Axially Graded Index Lens (AGILE) as a non-tracking solar concentrator

Investigators

Olav Solgaard, Associate Professor, Electrical Engineering; Reinhold Dauskardt, Professor, Material Sciences and Engineering; Nina Vaidya, Graduate Researcher, Stanford University

Abstract

We are working on making a novel non-tracking and low cost solar concentrator: Axially Graded Index LEns: AGILE; that has potential to change the economy of the solar cell industry. The project is funded by GCEP exploratory grant for the year 2010-2011. It is a fundamental law of physics that for solar concentrators, if we want to channel the solar energy from a large area onto a smaller one, the density of modes must be higher at the output. The AGILE takes advantage of the fact that the density of electromagnetic modes radiating through an area is proportional to the square of Refractive Index (RI) of the medium. In a well-designed AGILE, this requires that the area reduction ratio is less than or equal to the square of the ratio of refractive indices from top to bottom. In an AGILE, sunlight enters the system through an aperture of unity index; goes through a graded index material and is then absorbed in a semiconductor with *RI~3.5*. This enables a concentration factor of 3.5^2=12.25 without need of pointing to the sun. Larger concentration can be achieved by utilizing the fact that at any location on earth the sun only traverses a fraction of the full 2 Π steradians of the sky. Additional concentration requires higher RI gradation. Yet higher non-pointing concentration require optical metamaterials with RI>3.5. It should be noted that there can not be any air gap between the AGILE and the solar cell; in order to get all the modes into the cell. In addition to solar concentration, the AGILE's unique imaging properties also has exciting applications in illumination, photography and communications.

The basic AGILEs that we are demonstrating in the exploratory phase of our research give a completely passive concentration of several suns. We have made an AGILE tested at IR frequencies with Silicon nanoparticles suspended in PDMS to make the graded index material. We are now working on making Al AGILE arrays filled with polymers of varying refractive index to achieve the concentration of light with low loss materials working over the broadband solar spectrum. The AGILE is a simple concept that rests on fundamental physical laws, and it will simplify PV systems, but its development presents substantial challenges in material science. The AGILE require transparent materials with RI ranging from 1 to 3.5 or beyond. The extreme low RIs will be achieved in porous materials and sol-gels, while the higher RI materials will be created in polymers with controlled distributions of high-RI nanoparticles. The fabrication process is in progress and will finish before the end of the exploratory project period.

In the future, hopefully long before we have depleted our reserves of fossil fuels and radioactive ore, our civilization will depend on solar energy conversion. This will take many forms, but photovoltaics (PVs) will most likely play a big part. For large scale Photovoltaic conversion, real estate will be the limiting factor; and only PV technology the highest achievable conversion efficiency will be viable. Our future research will bring this future closer by enabling two important advances; (1) high efficiency flat panels for residential installations, and (2) robust, easy to maintain, large scale PV installations that may operate in hybrid fashion, e.g. by combining PVs with solar thermal and/or solar thermo-emission.

The AGILE enables high-efficiency, passive flat panels by creating low-cost, miniature, passive concentrator arrays that power high-efficiency PVs (triple-junction III-V semiconductors in today's technology). These passive flat panels will be plug-ins for today's silicon panels. The low-cost and simple installation of the AGILEs, combined with the reduced area of the PVs, will make this conversion technology significantly cheaper than competing PV technologies, but most importantly, it will boost total energy production from residential installations by more than several factors over high-quality PVs. In high-concentration utility scale conversion systems, the AGILE translates into reduced requirements on design, optical components, construction quality, pointing accuracy, and long-term stability. Combining concentrators with high efficiency solar cells is the best way to make solar energy large scale by harnessing high efficiency at an optimum cost with minimum land utilization. If our research is successful, it will significantly increase power conversion in residential and utility-scale PV installations, with commensurate reduction in green-house gasses.

Introduction

Photovoltaic (PV) solar energy conversion is expected to play a major role in satisfying our future energy needs, but for solar to provide a significant fraction of our total energy will require exceptionally large areas, so real estate will in many cases be the limiting factor. Combined with the high cost of installation and maintenance, this creates a strong impetus for using the absolutely most efficient conversion technology. Presently that means concentrated photovoltaics (CPVs) with high-quality, crystalline, multi-junction semiconductor devices. We propose to fundamentally change the economy of this type of system by developing the Axially Graded Index Lens (AGILE) that provides completely passive concentration of about one order of magnitude. The operational principle of the AGILE is explicitly based on the fact that the number of states of an optical aperture is proportional to the square of the Refractive Index (RI). A central part of the project is to develop optical-quality materials that can be graded in index from unity to 3.5 (the RI of semiconductor PVs), and practical fabrication, based on printing and molding technologies, for graded-index optics. This material and device research will inform, and be informed by, parallel work on system integration. We designed and fabricated the basic AGILE structure in the GCEP exploratory grant stage.

Background

There are various companies and researchers working on Concentrated PhotoVoltaics (CPVs). The differentiating factor of AGILE with the competing technologies is that concentration is achieved without need to track the sun and very low cost production is expected. The present parabolic shaped concentrators (CPCs) have a typical concentration factor of $1/\sin(\Theta)$, where Θ is the acceptance angle. For even as little as 25 degree acceptance angle this ratio is only about 3. The maximum concentration from a parabolic 2-d concentrator is $1/\sin^2(\Theta)$. AGILE design; when optimized with a parabolic shape could have a much higher concentration of RI2/ $\sin^2(\Theta)$. SolFocus do not grade the refractive index in their parabolic concentrating component and we believe that by using a graded index material we can achieve even more concentration with less stringent pointing accuracy requirements. Other companies are focusing on solar thermal power like eSolar but this also needs extremely expensive and accurate pointing systems and land utilization. We see the focus on high RI materials as the strength of our project. Current concentrator systems do a good job of concentrating light from a limited range of angles, and the principles developed for this type of non-imaging optics will be used in our concentrator optics, but the key to substantial improvement is precisely the high density of states provided by high RI materials. The best existing passive concentrators takes advantages of the RI of 1.45 of common optical glasses. The short term goal of our project is to improve these systems by going to high RI materials like SiN and SiC. By increasing the RI from 1.45 to 2.5, we improve the concentration of these systems by a factor of $2.5^2/1.45^2=3$. This three-fold improvement will make a very significant difference in practical systems, and in the long term there is potential for substantially bigger gains.

Results

The exploratory stage of the project included proof of concept of the initial project idea and simulations presented in our initial proposal. The operation of AGILE can be clearing seen from these ray tracing simulations. In the AGILE Fig.1a) the RI is graded from 1 at the top to 3.5, which is the RI of Silicon. We see that the incident rays (red) all exit through the output aperture, some without any reflections and some after one or more reflections from the sidewalls of the AGILE. To show the effect of sidewall reflections, we show the rays that have reflected in green. The perfect light capture of the AGILE in Fig. 1a) is contrasted in the homogeneous filled AGILE of Fig. 1b) and the empty one of Fig. 1c). In both of these cases, a substantial amount of the incident light is reflected back out of the input aperture, even at the incident angle of only 20 degrees that is shown in Fig. 1. For higher incident angles, the fraction of the incident light that is back reflected becomes larger, meaning that the homogeneously-filled or empty "light funnels" do not work. Hence the effectiveness of the graded index AGILE.

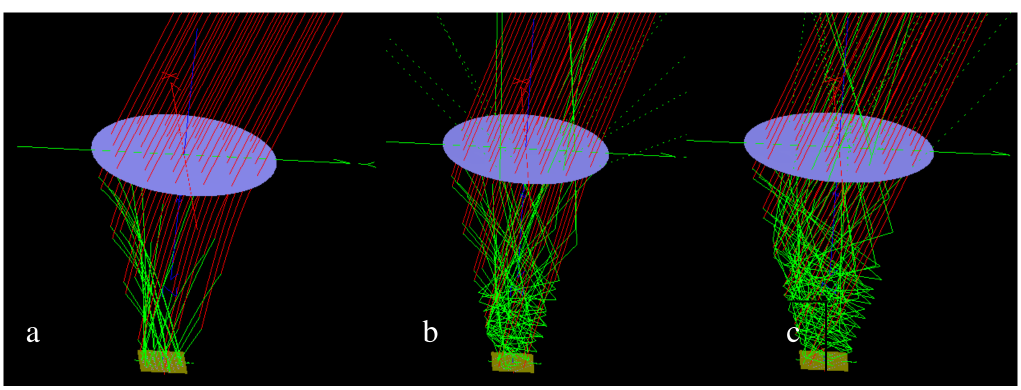

Figure 1: An AGILE linearly graded from RI=1 to RI=3.5 (a) concentrates light perfectly. In contrast, AGILEs that are homogeneously filled with PDMS (b) or empty (c) reject a substantial amount of the incident light even at a modest incident angle of 20 degrees.

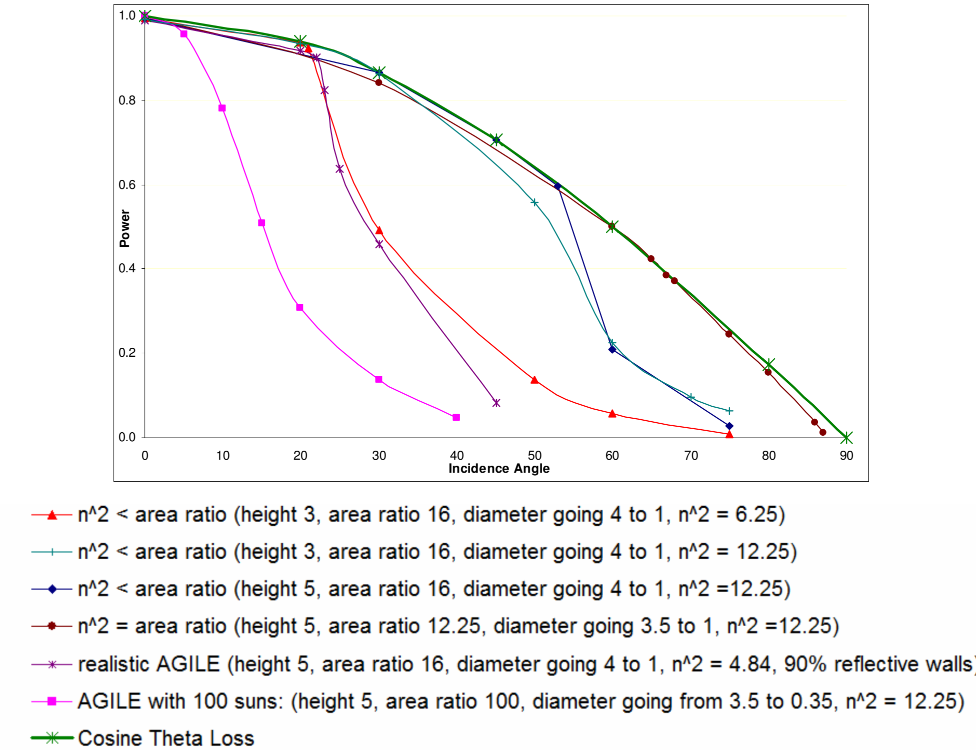

Figure 2: Summary of power intensity simulations for different AGILE geometries.

The results of our numerical simulations of AGILE power concentration are summarized in Fig. 2 that shows the calculated output power for different geometries and incidence angles. The graphs show the power through the output aperture relative to the power in an input beam which has a cross section equal to the input aperture, which means that the maximum possible output power goes as cosine theta, where theta is the incident angle (green solid line). As expected, AGILEs with area ratios smaller than RI^2 follow the cosine-theta loss very closely up to angles as large as 85 degrees. As we make the height of the AGILE smaller and the area ratio larger, the curves deviate from the cosine theta curve. An example simulation (purple curve) was done with RI graded from 1 to 2.2 with 90% reflective walls and area ratio of 16; and it can be seen that it drops power drastically beyond about 23 degrees. In other words, this AGILE would catch all rays in a 46 degree cone around the normal, which would be sufficient for most passive CPV applications. The simulations also show that the AGILE can achieve a concentration of 100 suns with an acceptance angle as large as 30 degrees.

Development of robust, low loss, transparent in broadband and inexpensive graded RI materials is critical to the success of our project. We have successfully fabricated graded RI structures by filling stencils with layers of thin films with controlled distributions of nano-particles (Fig. 3).

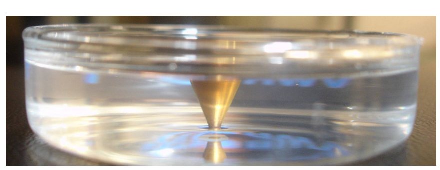

Figure 3: PDMS stencil wilt gold deposited side walls for AGILE fabrication.

Initial AGILE fabrication was done as follows:

- Silicon nanoparticles (IR=3.5) were dispensed in a PDMS matrix. Si and PDMS both have transparency bands at Infra Red wavelengths. PDMS, which is CH3[Si(CH3)2O]*n*Si(CH3)3, is very stable and does not react with Si. Si particles used are of 100nm average diameter, i.e. much less than the design source wave lengths in IR.
- Molds of Aluminum, Teflon, and Polypropylene were micro-machined. Teflon had the best thermal properties for PDMS curing without sticking, and also gives a good surface finish.
- Stencils were made by using these molds by curing PDMS around them, and then removing the molds.
- Gold was sputtered on the side walls of the stencils to make them reflecting.
- Ten layers of PDMS solution with increasing density of Si nano-particles were cured in the stencils to complete the AGILE.

The first measurements of our Si-nano-particle AGILEs showed a lower transmitted power than expected for this material system. Close inspection of the fabricated AGILEs indicate that the reasons for the extra loss are reflections from the interface between the AGILE and the photodetector underneath, reflections from the interfaces between the 10 PDMS films, and scattering from clusters of Si nano-particles. Each of these problems is being addressed in the second generation AGILEs we are now fabricating and testing. We are now using arrays of Aluminum molds that allow us to create a high-quality optical surface on the AGILE output for a close coupling to the PV material, and we are developing rapid dispensing techniques that minimize the discontinuity between layers of different RIs. Lastly, we are investing surface treatment of the nano particles to stop them from attaching to each other and clumping.

As a next step we are fabricating AGILE arrays for visible light frequencies. Using Aluminium arrays and filling them with layers of different refractive index polymers/optical adhesives/glass slab and transparent nano particles (SiC and SiN) in polymer solutions. Single sided AGILE with high index glass at the end as shown in the figure below, This structure has the issue that modes collected at the bottom in the high index material have to be directly incident on the detector, any air gap would add huge losses. For ease of detection a back to back structure is being fabricated so that light goes from air to high index material and then back in air and if the output power is comparable to input power then we have proof of concentration in the middle neck of the structure.

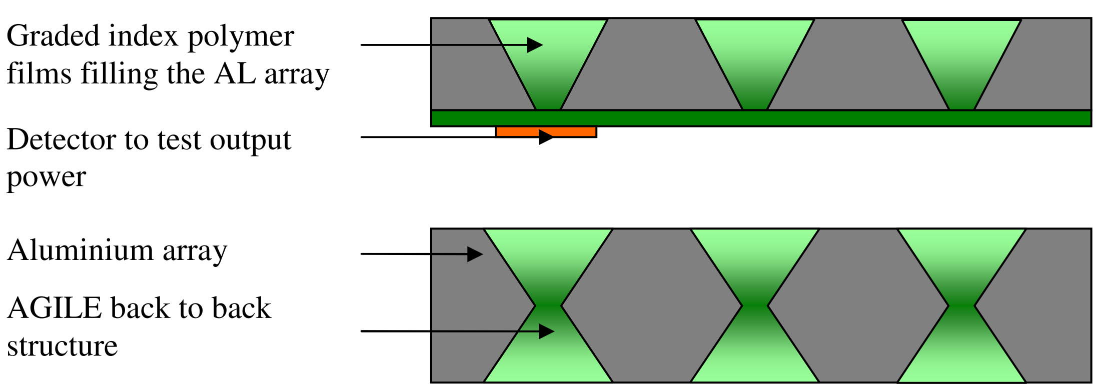

Figure 4: AGILE fabrication

The plan for creating graded-index materials with RI up to and beyond 2.5 is based on the use of high RI particles of sub-wavelength dimensions. The materials of choice are silicon nitride (Si_3N_4) and silicon carbide (SiC). Silicon nitride is chosen for its relatively high RI (RI=2 for stoichiometric Si_3N_4, and up to RI=2.3 for Si-rich SiN). Silicon carbide has even better potential as the main building block of high-RI optics. Its RI ranges from 2.6 to 2.7 over the solar spectrum. To create concentrator optics, we will use our extensive experience with these materials and with graded-index optics based on particles suspended in glass and polymer matrices. In the long term, we plan to go beyond an RI in the 2.6 to 2.7 range that is achievable with Silicon Carbide by shifting our focus to optical meta-materials. Optical meta-materials for a wide range of applications and purposes have been proposed over the last five to ten years. Most promising for high RI are materials based on nanocone structures, which are fabricated by a scalable low temperature process [5]. We will also explore the possibility of using magnetic sub-wavelength particles as a possible way to increase the RI.

Progress

The AGILE concentrator enables cost-effective, utility-scale, photovoltaic installations by simplifying the design, construction, installation and most importantly; the maintenance of high-concentration (~1,000 suns) concentrated solar PV systems. The basic completely passive AGILEs that we have simulated and demonstrated in the exploratory phase of our research give a concentration of several suns. In high-concentrations systems this translates into reduced requirements on design, optical components, construction quality, pointing accuracy and long-term stability. Over the life time of the PV installations, this leads to substantial cost savings and allow the facility to operate at maximum efficiency even under sub-optimal conditions. As stated before AGILE would be used for two types of systems. This is applicable to the residential passive panels. The large scale utility installations will involve pointing, but with sharply reduced pointing-accuracy requirements to achieve a prescribed concentration, i.e. 1,000 suns. So both these types of AGILEs will have large scale implementation and hence potential for high impact on reducing green house gas emissions.

The AGILE is a simple concept that rests on fundamental physical laws. AGILE would greatly simplify PV systems, but its development presents substantial challenges in material science and fabrication. The AGILE require transparent materials with RI gradually ranging from 1 to 3.5 or beyond. The extreme low RIs will be achieved in porous materials and sol-gels, while the higher RI materials will be created in polymers with controlled distributions of high-RI nano-particles and meta-materials. The planned fabrication process for large AGILE arrays is to fill low-cost, moulded stencils with thin films of decreasing RI till the stencil is filled and the large-scale AGILE array is completed. This is an automated process that relies on well-proven techniques, giving it the potential for low-cost production and economies of scale. The resulting AGILEs will be low cost, robust and easy to install which save expensive solar cell area and real estate, giving them the potential for wide-spread adoption.

Future Plans

The main focus of the first year was to find the design and fabrication combination to achieve the large range of gradient material needed for AGILE which should be low loss and efficient across a large part of the solar spectrum; as detailed above we are fabricating the AGILE arrays and ready to test the second batch of transparent AGILEs. As a next step we will explore techniques to co-segregate both high RI nano-particles and sacrificial porogen nano-particles to create low RI matrix regions within the same hybrid glass matrix material by particle-surface interactions, similar work has already been done with nano porosity by Prof. Dauskardt [1,2,3,4]. Multi-stage film deposition for this gradation will also be attempted to achieve the desired wide range of RI values. This work includes controlling both the hybrid matrix compositional gradient in the AGILE, as well as co-segregation of nano-particles and porosity to either increase or decrease the dielectric properties. We are going to work with SiC and SiN nano-particles in matrix polymers to achieve high index transparent materials. In parallel to the material and device work, we will start system simulations to begin the process of finding the system configuration that best utilizes the AGILE.

In the subsequent year, the research and development on the basic AGILE materials and structure will be completed, and the focus will shift to low-cost manufacturing processes for arrays of AGILEs to enable large-scale implementation. At this point, we will know enough about the AGILE to be more specific in the systems work. Flat-panel and high-concentration systems will be explored, and complete designs, including electronics and thermal management, will be developed. In the following years, we will demonstrate a small-scale, but complete AGILE system (Figure 5 below). We will test these systems in realistic environments to asses their viability and explore their practical limits. Work will continue on lowering the fabrication and system costs and making the system robust and durable for long term use, with the aim to establish a commercially transferable technology.

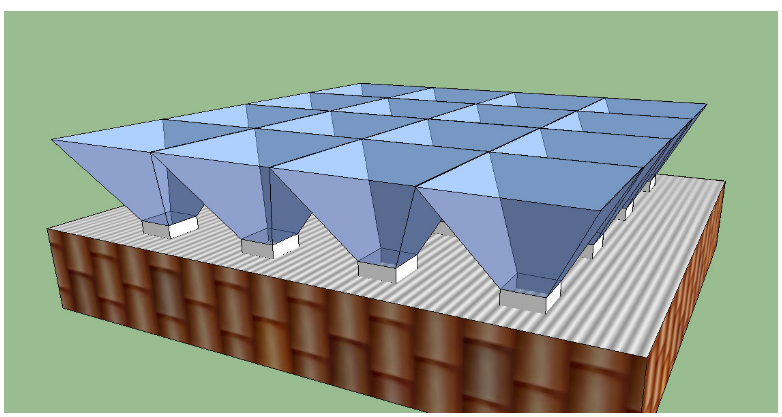

Figure 5: AGILE passive roof-top system.

References

1) G. Dubois, W. Volksen, T. Magbitang, R. D. Miller, D. M. Gage and R. H. Dauskardt, "Molecular Network Reinforcement of sol-gel glasses," **Advanced Materials**, 19, 3989–3994, 2007.
2) D. A. Maidenberg, W. Volksen, R. D. Miller, and R. H. Dauskardt, "Toughening of Nanoporous Glasses Using Porogen Residuals," **Nature Materials**, **3**, 464 - 469, 2004.
3) Dubois, Volksen, Magbitang, Sherwood, Miller, Gage and Dauskardt, "Superior Mechanical Properties of Dense and Porous Organic/Inorganic Hybrid Thin Films," **J. Sol-Gel Science and Technology**, 48,187-193, 2008.
4) Ong, Volksen, Dubois, Lee, Brock, Deline, Miller and Dauskardt, "Molecular Controlled Fracture and Release of Templated Nanoporous Organosilicate Thin Films," **Advanced Materials**, 20, 3159–3164, 2008.
5) J. Zhu, Z. Yu, S. Fan and Y. Cui, "Nanostructured photon management for high performance solar cells", Material Science and Engineering: R: Reports, vol. 70, pp. 330-340, 2010

Contacts

Olav Solgaard: solgaard@stanford.edu
Reinhold Dauskardt: rhd@stanford.edu
Nina Vaidya: vaidya1@stanford.edu