens system for collimation. Measurements are taken under collimated illumination incident at angles ranging from 0° to 90° while keeping the position of the CPV systems fixed (no tracking). Heating of a PV cell due to solar radiation is very common for PV cells. PV cells in CPV systems, due to the optical concentrator, may be subject to additional heating. Although we did not measure the temperature of our cells during measurements, the light source for each measurement remained at the same intensity. Thus the comparison among different samples of our series should not be strongly influenced by the temperature. The samples are characterized under a variable bias voltage between -1.4 to 1.7 V , including 0 V (short circuit).

Figure 3 shows the photocurrents as a function of bias voltage for the PV cells with encapsulant materials of different refractive indices as well as the unencapsulated PV cell. The inset of Fig. 3 shows photographs of the three fabricated CPV systems with two molded lenses and one unencapsu-

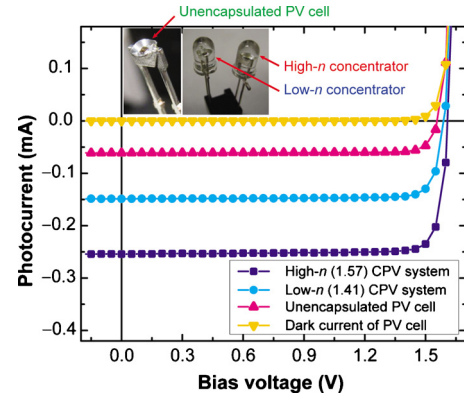


FIG. 3. (Color online) Measured photocurrent as a function of bias voltage for PV cells encapsulated with high (1.57) and low (1.41) refractive-index materials as well as the unencapsulated PV cell. The inset shows photographs of the three fabricated CPV systems with two molded lenses and one unencapsulated cell.

lated cell. The measurements shown in Fig. 3 are taken under normal-incidence illumination. At first, we confirmed that the measured dark currents of all fabricated PV cells are very low and limited by the measurement-instrument resolution (less than 0.1 nA); one example of the dark-current-versus-voltage curve is shown in Fig. 3 (orange line). The curve shows that the photocurrent of the PV cell using the high-refractive-index encapsulant ($n=1.57$) is higher than the PV cell using the low-refractive-index encapsulant ($n=1.41$) as well as the unencapsulated PV cell. The short-circuit photocurrent of the PV cell using the high-refractive-index encapsulant ($n=1.57$) is 0.254 mA , which is 71% larger than that of the PV cell with low-refractive-index encapsulant ($n=1.41$), which is 0.149 mA . The difference of the short-circuit photocurrent becomes even larger when comparing the PV cell with high-refractive-index encapsulant ($n=1.57$) with the unencapsulated PV cell, where the former has a photocurrent that is 316% larger than the latter (the short-circuit photocurrent of the unencapsulated PV cell is 0.0611 mA). Note that this measurement results show a clear trend, consistent with the theoretical estimation of the maximum geometric concentration ratio.

The total photocurrent consists of two components: a dark diode-like component which depends on the bias voltage and a light generated component which depends on the flux density.⁹ Since the total photocurrent is a function of the bias voltage and the flux density is a function of the concentration ratio, there is a mathematical relationship between the total photocurrent, as well as the open-circuit voltage, and the concentration ratio. To extract the concentration ratios of our three CPV systems experimentally, we use the relationship between the open-circuit voltage and the concentration ratio of the concentrator, which is given by¹⁰

$$V_{oc,C} = V_{oc,1} + m \frac{kT}{e} \ln C, \quad (2)$$

where $V_{oc,C}$ and $V_{oc,1}$ are the open-circuit voltages at a concentration ratio of C and 1, respectively, and m is the ideality factor of the diode. In our experiment, the measured m is 1.31 and the open-circuit voltages of the PV cells having a

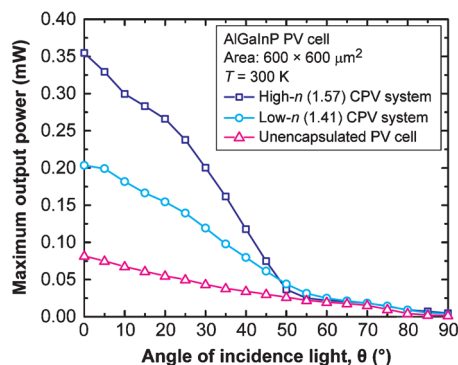


FIG. 4. (Color online) Measured maximum output power as a function of the light incident angle for the CPV systems encapsulated with high-refractive-index material, low-refractive-index material, as well as not encapsulated.

high-refractive-index encapsulant, low-refractive-index encapsulant, and no encapsulant are 1.608 V, 1.588 V, and 1.556 V, respectively. Using that the concentration ratio of the unencapsulated CPV system is 1 and all of our PV cells are working at low-injection conditions (based on their relatively low photocurrents), then the deduced concentration ratio of the CPV systems encapsulated with the low-refractive-index silicone and high-refractive-index silicone are 2.56 and 4.60, respectively. A significant enhancement of the concentration ratio can be seen from the above calculation, which gives values larger than the simple n^2 -dependency [see Eq. (1)]. As previously mentioned, our CPV systems, except for the unencapsulated CPV system, have a dome which can make a variable entrance angle along the perimeter of the dome. Therefore, unlike the unencapsulated CPV system, the concentration ratio of the dome-shaped concentrators can be beneficial not only in terms of the increase in the refractive index but also in terms of the variable entrance angles along the surface of the dome.

Figure 4 shows the maximum output power as a function of the light incident angle for the CPV systems encapsulated with a high-refractive-index material, low-refractive-index material, as well as unencapsulated. The figure shows that the output power decreases with increasing incidence angle. This could be explained by the fact that the optical flux that reaches the cell is maximum at normal incidence, and decreases with increasing incident angle; this is because the position of the incident light is no longer in alignment with the center of the dome. The output power of the CPV system with high-refractive-index encapsulant is larger than that of the CPV system with low-refractive-index encapsulant as well as the unencapsulated CPV system for incident angles between 0° and 45° . For example, at normal incidence, the

maximum output power of the CPV system with high-refractive-index encapsulant is 0.354 mW, which is 74.4% larger than that of the CPV system with low-refractive-index encapsulant, which is 0.203 mW. If compared with the output power of the unencapsulated CPV system, 0.0817 mW, it shows an increase of 333%. As incident angle increases, the difference in output power of CPV system due to different encapsulant is reduced. At a range from 45° to 90° , the differences among the CPV systems are negligible, which results from the very small light flux incident on the PV cells at these high angles.

In summary, AlGaInP CPV systems encapsulated with silicones having different refractive indices ($n=1.57$ and 1.41) and unencapsulated CPV system are fabricated. Based on the photocurrent measured under different incident angles, the concentration ratios are extracted and compared to calculated concentration ratios. The CPV system encapsulated with a higher-refractive-index material has a higher photocurrent and higher output power than the CPV system encapsulated with a lower-refractive-index material as well as the unencapsulated CPV system. When encapsulating the AlGaInP PV cell with a high-refractive-index ($n=1.57$) encapsulant, the output power increases by 333%. This demonstrates that the use of high-refractive-index material in a CPV system enables increased concentration ratios, resulting in efficiency improvements of the CPV system and reduction in manufacturing costs.

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