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Scattering-Based Solar Concentrator

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Scattering-based solar concentrator

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Scattering-based solar concentrator

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This work shows a laboratory based demonstration that elastic scattering from a layer of wavelength-sized particles can be used to concentrate sunlight for use in photovoltaic power production. The concentrator design consists of a layer of particles dispersed across a mirrored glass plate. Photovoltaic cells line the edges of the plate, which receive light that is coupled into the plate via scattering by the particles and confined thereafter by total internal reflection. All materials used to construct the concentrator are low-cost off-the-shelf items typically available at hardware stores. The net power produced is compared to a single, bare cell that is directly illuminated by the same light source. This comparison shows a promising trend in terms of overall concentrator size that may eventually yield a concentrator capable of producing more power than that produced by the same amount of cell material under direct illumination.

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I am very thankful to my advisor dr. Matthew Berg. He gave fabulous ideas about my research from the beginning, the theory of the whole experiment, until the end while I am writing my thesis. His dedication to physics career influence me a lot too. I learned that a lot effort and passion should be put into my physics career so to know the world better and make life joyful. I also learned from him, as well as other group members, that physical theories are important for not only theoretical research but also experimental physics. Knowing physical theories will help to inspire new opportunities and help with trouble shooting during experiments.

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CHAPTER I

INTRODUCTION

In the ongoing effort to advance the viability of solar power, two broad technical challenges can be identified: raising the conversion efficiency of solar to electrical energy and improving the collection and delivery of sunlight to a photovoltaic (PV) cell. The former challenge involves the physical properties of semiconductor materials and has been the focus of much research effort. Indeed, this attention is well justified as the expense and manufacturing-related environmental impact of solar power rests largely on the semiconductor materials involved [1, 2]. However, there is also promise in the latter objective, i.e., the collection and delivery of sunlight to a cell. This light manipulation has been accomplished with concentrator photovoltaic (CPV), which typically involves reflective and/or refractive focusing of a large area of incident sunlight onto a smaller area containing the cell [3]. Thus, CPV have the potential to advance solar power viability by requiring less cell material for the same power yield.

While most common, sunlight concentration via geometrical-optics based approaches, e.g., lenses, mirrors, and prisms is not the only possibility. An often overlooked option is scattering, which alters light propagation through interference effects, i.e. scattering, caused by small wavelength-sized particulate matter. In fact, the effects of reflection and refraction themselves can be described as large-scale manifestations of many complex scattering events, which is the basis for physical optics

[5]. Scattering offers intriguing possibilities to control light that are not seen in geometrical optics. The research reported here explores an initial effort to investigate the possibility of sunlight concentration based on scattering from micrometer-sized dielectric particles. Specifically, we will show how scattering from small particles can be used to couple sunlight into a planar waveguide, where it is then routed to PV cells. We call this concept particle-assisted CPV. Our study will systematically examine the manner in which microparticles on a planar substrate concentrate light using a series of controlled laboratory-experiments.

CHAPTER II

CONCENTRATOR CONCEPT

The main idea behind particle-assisted CPV relates to a general behavior of light scattering from wavelength-sized, and larger, particles. If the ratio of nominal particle-size R to wavelength λ is sufficiently large, the intensity of light scattered around the forward direction ($\theta = 0$) can be orders of magnitude stronger than that scattered into the side and backward directions. This behavior persist for a range of particle sizes in the so-called resonance region, i.e., where $R \approx \lambda$ ranging up to several λ in size. Now suppose that such a particle were placed on a glass plate and the arrangement illuminated along the normal direction. The preferential scattering of light around the forward direction means that a portion of that light would propagate into the plate at an angle exceeding the plate's critical angle θ_c, i.e., $\theta > \theta_c$ .Such light is then trapped in the plate via Total Internal Reflection (TIR) until it is either re-scattered out of the plate, e.g., by surface imperfections or other particles, or until it eventually reaches the plate edges.

Figure (1) shows how this enhanced forward-scattering can be used to concentrate sunlight. First consider a simple, planar mirror illuminated by sunlight along the normal direction as shown on the left in Fig. (1). Clearly, this light will simply be reflected back by the mirror. Photovoltaic (PV) cells lining the mirror's edges would receive only a small fraction of the incident light, which would largely originate from scattering from imperfections within the glass plate. However, if the mirror is coated with a layer of wavelength-sized particles, scattering beyond the critical angle will result in a much larger portion of the incident light being redirected via TIR to the PV cells, see Fig. (1) right. Because the area of light incident on the mirror is larger than that of the edges (cells), there will be an increase in intensity of the light reaching the cells as compared to direct illumination of the cells. Thus, scattering by the particle layer is able to concentrate the incident sunlight by coupling that light into a "trapped mode" of the plate.

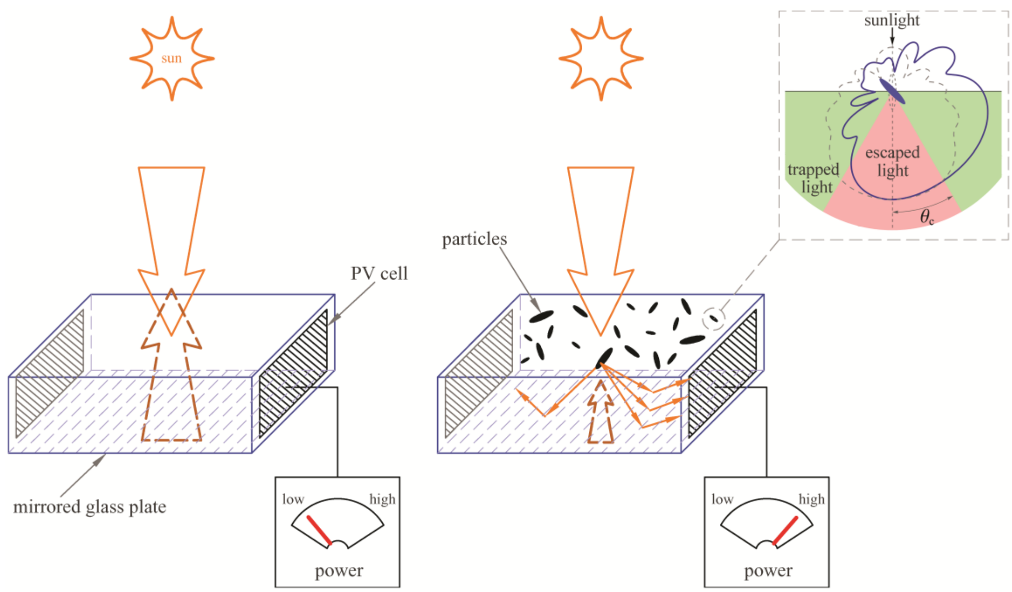

Figure 1 Concept for particle-assisted CPV.

The illustration on the left shows the illumination geometry of a "bare concentrator," i.e., a mirror lined with PV cells and no particles on the top (glass) surface. Incident sunlight is mainly retro-reflected, yielding little power from the PV cells. Application of the particle layer (right) results in the scattering of a portion of this incident light, which is then partially confined within the glass plate. The result is a concentrated illumination of the cells lining the plate edge and a much enhanced power yield.

There is more detail to this process, however. Light scattered along, and very close to, the forward direction does not become trapped by TIR since $\theta < \theta_c$. This is why a reflective backing, i.e., a mirror is used; reflection of this light provides another opportunity for light to interact with the particle layer and increase the change that higher-order scattering events eventually lead to further light trapping. Nevertheless, this retro-reflected near-forward scattering is largely a loss mechanism for the concentration process. Another more obvious loss is direct back-scattering of the incident sunlight by the particle layer. Thus the optimal situation is a layer of particles that scatter preferentially into the side directions, specifically $\theta_c < \theta < \pi/2$. Since the angular patter of scattered light depends on the particle shape, size, and refractive index, a variety of particle types are investigated to study the effect these characteristics have on the concentration effect.

CHAPTER III

CONCENTRATOR CONSTRUCTION

Previous to this work, a small concentrator sized 22×29mm with four solar cells was constructed. Both an indoor lamp and the outdoor sunlight were used as a light source. Measurements of output power were performed with dry cement particles which were measured and then spread over the surface of the concentrator. These measurements resulted in the conclusion that output power increased for certain amounts of dry cement. Furthermore, the increase in power was greater than the power outputted by the concentrator without any particles. This proves our technique can enhance the power output of a concentrator; however, the amount of particles spread on the concentrator was not accurately measured.

For this experiment, the amount of particles used were measured accurately using a balance with high precision. A halo lamp was used to ensure stable input illumination. During my research period, two more concentrators of larger dimensions were built. The construction of these planar concentrators is simple and involves low-cost materials. The mirror is a standard second-surface mirror (Edmund Optics). Rectangular PV cells 2×22mm in size (Solar Made, mo. SC-1) were electrically connected in four series by coated copper wire, as one series on each side. Then the UV-cured optical adhesive (Norland, mo.NOA61) was spread across the tiny solar cells of one series and the series was then fixed to the mirror's edges. A Short Wave UV Quartz Pencil Lamp (Edmund

Optics, mo. 40759) was carefully put on the edges of the mirror to cure the glue. Usually, it takes approximately 30 minutes to cure every solar cell. After all four series were fixed to the mirror, they were electronically connected and heat shrink tubes were used to coat the wire joint. In all, three concentrators were constructed: 22×29mm (small), 127×178mm (medium), and 204×254mm (large) in size. This variety of concentrator size is used to study the scalability of the concentration effect which will be discussed later. Figure 2 shows photograph of these concentrators.

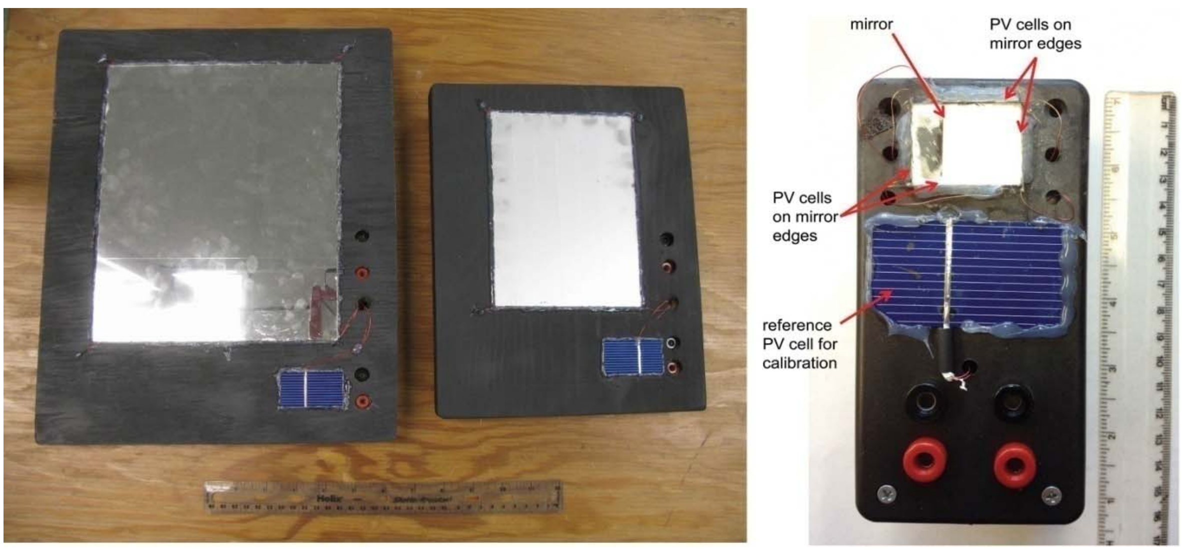

Figure 2 Prototype concentrators; large, medium, and small, from left-to-right.

Each concentrator consists of the mirror lined with PV cells connected in series to two banana-type sockets. The mirror is mounted to a wooden board (painted black) for structural stability. Each concentrator also includes a “reference cell,” which is a bare PV cell not associated with the mirror that is illuminated by the same incident light.

CHAPTER IV

MEASUREMENT

A standard 500 W halogen shop-lamp (Feit Electric) was mounted over the concentrator at a fixed height sufficient to cast approximately uniform illumination for all three concentrators. After the lamp was turned on, the open circuit output voltage of the concentrator without any powder would decrease with time. The lamp reached constant output after being left on for approximately an hour and a half. This is because when we first turned on the lamp it was at room temperature and would heat up until it reached a maximum temperature from being used continuously and the same goes for the concentrator. In order to account for this, the lamp and the concentrator were always "pre-warmed" for 1 hour 40 minutes before each experiment. By performing the pre-warming procedure we eliminate temperature as a variable from our experiment. Each experiment took no more than two hours, so performing one complete experiment took a maximum of four hours.

While the lamp and concentrator were pre-warming, the powder was prepared by dividing them into accurately measured equal amounts (i.e. 0.01g for small concentrator) so that the amount on the surface of the concentrator could be increased by regular increments. Two different methods for putting on powder were used. The choice of method depends on the mass of powder to put on each paper, i.e., the mass increment of particles on different concentrators.

For the small and medium sized concentrators, the mass of the vial with powder inside was measured first, then after pouring out some powder carefully, the mass of the vial was measured again. If the mass of the vial decreased more than 0.01g some powder would be poured from the paper back to the vial. If the mass of the vial decreased less than 0.01g more powder would be poured on the paper. This procedure is repeated until the mass of the vial decreased by 0.01g with uncertainty less than 0.001g. For the medium concentrator the same procedure was performed and the mass gap is 0.2g with uncertainty less than 0.002g.

For the large concentrator we used a mass gap of 0.5g, which is comparable to the paper's mass, so we used a simpler way to prepare the powder. The mass of the paper was measured first and the powder was then poured onto the paper step by step until the mass increased by 0.5g with an uncertainty of 0.005g.

To measure the power produced by the concentrator, the output terminals were connected to a set of fixed resistor R_V with an even gap. Particles were dispersed onto the mirror first. For the joint compound and baby powder, a fine metal-mesh sieve (TWP Inc., 90 Mesh/inch) was used to spread the particles on the mirror. The dry cement was finer than the other two particles; therefore, it was spread on the mirror by the paper directly. The voltage across the load was then recorded. For each particle mass, the peak power produced, $P = V^2/R$, was determined by varying the load resistance. For example, Table 1 shows the voltage with the corresponding resistance and power when 0.5g dry cement was put on the large concentrator. From Figure 3, we can see that the maximum output power is 14.96mW when the mass is equal to 0.5g. For each mass there was a set of voltage values as well as power measured and the maximum output was recorded.

Then steadily, the amount of particles on the mirror was increased and along with this measurements were repeated.

Table 1 Obtain the maximum output power

R(kΩ)	V(V)	I(mA)	P(mW)
5	7.58	1.516	11.4913
6	9	1.500	13.5000
7	10.2	1.457	14.8629
8	10.94	1.368	14.9605
9	11.41	1.268	14.4653
10	11.72	1.172	13.7358
11	11.97	1.088	13.0255
12	12.15	1.013	12.3019

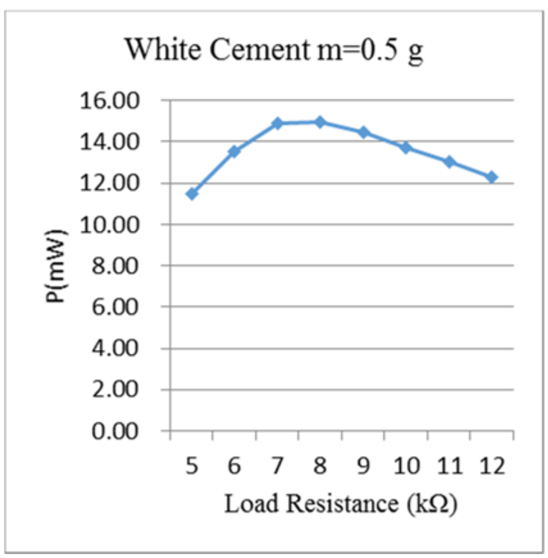

Figure 3 Output power vs. different load resistance

After spreading 0.5g dry cement on the concentrator surface, output voltage across the concentrator's terminals was measured as the load resistance varied from 5 kΩ to 12 kΩ. Output power peaks at 14.96mW with 0.5g dry cement on the large mirror

From each peak power for a given m, the overall performance of the concentration effect can be quantified as

$$\eta = \left(\frac{P - P_0}{P_0} \right) \times 100. \tag{1}$$

In Eq. (1), P_0 represents the peak power produced by the concentrator when no particles are present, i.e., the concentrator is bare. Thus, what η represents is the extra power produced by the concentrator due to the particles as compared to the power produced without them. In other words, this fraction represents is the *percent* enhancement in concentration due to the particle light-scattering effect.

CHAPTER V

CONCENTRATOR PERFORMANCE

The following three powders were tested on the small concentrator; joint compound, dry cement, and baby powder. The powder which gave the greatest enhancement in output power for the small concentrator was tested on the medium and large concentrators.

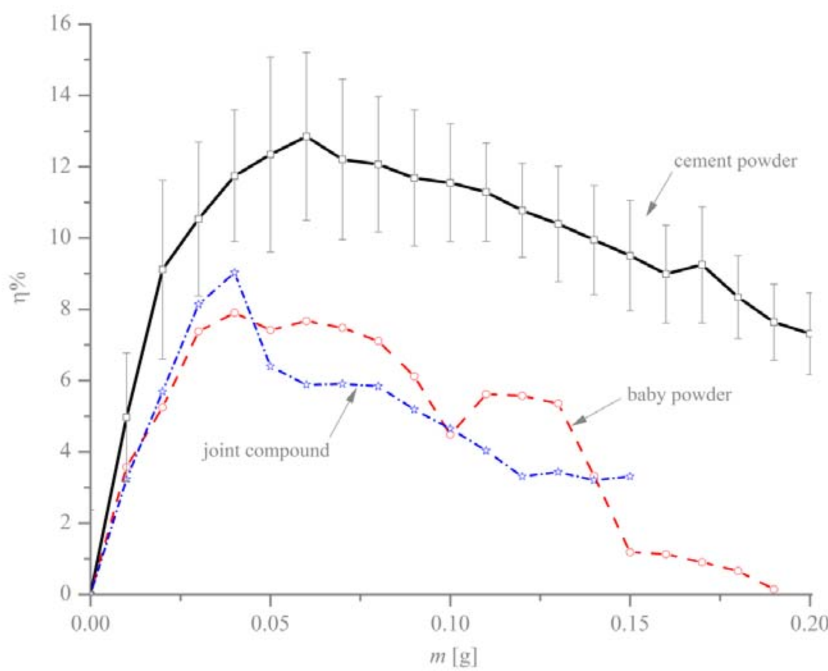

Figure 4 Percent power-enhancement due to particle light-scattering, Eq. (1), as a function of particle number as measured by the total powder mass for the small concentrator shown in Fig. (2).

Figure 4 shows η for the small concentrator as a function of increasing particle number, as quantified by m, for the small concentrator. The three curves show the power enhancement for the three types of particles used: cement, joint, and baby powder. For the cement powder, error bars are shown to indicate the standard deviation of η for three repeated measurements. This range of deviation is indicative of the other particle types, the measurements for which were also repeated three times, and thus are not explicitly shown in the plot. Several general characteristics are important to notice here. First, regardless of the particle type there is always an initial increase in power with particle number. The increase reaches a clear peak, which for this (small) concentrator is approximately $\eta = 12.5\%$ and occurs for the cement powder. Similar, yet weaker enhancements, are seen for the other particles as well. The decay of η beyond this peak appears to be somewhat more particle dependent than the peak itself.

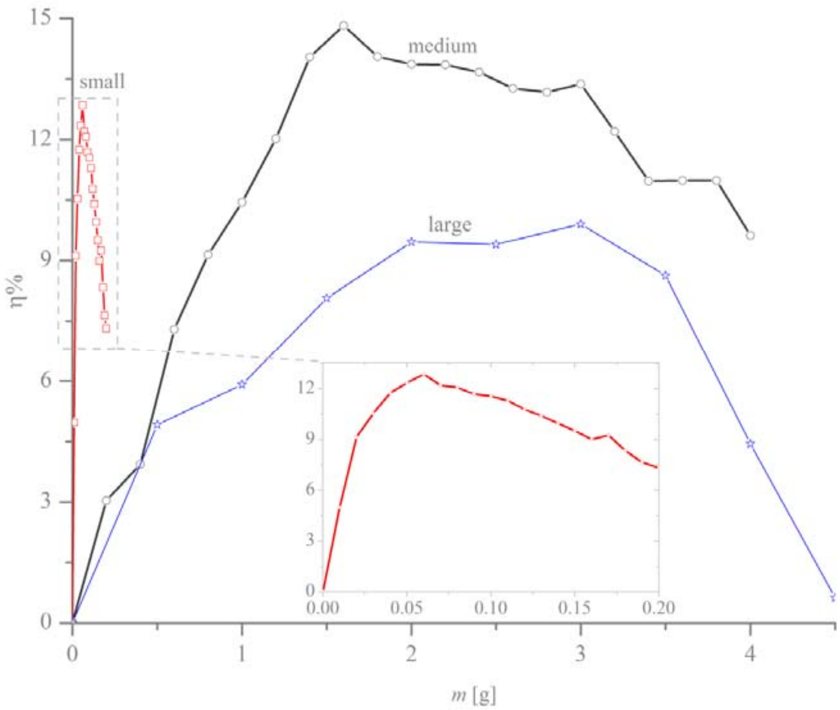

Figure 5 Dependence of the percent power-enhancement due to particle light-scattering, Eq. (1), as a function of particle number with concentrator size.

To study the effect that increasing the concentrator size on the power enhancement, the same measurements are conducted on the medium and large concentrators. The results are shown in Fig. 5 for the best-performing particle type – the cement powder. Here, the same general trends as in Fig. 4 can be seen. A notable difference is that the peak enhancement appears to increase slightly with concentrator size to a point, i.e., the medium concentrator, beyond which there is a decrease (large concentrator).

Table 2 Summary of Concentrator Performance

Concentrator	N_c	P_m [mW]	P_m / N_c [mW]
small	4	0.110 ± 0.001	0.028 ± 0.0006
Medium	24	5.02 ± 0.12	0.21 ± 0.005
Large	36	16.1 ± 0.33	0.45 ± 0.01
reference cell	1	1.56 ± 0.016	1.56 ± 0.016

An important consideration is the practicality of this concentration concept. To assess this, the maximum power P_m produced by a concentrator using the best-performing particle type (cement) and particle number is compared to the total number of cells N_c used in the concentrator, see Table 1. The results show that for the small and medium-sized concentrators, the power per cell is substantially less than that produced by the single, bare, reference cell, which is directly illuminated by the shop lamp. However there is an important trend with increasing concentrator size. While the power per cell of the small concentrator is nearly 1/80 that of the bare, reference cell, the large concentrator is about 1/3 that of the reference cell. The trend suggests that further increase in concentrator size could potentially yield a power performance that is comparable to the reference cell. Moreover, given that such simplistic particles are used here, one could imagine that further enhancement in performance is likely by extending this investigation to a wider range of particle types.

CHAPTER VI

PARTICLE MORPHOLOGY

From Figs. 4 and 5, it is clear that light scattering from the particle layer causes a substantial (~15%) enhancement in the power produced by the concentrator as compared to the bare concentrator. Such results validate the premise of this work, i.e., that scattering from wavelength sized and larger particles can couple incident light into a "trapped" TIR mode in the glass plate. What is less obvious is what role the particle morphology plays in this enhancement. Some insight can be obtained from Fig. 6 where scanning electron microscope (SEM) images of the particles are presented. Overall, each powder consists of highly irregular particles spanning a wide range of sizes. The lowest performing particles, i.e., the baby powder, shows the narrowest distribution in particle size, approximately $25\ \mu m$. Comparing the cement and joint-compound powders, the latter shows a number of more-regularly shaped particles, e.g., sphere-like, as compared to the former. Thus, it seems that the best performance can be attributed the highly irregular shape of particles of the cement particles over a large size range. Work is ongoing to better understand this trend.

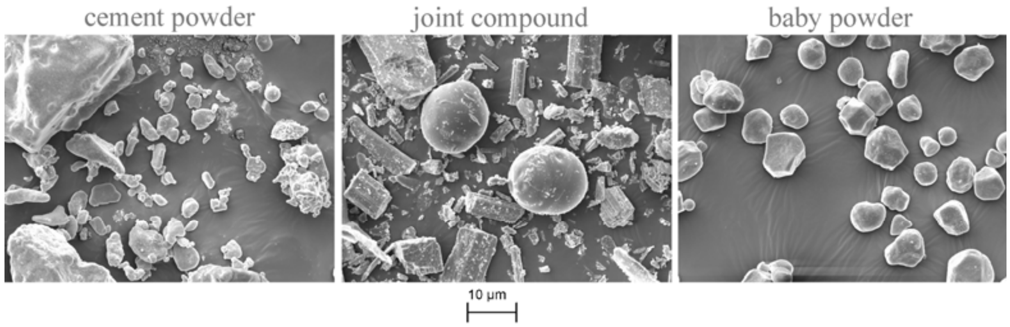

Figure 6 SEM images of the three particle types used in the measurements above. From left to right: cement, joint-compound, and baby-powder.

To say more, consider light scattering from a single spherical particle on the concentrator. Because of the particle's symmetry, incident light scattered along the forward direction into the concentrator plate will be equally scattered out of the concentrator after having reflected (normally) from the mirrored bottom, i.e., provided the interaction between the particle and glass plate is ignored for simplicity. Thus, in a highly simplified sense, spherical and spherical-like particles will perform poorly in the concentrator as compared to highly irregular particle shapes. This is because the latter may scatter light preferentially into the plate due to the lack of symmetry in their shape. While this explanation is rather speculative, it is consistent with the observation that the cement powder performs better than the joint-compound and baby powder, since the latter contain many sphere-like particles. Moreover, one could understand why the joint-compound out-performs the baby powder from the range of particle sizes. A broader distribution of sizes means that the particle collection can interact more efficiently across the broad shop-lamp spectrum.

Further work is underway to better understand the role of particle morphology on the concentration effect. For example, the discrete dipole approximation can be used to accurately model the scattered light distribution of irregular particles on a planar surface. Such work can also reveal the distribution of electromagnetic-field intensity within the particles and glass plate, and thus, further illustrate how the scattering process couples light into the plate via TIR.

CHAPTER VII

CONCLUSION

The measurements reported here demonstrate that scattering from a layer of wavelength-sized particles can couple light into a mirrored glass plate where after it is routed by TIR to PV cells lining the plate. The process depends on the particle size, morphology, and number density on the concentrator surface. Overall, its performance in terms of power production per PV cell appears to approach, and may even exceed, that of a single bare cell under direct illumination. This is an important finding since the materials used to construct the concentrator are low cost and most are available off-the-shelf at a local hardware store. Further research is underway to understand the influence of the various loss mechanisms that degrade the concentrator performance and the optimum particle properties to use.

CHAPTER VIII

PUBLICATION

A paper including this work has been submitted to Optics Express. The paper is in the status of pending.

CHAPTER IX

FUTURE WORK

This experiment shows that the use of particle scattering can improve the performance of a concentrator. There are a number of ways the procedures of this experiment can be improved, also the theory of particle scattering can be further developed to improve understanding the phenomenon observed. This leaves a lot open for future research.

In order to improve our understanding of the role of particle size played in the experiment, other particle sizes should be tested. Ideally, future work would use particles that were comparable to the wavelength of visible light and be roughly uniform in size and shape. If the particle sizes can be controlled within certain tolerances, two or more kinds of particles can be mixed in order to produce irregularly sized particles. For example, mixing the baby powder with another particle of a bigger but uniform size could result in irregularly sized particle. By controlling the ratio of the amount of each type of particle used, we can better quantify the role of particle size. Even further investigate could quantify the way the differently sized particles are distributed. Changing this distribution could affect absorption.

There are many ways to improve the performance of solar cells. The results seen in Table 2 showed the bigger the concentrator is the greater output per solar cell we can obtain; therefore, by building larger concentrator, it is possible to obtain a better performance per solar cell. A large variety of concentrator sizes as well as a variety of amount of solar cells should be performed in future work. Moreover, the method of increasing the amount of solar cells is not limited to increasing the size of the concentrator. In figure 1, the light scattered by the particle on the surface of the mirror will be reflected back to the particle layer. The second order and higher ordered scattering will result in loss of solar energy. To reduce the lost energy in higher scattering, we can replace the mirror by solar cells, or rather, a large solar panel with a piece of glass above it. The solar panel can absorb some light from the first order scattering, leaving less light for higher order scattering, which leads to less energy lost.

An experiment with different incident light directions should also be considered in order to optimize the light coupling. The diagram to the right in Figure 1, illustrates that the front scattering light occupies a large proportion of the light scattered in to the mirror. In the same way, while the light with $\theta < \theta_c$ was reflected by the mirror and back to the particle on the surface, the front scattering of second order scattering will result in a greater loss. So tilting the direction of incident light will make more light reflected by TIR instead of second ordered scattering, as shown with the solid-line pattern.

Finally, one last improvement would be to better control the experiment temperature. Solar cells, the same as all semiconductor products, are very sensitive to the temperature. As we mentioned before, the output of the solar can drop right after the halo lamp is turned on. The reason for this is not only because of the uncertainty of the lamp's output itself but also because of the sudden shift of temperature. The results from future experiments will be more convincing if we can maintain a more steady temperature.

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