Chapter 7

SUMMARY AND OUTLOOK

The goal of this thesis was to push the boundaries of photovoltaic efficiency in response to both current market forces and the scientific imperative to test the limit. Today's current photovoltaic efficiency record for a cell is 46% and for a module is near 39%. We aimed to use spectrum-splitting photovoltaics, in which broadband sunlight is split into separate frequency bands and sent to solar cells of different bandgap. In the best case, well-separated photons generate the highest possible voltage leading to higher overall solar-to-energy conversion efficiency, bringing up the peak power conversion efficiency and lifetime energy production which contribute to lower the $/W and LCOE, respectively.

The Holographic Spectrum Splitter design used volume phase holographic diffraction gratings to split white light into four spectral bands. Each band would be converted by a dual junction tandem multijunction solar cell allowing eight junctions with a four-way split. The design had a high efficiency potential of >37%, just eking out a record efficiency. The design complexity made simpler, slightly less efficiency designs more favorable. The underlying logic of optically recordable spectrum-splitting optical elements with the ability to diffract all transmitted light into a single diffracted order remains sound, however. Sinusoidal diffraction efficiency profiles and diffraction angle dispersion must be address for higher efficiency.

High-contrast gratings were shown to be an interesting, angle-independent single layer alternative to Bragg reflectors in photovoltaic applications. High refractive index combined with low loss was shown to be the key factor in their performance. This difficult combination makes short wavelength visible high-contrast gratings an unrealized technology. Given the very high demands of the Tandem Luminescent Solar Concentrator, alternative applications may be better suited for HCG use, such as multispectral imaging or color filtering for imaging. Similarly, the TLSC concept would be better deployed to improve the efficiency of mediocre Si solar cells rather than high efficiency silicon cell for which the presence of the waveguide diminishes the performance of an already excellent bottom cell. Similarly, applications paired with lower bandgap quantum dots and lower bandgap cells embedded in the waveguide have the potential to relax the current narrow range of specs for the HCG to give high efficiency.

The Polyhedral Specular Reflector design still has potential to be a world record efficiency device. The solid, index matched optical path with embedded DBR filters results in strikingly high efficiency spectrum splitting. However, concentration via CPC was attempted at a challenging size scale. Our path lengths were long enough that plastic materials absorbed considerable. At the same time the curvature was nearly impossible to realize in glass. Additionally, the difficulty of developing in-house processing capabilities for seven solar cells were underestimated. While GaAs and InGaP solar cells are commonly manufactured, the five additional bandgap cells were new territory for our team. Finally, our designs required micro-assembly and precision optics fabrication tools that pushed the boundaries of what is currently possible. Advances in these areas would benefit the future development of a photovoltaic technology like the Kirigami PV spectrum-splitting design. Taking on these large challenges simultaneously hampered our ability to realize a record breaking spectrum splitting efficiency despite having a design that could get there.

Overall, this thesis shows that multiple designs of spectrum-splitting photovoltaics has the potential to surpass the efficiency of today's state-of-the-art flat-panel and CPV technologies. Efforts to take the PSR concept and develop a commercial solar technology were hampered by a combination inability to realize all of the designed bandgaps of cells in the allotted time, lack of high precision glass/plastic molding and microassembly capabilities to iterate our prototyping process faster and by external market forces. In today's market the potential for higher efficiency in a new form is not as compelling as it had been earlier in the past decade when silicon raw materials prices spiked and before silicon grew sufficiency to enjoy many incumbency advantages. Whether or not the market opens again to concentrating photovoltaics or not remains to be seen. While the highest efficiency cells and modules are CPV, the technology may have missed its moment to grow enough to reap the economies of scale that would allow it to drop in price to a level competitive with silicon. If so, the future of spectrum-splitting PV innovation will lay with technologies like the TLSC which could integrate into today's silicon photovoltaics industry.

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Appendix A

OPTICAL DATA

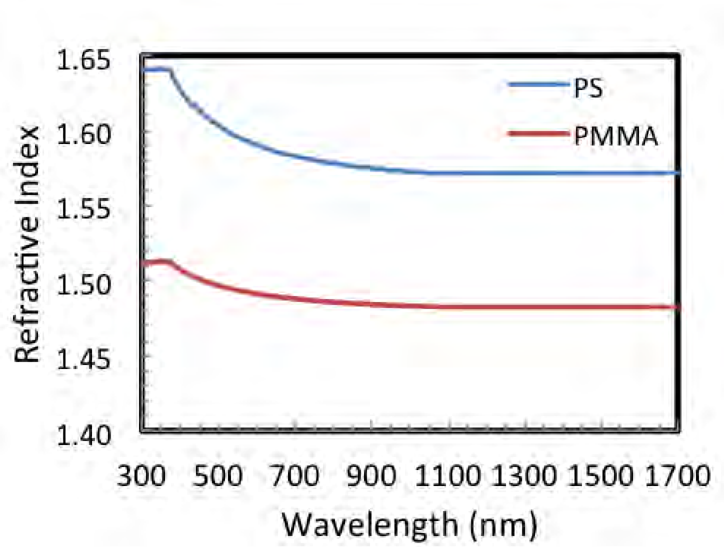

Figure A.1: Refractive index for polystyrene (PS) and polymthylmethacrylate (PMMA), the materials used for the high and low refractive index layers, respectively, in the polymer filters.

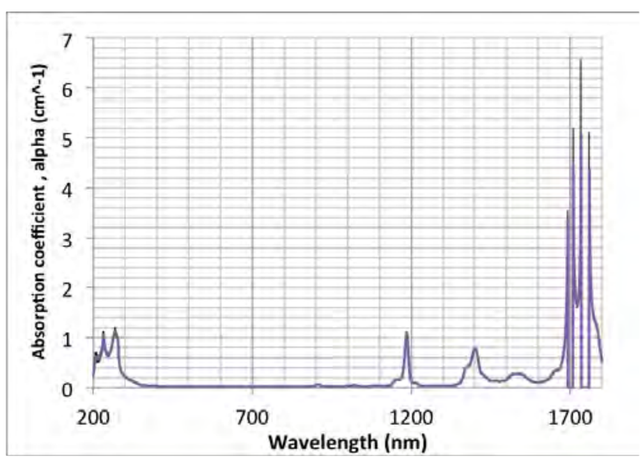

Figure A.2: Sylgard 184 2:1 base:curing agent absorption coefficient.

Appendix B

CPC DETAILS

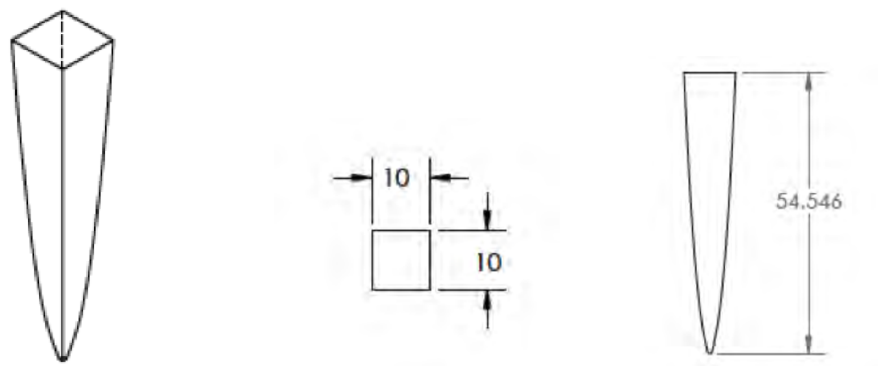

Figure B.1: perspective, top and side views of the 194X concentrator defined by the prototype design.

Sample name	Efficiency
12/4 898	62.0% ± 3.4%
11/26 #1	69.6% ± 3.1%
11/26 #2	67.7% ± 3.8%
11/25/14 898	64.6% ± 6.4%
PDMS	62.2% ± 4.3%
11/25 897	66.8% ± 4.5%
12/2 10:1	63.5% ± 2.0%
11/25 #3	66.3% ± 2.5%
11/25 #4	68.4% ± 2.6%
12/4 897 B	68.57% ± 1.7%
Average	66.0% ± 3.6%

Table B.1: Measured concentrator efficiencies

Mold fabrication

1. Mix 4:1 ratio of base to binder of Sylgard 184 together in a centrifuge tube
2. Use the PDMS centrifuge to mix and then spin the mixture to blend the two components and then remove some of the incorporated air

3. place the open vacuum tube under mild vacuum (with a dessicator in our case) to further remove air from the mixture for 10-15 minutes
4. Pour mixture around suspended positive part
5. Further degas for up to 40 minutes
6. Cure for 40 minutes at 80°C
7. When cool, gently extract the positive from the PDMS

Mold use

1. Mix 2:1 ratio of base to binder of Sylgard 184 together in a centrifuge tube
2. Repeat the mixing, degassing and curing procedure as above
3. Add collar to the mold to create an extra height to use to extract the CPC from the mold
4. Pour the PDMS mixture into the mold and degas for up to 40 minutes
5. Cure for at least 40 minutes at 80°C

Appendix C

COST MODEL

Technoeconomic analysis and bottom-up cost model

- Define the product, i.e. for a solar technology, to compare to alternatives this should be an installed area of a particular size in a particular place to be able to arrive at an LCOE that can be compared to competing technologies, especially for a higher $\$/W_p$ technology for which the advantage will be in LCOE rather than in $\$/W_p$.
- fill in missing components, e.g. racking and mounting hardware that have not yet been specified. Go with off-the-shelf, conventional parts where possible
- Compile a full bill of materials for the product
- Identify multiple sources for each input and find listed prices for off-the-shelf parts and get quotes (ideally 3+) for custom items

Bottom-up cost model

- For a bottom up model specify all steps to get from inputs to the final product in consultation with all project partners
- To incorporate scaling, get quotes at varying orders of magnitude until the price stops changing.
- Identify vendors operating at different scales – some respond well to pet projects. These are not likely to be the same vendors who can handle gigawatt scale production.