IMPACT OF STRUCTURED GLASS ON LIGHT TRANSMISSION, TEMPERATURE AND POWER OF PV MODULES

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ABSTRACT: PV modules were fabricated using structured glass and investigated for the effect on light transmission and module temperature. Four different types of commercially available structured glass were investigated: grooves, pyramids, inverted pyramids and a very light structured type with only 5% increased surface area, along with flat glass modules for experimental control purposes. Measurements of light transmission were collected as a function of angle of incidence using an AM 1.5 G pulsed solar simulator. Results show an increase in I_{sc} of up to 3.2% for pyramid structures with normally incident light, and the gain increases at higher angles of incidence. Wind tunnel testing was used to evaluate the effect of structured glass on module temperature. It was found that the surface structure has a significant cooling effect, increasingly pronounced at higher wind speed. In an outdoor environment, there were observed to be competing influences on module temperature: at low wind speed and high irradiance the increased light transmission associated with structured glass serves to increase module temperature, whereas at higher wind speeds, the increased convective module cooling serves to decrease the module temperature. Both the decreased temperature and increased light transmission will serve to increase the power output of the textured glass modules.

Introduction and Theoretical Background

Glass with a flat outer surface is most commonly used in PV modules. Structured glass has been developed as an alternative that can potentially improve module performance in two ways. First, light management in the module can be improved, leading to an increase in I_{sc}. Second, the structured glass can enhance cooling to maintain a lower module operating temperature and a higher V_{oc}.

Approximately 4% of normally incident sunlight is reflected off the surface of a flat glass module and lost for power conversion due to Fresnel reflection. The fraction of sunlight that is reflected by flat glass increases as the angle of incidence increases, as shown in Figure 1. The angle of incidence is an important parameter for fixed solar installations, where the sunlight incidence angle changes throughout the day as the sun moves across the sky.[1] Structured glass can trap more light by redirecting the reflected rays at the front surface and giving them a second chance to enter the glass and reach the cell (Figure 2). Additionally, the structures can recapture more light that would otherwise escape due to reflections within the module.[2]

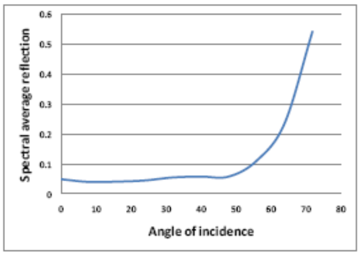

Figure 1: Effect of angle of incidence on spectral reflection.

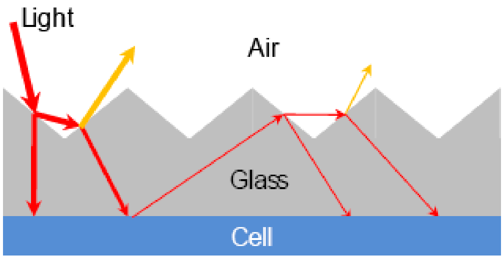

Figure 2: Interaction of light at the air-glass interface for structured glass.

Module power output decreases as the module's temperature increases. In the case of many crystalline silicon modules, the power loss is equivalent to 0.5% / K. The thermal resistance of the air-glass interface at the front surface of the cell is known to limit module cooling.[2] Structured glass is of potential interest as a technology that may enable a decrease in module temperature, and hence an increase in module power output, via increased surface area at the air-glass interface.

In an outdoor operating environment, module performance is significantly impacted by varying environmental factors such as ambient temperature, irradiance, and wind speed,[3] in conjunction with the design of the module itself. Light transmission and convective cooling properties of the modules are expected to be most important at high irradiance and high wind speed, respectively.

We investigated the light trapping and temperature reduction effects of structured glass modules through solar simulator, wind tunnel and outdoor exposure experiments.

1 Light transmission

Prior to lamination into mini-modules, the power output of several crystalline silicon solar cells was measured using an AM1.5G cell solar simulator. Commercially available glass with four different structures (Figure 3) was used to build mini modules (Figure 4). Control modules with a flat glass surface were also fabricated. The I-V curves of the mini modules were measured using an AM1.5G pulsed solar simulator (Figure 5). The electrical characteristics were measured as a function of angle of incidence between 0º (normally incident) and 80º (highly oblique incidence).

Figure 3: Textured glass surfaces used in study

Figure 4: Pyramid glass one cell module

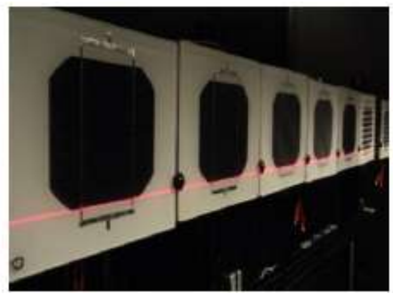

Figure 5: Modules on in solar simulator dark tunnel

Light Transmission Results

Comparison of I_{sc} from the modules clearly demonstrates that the structured glass surfaces transmit more light to the cells than glass with a flat surface. With normally incident light (Figure 6), the greatest improvement was seen for the pyramid structures, which showed an I_{sc} increase of 3.2% relative to the flat glass control. As the angle of incidence is increased further, the percent improvement of I_{sc} for the structured surfaces becomes more pronounced with the greatest percent increase in I_{sc} observed for the grooved surface structure at highly oblique angles (Figure 7). More modest increases in I_{sc} are observed for the lightly textured glass.

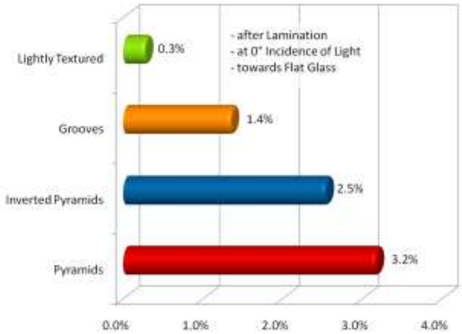

Figure 6: Percentage increase in I_{sc} for normally incident light.

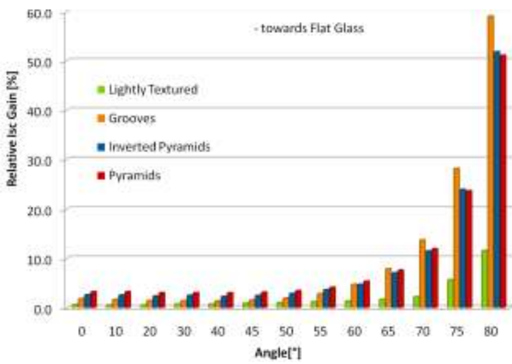

Figure 7: Effect of textured glass on I_{sc} as a function of angle of incidence

Figure 8: Set-up in wind tunnel

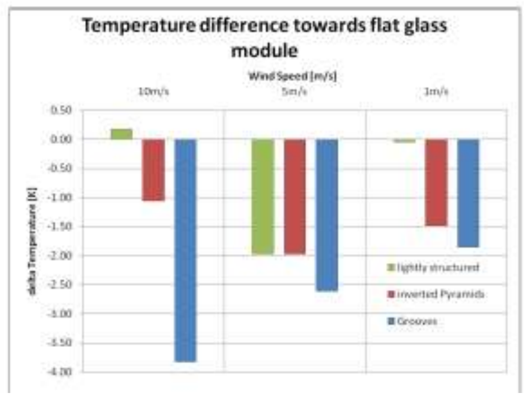

Figure 9: Effect of wind speed on module temperature

2 Wind Tunnel

To study the impact of structured glass on module temperature, 550 mm x 550 mm modules were fabricated with Kapton heater foils instead of cells. The modules were mounted individually inside a wind tunnel sequentially in time. They were heated by supplying a constant electrical power. The wind tunnel was used to supply a laminar flow of air at wind speeds of 1 to 10 m/s and tilt angle of 45º (Figure 8). The temperature of these modules was measured using thermocouples on the module interior and exterior. Module temperature uniformity was assessed using a thermal imaging camera.

Wind Tunnel Results

The results (Figure 9) demonstrate that the structured glass has a significant cooling effect on PV modules. The greatest cooling is observed for the grooved structured module at high wind speed: 3.5^{o}C at wind speeds of 10 m/s.

3 Outdoor Tests

Mini-modules, with a 3x3 arrangement of 6” cells, were fabricated at Fraunhofer CSE and then mounted for outdoor testing at the National Renewable Energy Laboratory (NREL). The outdoor experiments included modules with flat glass (reference), grooved glass, pyramidal textured glass, and lightly textured glass. All these modules were fabricated with TPE backsheet, and EVA encapsulant, using the same lamination process. Thermocouples to monitor module temperature were laminated between layers of encapsulant in the gap between cells. The experimental runs took place over several weeks in the summers of 2009 and 2010 and collected data on ambient temperature, irradiance, wind speed, wind direction, and the temperature, I_{sc} and V_{oc} of each module.

Outdoor Test Results

Figures 10 and 11 show the difference in I_{sc} and V_{oc} for structured modules relative to a flat glass control module for days on which there were mostly clear skies and consistent wind speeds. Module V_{oc} was found to be 50 – 80 mV higher for the grooved and pyramid structured glass modules compared to the flat glass reference module. The lightly textured glass module has a V_{oc} that is 10 mV higher than the reference module throughout the bulk of the day. Corresponding wind speeds ranged from 5 - 10 m/s, as shown in Figure 12 (day 142).

The data for the effect of structured glass on I_{sc} showed an I_{sc} increase of 3.5 % for grooved and pyramid structured glass during the middle of the day, with improvements above 40 % in the early morning and evening when the sun is at a higher incidence angle. Lightly textured glass showed an improvement of 2 % in I_{sc} during the middle of the day, with a more modest dependence on time of day, consistent with the angle-resolved results indoor tests on the solar simulator, reported in Part I.

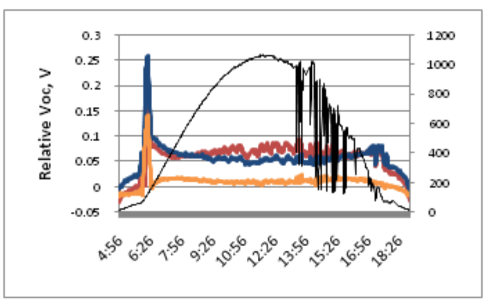

Figure 10: Difference in V_{oc} between structured glass and reference module: Grooves (red), pyramids (blue), and lightly textured (orange). Irradiance (black, W/m^2) is also shown. Sharp peaks near 6:00 AM are due to discontinuous measurements recorded by the DAQ system. Data is from May 22, 2010.

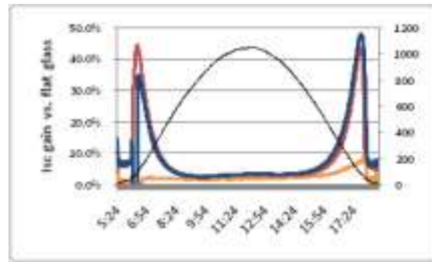

Figure 11: Gain in I_{sc} of structured glass modules relative to reference module: Grooves (red), pyramids (blue), and lightly textured (orange). Irradiance (black, W/m^2) is also shown. Sharp peaks near 7:00 AM are due to discontinuous measurements recorded by the DAQ system. Data is from August 13, 2010.

Outdoor Test Results: Module Temperature

A six-day interval, May 20 – 25 2010 was selected for mostly clear skies and moderate wind speeds. Figure 12 shows the irradiance and wind speed data during this interval. Both irradiance and wind speed were analyzed and found to have a significant impact on module temperature, with the magnitude of the effects depending on the type of structured glass used.

Module temperatures as a function of wind speed and irradiance are shown in Figures 13 – 14. Wind speed data bins are 1 m/s wide and labeled with the lower limit of the bin, (i.e., bin 0 includes data for wind speeds ranging from 0 – 1 m/s). Representative irradiance values are shown by selecting data with irradiance values of 500 – 600 W/m^2, 800 – 900 W/m^2, and 1100 – 1200 W/m^2. The module temperatures relative to ambient temperature (Figure 13) are shown alongside the temperature differences between structured and reference modules (Figure 14).

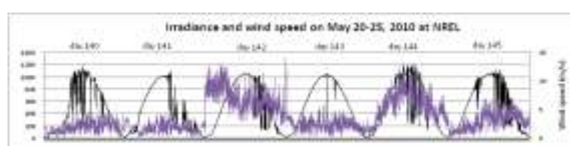

Figure 12: Irradiance (black) and wind speed (purple) on days 140-145 at the module outdoor testing location at NREL. Data shown here are collected only during the day, i.e. when irradiance > 0. Wind speeds of up to 13 m/s occurred during this period.

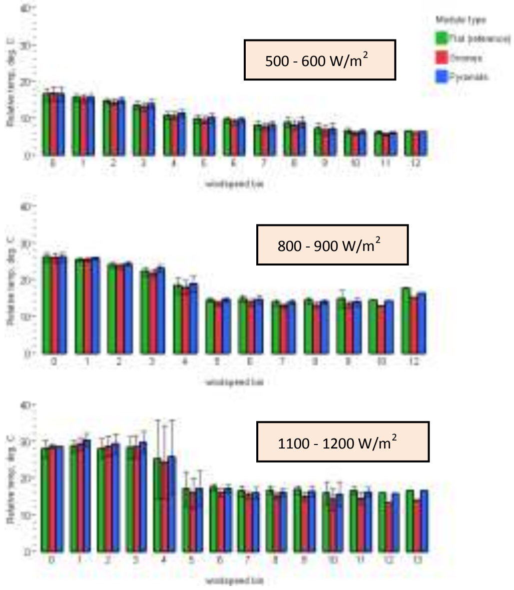

Figure 13: Module temperatures, relative to ambient temperature, vs. wind speed bin (m/s), for three levels of irradiance.

Several effects are observed in the data. As expected, the effect of irradiance was found to be particularly important for all modules tested, with temperatures increasing with increasing irradiance. The cooling effect of the wind was also observed on all modules with the modules becoming cooler as the wind speed increased. These first two effects, irradiance and wind speed were found to have greater influence on module temperature than glass texture, but the effect of glass temperature was still found to be significant.

When the wind speed is below 3 m/s, the structured glass modules become warmer relative to the reference module, particularly at higher irradiance. This effect is ascribed to increased light absorption in the structured glass modules, as observed in Part I. However, as wind speed increases, the structured glass modules become cooler relative to the reference module. This effect is ascribed to the improved convective cooling of the structured glass front surface, which decreases the thermal resistance of the air-glass interface by increasing surface area. The cooling enhancement at high wind speeds is most apparent in the high irradiance data, where up to a 2.5 ^{o}C temperature difference is seen at winds of 12 m/s for the grooved glass module.

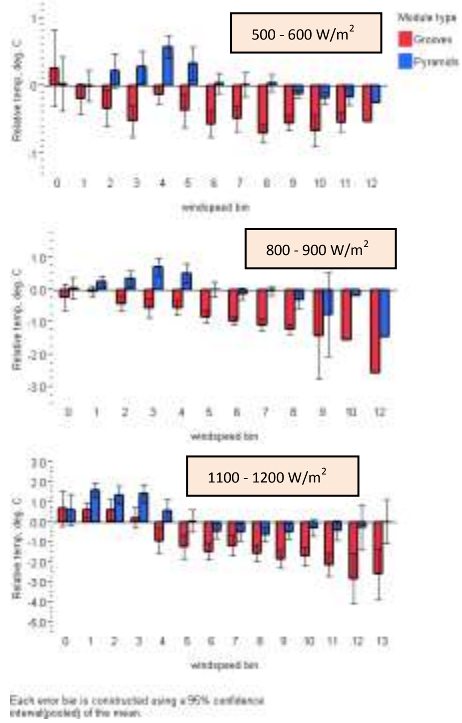

Figure 14: Difference between structured glass module and reference module temperatures, vs. wind speed bin (m/s), for three levels of irradiance.

Conclusion

Studies were undertaken to investigate the effect of module glass texture on light transmission and module temperature. Structured glass was shown to enhance I_{sc} by up to 3% at normal incidence, with the effect being considerably more significant at higher angles of incidence. This observation is consistent with less light being reflected from the air-glass interface, and more light that is reflected from within the module being totally internally reflected back onto the cells.

Structured glass was found to have a significant cooling effect on PV modules. Tests conducted in a wind tunnel showed that structured glass modules operate at lower temperature than flat glass modules with the greatest effect seen at high wind speed. At a wind speed of 10 m/s, a module fabricated with grooved glass was found to be 3.5^{o}C cooler than flat glass.

Module temperature was also measured in the outdoors. It was found that at low wind speed the temperature of structured glass modules was slightly higher than that of flat glass modules. This effect is attributed to increased light transmission to the cells. Interestingly, as the wind speed increased, the structured glass modules were observed to be progressively cooler than the flat glass modules; an effect attributed to increased convective cooling of the structured glass.

Future work on this project may include the development of a model to incorporate the competing effects of enhanced light capture and decrease thermal resistance on module temperature, the systematic comparison of all measured glass structures, and an estimation of the energy yield improvement that can be expected by replacing flat with structured glass in a solar module.

References

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