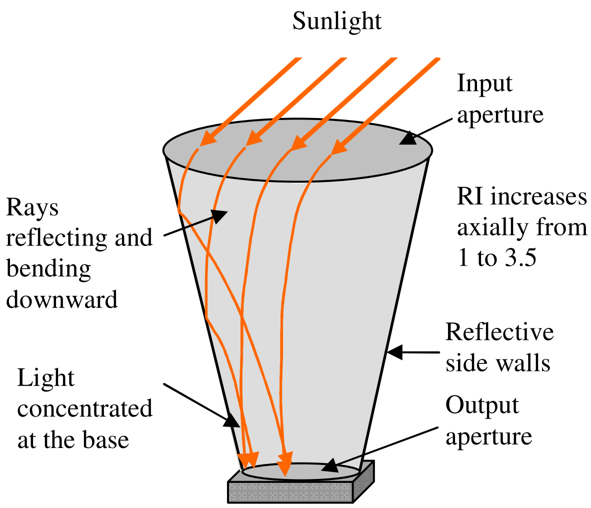
EE412 Final Report
AGILE: Axially Graded Index Lens Fabrication

June 2011
Nina Vaidya
Prof. Solgaard
Project Mentor: Tom Carver

Abstract:
The aim of my EE412 project was to fabricate graded index optical lenses which was successfully designed, made and tested.
The project aims were to:

- Characterize refractive index of different laminated stacks of optical materials/optical adhesives
- Summarize and fine tune a process to make graded index optical lens material
- Test the fabricated AGILEs

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.
It is a fundamental law of physics that the number of modes, or states, on the output of a loss-less optical system must equal the number of modes on the input. For solar concentrators, this means that if we want to funnel the solar energy from a large area into a smaller area, then the density of modes must be higher on the output. The AGILE takes advantage of the fact that the density of electromagnetic modes radiating through an area is proportional to the Refractive Index (RI). In a well-designed AGILE, the number of electromagnetic modes at the input (top) equal the number of modes at the output (bottom). 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 concentrator 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 $3.5^2=12.25$. Larger concentration can be achieved by utilizing the fact that at any location on earth the sun only traverses a fraction of the full 2π steradians of the sky. In practice, the AGILE support passive concentrator systems at about 60 to 100 suns. Additional concentration requires higher RIs. 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.



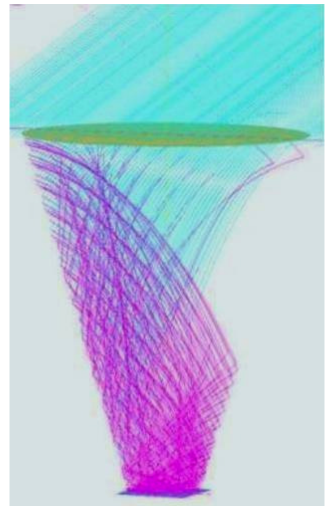


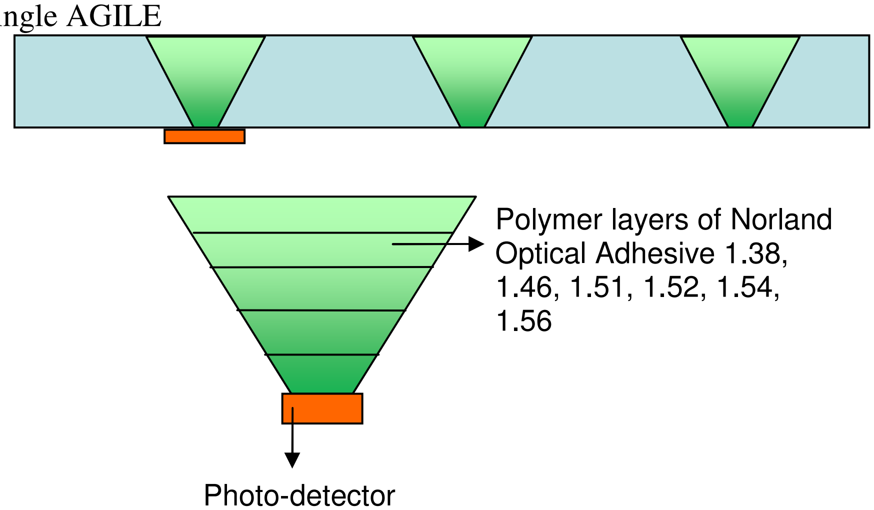
Figure 1. (a) Schematic of the AGILE. The graded RI bends rays towards the axis and concentrates them in the output aperture. (b) Ray tracing (right) confirms that light is concentrated at the output (bottom) of the AGILE.

Design and Materials:

Two Structures Were Designed:
1) Structure 1: Single sided AGILE

- Advantages:
  - Layered structure made up of different polymers
  - Photo-detector to measure the output power (orange rectangle in the diagram)
  - N^2 ratio = 1.28, area ratio = 1.96 (7mm to 5mm and height of 10mm)

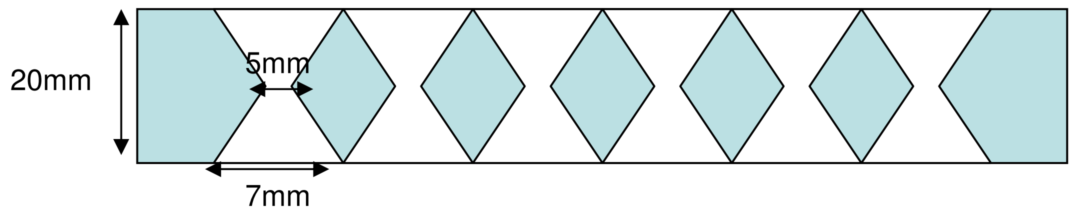
Figue 2: Single AGILE



2) Structure 2: Back-to-Back AGILE:

- Aluminium plate with conical holes which have larger diameter of 7mm and smaller of 5mm
- Advantages: Detection is easier, power goes from larger to smaller to larger aperture (less index mis-match)

Figure 3: Back-to-back structure



Materials:

UV optical adhesives of different refractive indices: NOA138 (1.38), NOA84 (1.46), NOA 89 (1.51), NOA74 (1.52), NOA68 (1.54), NOA63 (1.56)

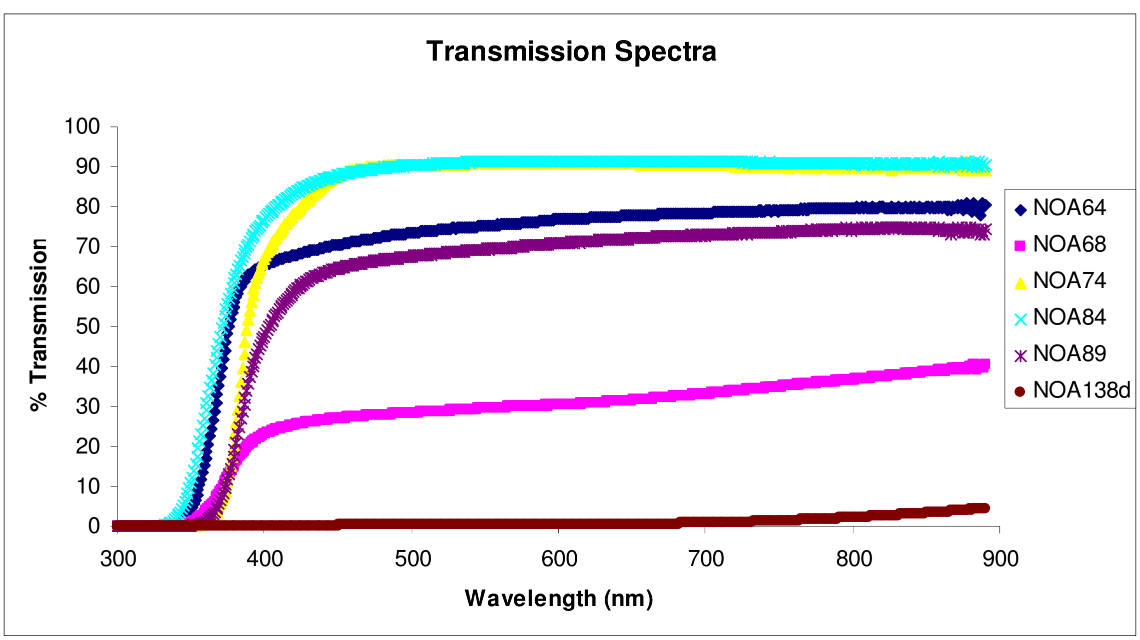
These UV curable adhesives would be used to fill the AGILEs

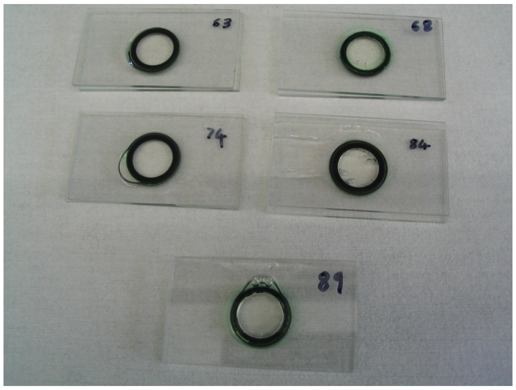
Spectral Transmission Measurements:

- Spectrophotometer measurements for different film samples to characterize the optical adhesives and the polymers was done
- Optical adhesives were put between two glass slabs with a spacer to make thin films and then this can be used a specimen for the transmission measurements for the polymers that are not characterized

When fully cured, NOA68 has very good adhesion and solvent resistance, but it has not reached its optimum adhesion to glass. This will come with aging over a period of about 1 week in which a chemical bond will form between the glass and adhesive. This optimum adhesion can also be obtained by aging at 50° C for 12 hours. This explained the low %T of NOA68. Same was the case for NOA74. %T of NOA138 is so low as it requires inert atmosphere while curing and this sample was made in air, hence almost an opaque film was obtained.

Figure 4: Transmission measurements of the different samples of materials used





- All except NOA138 (RI of 1.38) behave well and are characterized
- The NOA84 does show a lot of shrinking which is only a problem in this closed test structure and not in agile
- NOA68 and NOA74 need aging after curing

Figure 5: The samples sandwiched between the two glass slides with o-ring in between to make same thickness films of different materials

NOA138

- NOA is Aliphatic Urethane Acrylate* * 5-20% and Acrylate Monomer * 40%-85%
- The layer becomes cloudy and yellowish after UV cure, this layer thickness is about 1mm.
- On closer inspection, the adhesive exhibits oxygen inhibition when used as a coating. To overcome this, the adhesive must be cured under an inert atmosphere, such as nitrogen.

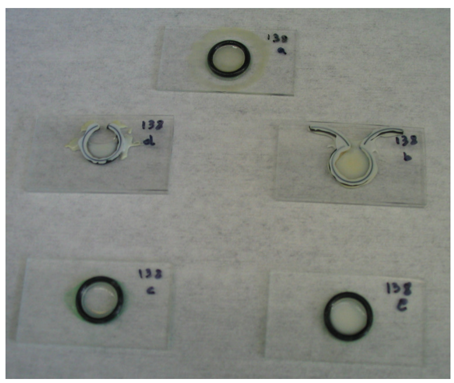


Figure 6: The NOA 138 samples that need to be cured in inert atmosphere, the first 138a sample is cured in air and hence is much cloudier than the others. The others have been made in different glove boxes and still cure cloudy even if the material is transparent to start with.

- Solution: rather than a NOA138 bottle, get smaller separate syringes (single use only in a glove box) because maybe the bottle is contaminated when it was first opened in air.
- Interaction between rubber and NOA138 was ruled out, because same happens just on glass or Aluminium surface.

Fabrication Method:
Agile Stencils: single and back to back structures were made from Aluminium blocks by machining with a custom made reamer to the right shape. The back to back structure was made by reaming from the two sides towards the centre.

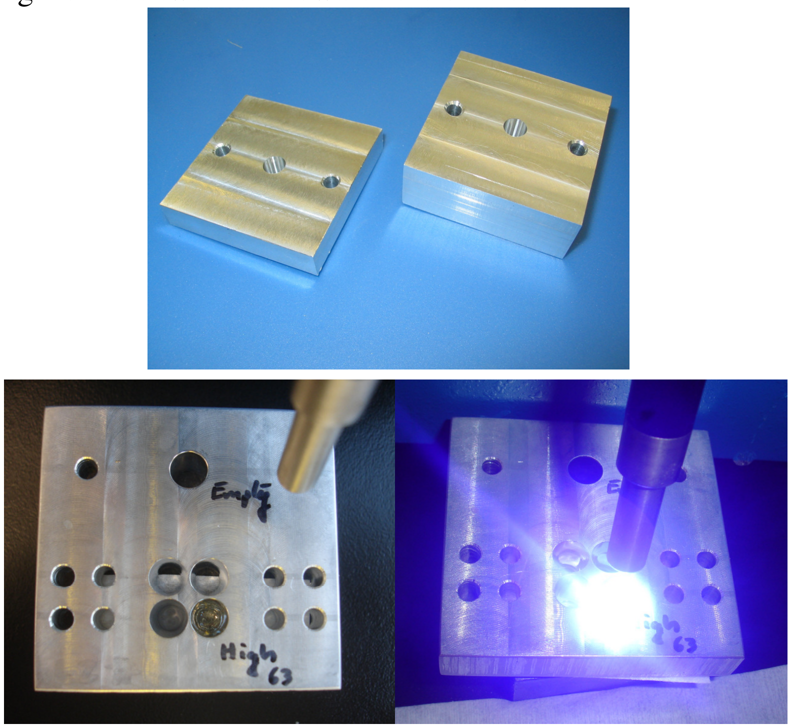
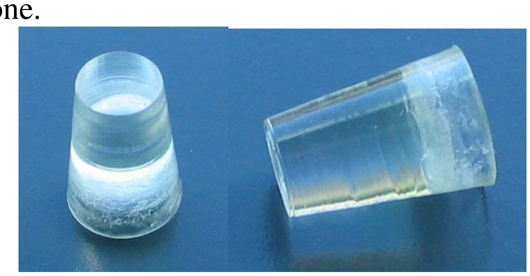


Figure 7: The stencils in the top picture and then the bottom pictures are of the AGILEs being cured.
Figure 8: Close-up of extracted AGILE (made with NOA138 as top layer which became cloudy). This structure could not be used. We made other graded index lens successful after this one.



Summary of fabrication process:
Micro-machining the stencil in Aluminium blocks and polishing the AGILE cones (Al polish with drill and Q-tip)
Degreasing and cleaning the cones in clean room.
Sealing the cones was done with PDMS and Elmer's glue backing (as it does not stick to the optical adhesives). Glass and PVA backing was used to cure back to back structure from both sides. We used PVA as it is water soluble. Then curing thin films of the different optical adhesives, this involved using the microscope to look for bubbles and the level and a vacuum chamber to de gas and take out bubbles before curing. We the used a UV cure gun to fabricate the structure.

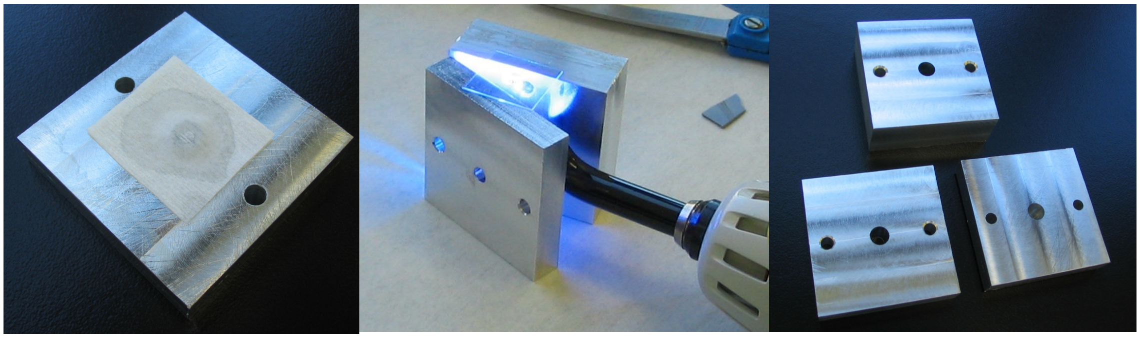


Figure 9: Pictures of how the AGILE was fabricated, first one from the left is how the back plate was attached that does not stick to the optical adhesives and can be peeled off after the cure, middle one is of a test structure make to test the back plate for the back to back structure so that it can be cured from both sides, the last picture is of the 2 single AGILEs and one back-to back structure.

Testing of AGILE performance:

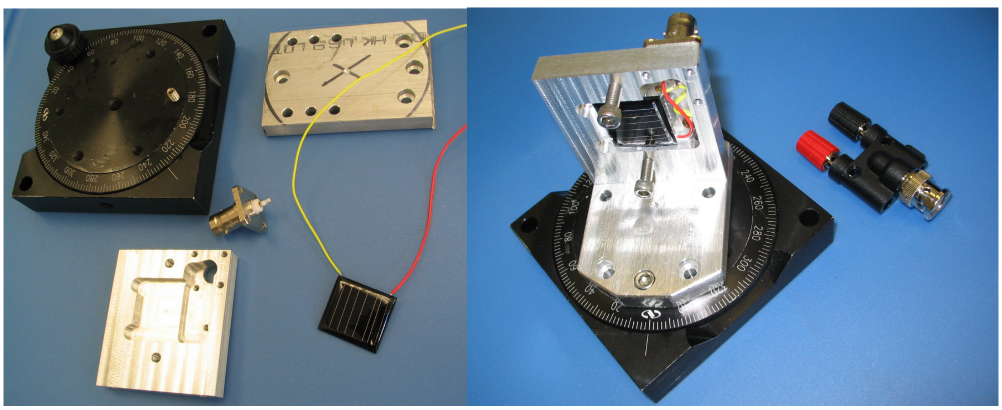


Figure 10 above shows how the solar cell detector was made. You can see the solar cell in the Aluminium housing mounted on a rotational stage for testing the output light from the AGILE.

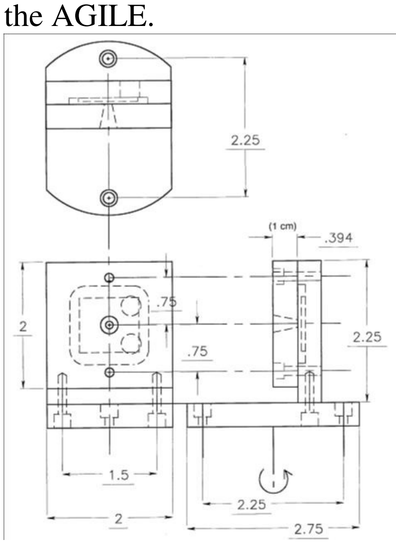


Figure 11: Housing CAD design

Final Test Set Up:

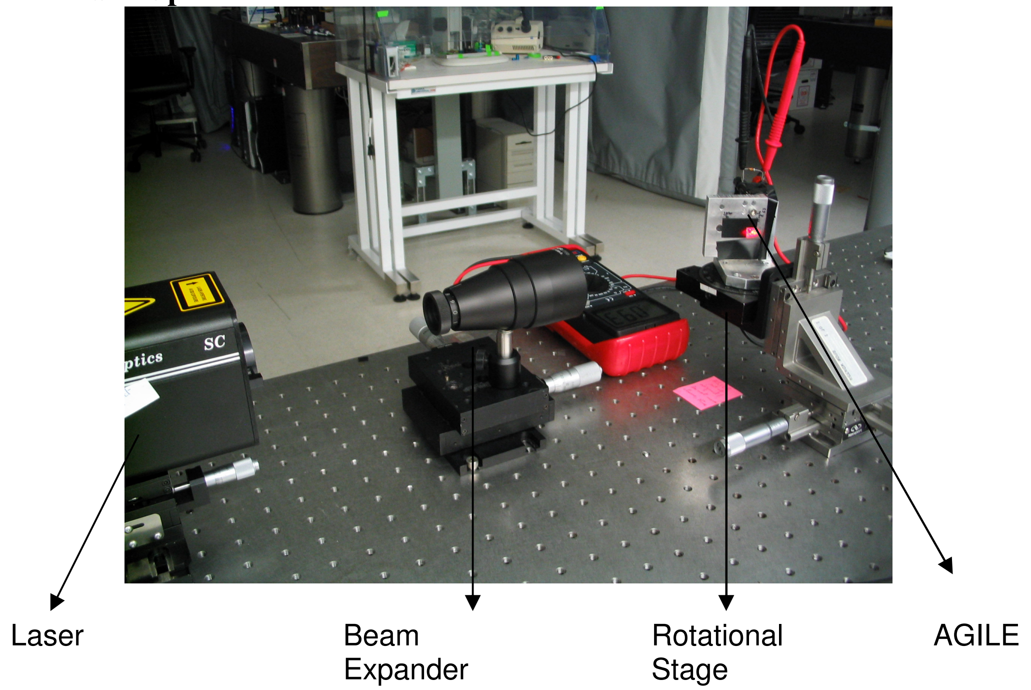


Figure 12: Test set up with the red laser, beam expander, AGILE on the rotational stage with the detector and voltmeter to measure the performance.

Statistical Rigor: The input face of the AGILE is located at the centre of rotation for every device. Angular measurement test results are symmetric (clockwise and anti-clockwise). The graphs drawn are from average values, each voltage reading has been taken at least 4 times and mean value calculated. The measurements are done in one plane but they also have full 360 degree symmetry (important for solar applications)

Characterizing the solar cell detector:

I-V curve for solar cell detector measured at different loads confirms operation of 100K load (final design load) in linear region and hence we can relate voltage measured from solar cell to light energy at output. Light intensity gain ratio = I/Io + V/Vo. The Isc (short circuit currents) are too small to measure

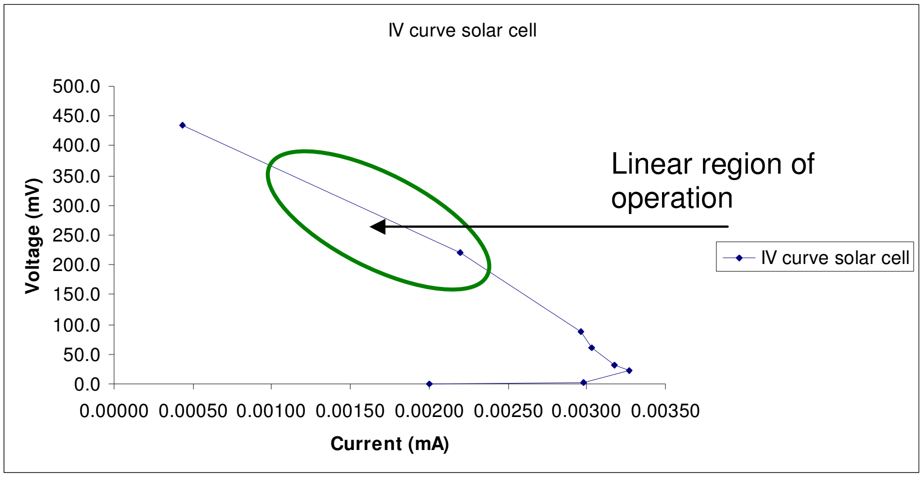
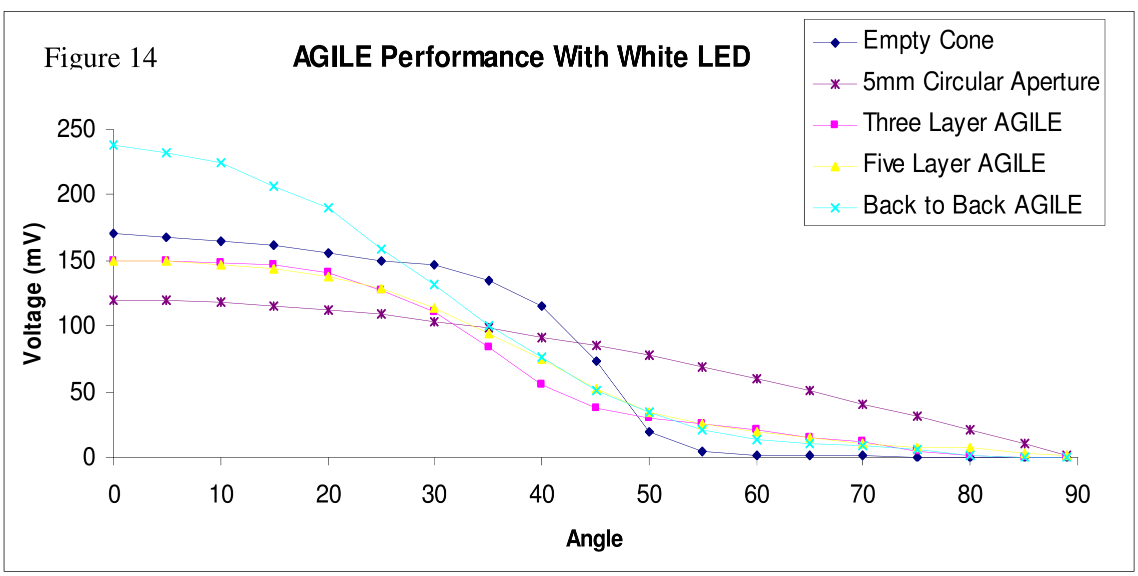


Figure 13: Testing the solar cell with different loads (the green circle indicates the linear region and our results are within this region as we will see next)

Discussion of Results:

- We have used the voltage obtained from the solar cell detector to represent the light concentrated at the output of the AGILE.
- There seems to be a sine wave superimposed over the curve for some of the red light tests. This could just be due to the way the single wavelength red light bounces around within the cavity between the agile and the detector; or within the different layers of the agile, or even within the plastic coating on the surface of the solar cell. The sine wave effect seems more pronounced with single wavelength because of destructive and constructive interference at specific angles for a given wavelength, and hence this effect is almost gone with the broader white light source
- The back to back structure gives very good performance and seems to concentrate all the light that can be incident on a 7mm diameter circular aperture. This could also be because light is now incident on a larger part of the solar cell and hence gives higher values of voltage. But mostly it is because there is better coupling of light to the detector with light going through low to high and then to low index.
- The back to back structure is a success and proves the effectiveness of the AGILE concept

Figure 14



Other interesting thing that we can see is how the results are spread between the 5mm diameter and 7mm diameter theoretical envelops that follow cosine theta loss (green and blue lines). Light concentration ability of the single AGILE structure falls around 40 degrees, this is inline with the limited range of refractive index gradient we have achieved when compared to the ideal of 1 to 3.5. Where as due to a better index matching between the back end and the detector, we can prove the concept of light concentration better with the back-to-back structure, we can see the yellow line follows the theoretical maximum blue line pretty well.

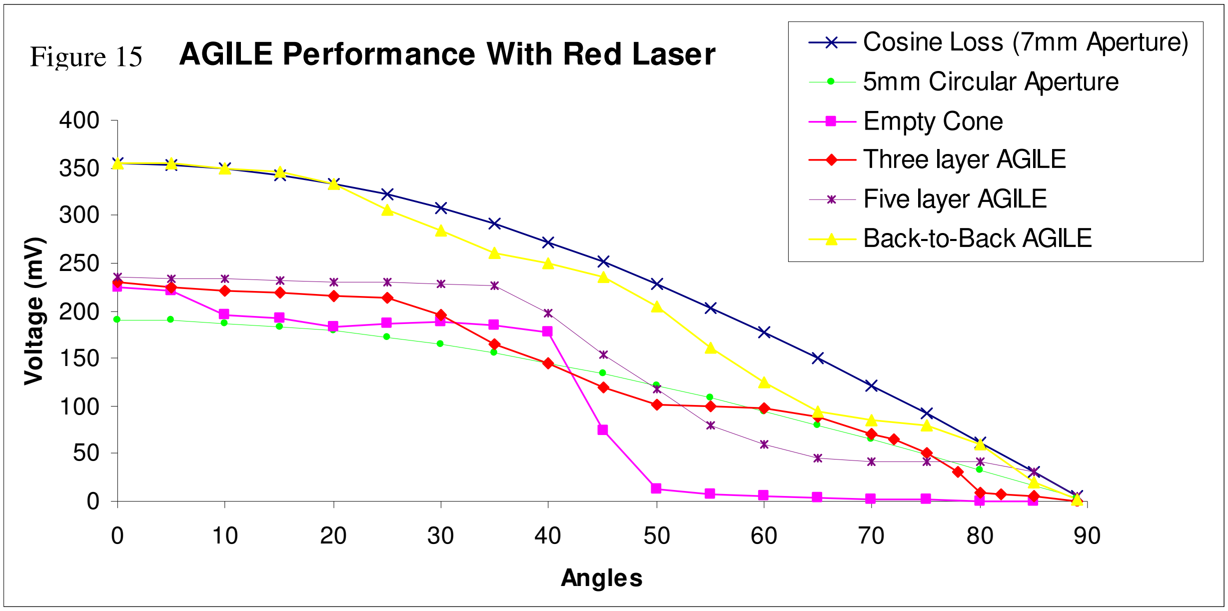


Figure 15

Concluding Remarks

- A process to make graded index optical lens material was fine tuned, which was the aim of this EE412 project
- Transmission of different laminated stacks of optical materials/optical adhesives was characterized
- Fabrication and testing of AGILEs was completed successfully
- Next steps: make AGILEs with a larger range of RI change with more aggressive area ratios, fabricate arrays of AGILEs and test the performance, investigate cheaper materials and faster fabrication methods, work can also be done with nano particles to make high index films.

Acknowledgements:

- Special thanks to my mentor Tom Carver who made the implementation of the project ideas possible and the EE412 professors, staff and students