DESIGN AND REALIZATION OF A NEW CONCENTRATING PHOTOVOLTAIC SOLAR ENERGY MODULE BASED ON LOSSLESS HORIZONTALLY STAGGERED LIGHT GUIDE

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ABSTRACT

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Concentrating Photovoltaic systems are good candidates for low cost and clean electricity generation from solar energy. CPV means replacing much of the expensive semiconductor photovoltaic cells with the cheaper optics. Although the idea is simple, CPV systems have several problems inherent to their system design, such as module thickness, expensive PV cells and overheating. Light guide systems are good alternatives to classical CPV systems that can clear off most of the problems of those systems. In this thesis we explore a new light-guide based solar concentrator by optical design and simulations. It is shown that this solar concentrator can reach 1000x geometric concentration, 96.5% optical efficiency with a ±1 degree acceptance angle. As a result of simulations, effectiveness of the horizontally staggered light guide solar concentrators is proved. A practical module study is carried on to improve the knowledge related to light guide CPV systems. The concentrator geometry is fabricated as a medium concentrator system with a geometric concentration of 45x and +-2 degrees acceptance angle. With the prototype level injection molding 74% optical efficiency is achieved and can be improved with a better mold manufacturing. A cost analyses is also performed with real manufacturing parameters and it is shown that grid parity can be achieved with this kind of light guide solar concentrators.

Keywords: solar energy, concentrating photovoltaic, CPV, optical concentrators, light-guides

ÖZ

KAYIPSIZ YATAY ADIMLI IŞIK TAŞIYICI TEMELLİ YENİ BİR YOĞUNLAŞTIRICILI FOTOVOLTAİK GÜNEŞ ENERJİSİ MODÜLÜNÜN TASARIMI VE GERÇEKLEŞTİRİMİ

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Yoğunlaştırmalı Fotovoltaik (CPV) sistemler güneş enerjisini kullanarak düşük maliyetle ve temiz olarak elektrik üretimi için önemli bir adaydır. CPV en basit anlatımıyla görece az maliyetli optikler ile çok pahalı yarı iletken fotovoltaik hücrelerin büyük ölçüde yer değiştirmesi anlamına gelmektedir. Fikir basit olmasına rağmen CPV sistemleri modüllerin kesitlerinin kalın olması, PV hücrelerin pahalı olması ve aşırı ısınma gibi sistem tasarımlarının doğasından kaynaklanan bazı sorunlara sahiptir. Işık kılavuzlu sistemler bu sorunlarının çoğunu ortadan kaldırarak klasik CPV yapılarına önemli bir alternatif haline gelmişlerdir. Bu tez çalışmasında optik tasarımlar ve simülasyonlar ile ışık kılavuzu tabanlı yeni bir optik yoğunlaştırıcı sistemi geliştirilmiştir. Bu güneş yoğunlaştırıcısı ile ± 1 derece kabul açısına, 1000x geometrik yoğunlaştırmaya, %96,5 optik verimlilik değerlerine ulaşılabileceği gösterilmiştir. Simülasyonlar ile yatay adımlı ışık kılavuzlu güneş yoğunlaştırıcılarının etkinliği kanıtlanmıştır. Uygulamalı çalışmalar ile CPV modülü üretilerek ışık kılavuzlu CPV sistemlerine ilişkin bilgi birikimi geliştirilmeye çalışılmıştır. Yoğunlaştırıcı sistemi 45x geometrik yoğunlaştırma değeriyle orta yoğunlaştırma seviyesinde ve +-2 derece kabul açısına sahip olarak üretilmiştir. Prototip seviyesinde plastik enjeksiyon yöntemi ile %74 optik verimliliğe ulaşılmış ve daha iyi bir enjeksiyon kalıbı imalatı ile bu sonuç daha da iyileştirilebilecektir. Gerçek üretim parametreleri kullanılarak maliyet analizleri de gerçekleştirilmiş ve ışık kılavuzlu güneş yoğunlaştırıcı sistemleriyle şebeke elektriği maliyetine denk maliyetle elektrik üretilebileceği gösterilmiştir.

Anahtar Kelimeler: güneş enerjisi, yoğunlaştırmalı fotovoltaik, CPV, optik yoğunlaştırıcılar, ışık kılavuzları

To My Family...

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CHAPTER 1

INTRODUCTION

Sun shining over the earth is an important renewable and clean energy source. It is continuously sending lots of energy to the world which is excessively enough for the needs of everyone. Although energy is continuous, clean and free, collecting and converting that energy is necessary to be accessible for the needs of human being.

Today's energy consumption is mainly from the limited fossil fuel resources. However generating energy from the fossil fuels produce emission that is harmful for human health and environment. Global warming which is a result of accumulation of carbon dioxide in the atmosphere is an irreversible effect of this fossil fuel emission. Obtaining energy from renewable energy sources can contribute to the solution of future energy shortage while it does not cause environmental pollution and global warming. Moreover exploiting the solar energy is becoming more and more a necessity to balance the increasing energy demand.

Photovoltaic (PV) systems can collect and convert the solar energy to a very useful type of energy, i.e., electricity. Although photovoltaic modules can convert this free energy effectively, its use has been limited due to high cost of these systems. The high cost has been the main obstacle for the large scale applications of PV systems for electricity generation from the solar radiation until very recently. Large PV installations like solar power plants above MW levels have been relied on the incentives provided by the industrialized governments. However, with recent price falls in the PV products, the PV industry is becoming less and less depending on excessive incentives. This is a very promising development for the future of the PV industry.

Energy harvesting from the sun is basically done with solar modules (or panels) which operates with the principles of photovoltaic effect occurred when light interacts with semiconductor materials. In the semiconductors, artificially generated p-n junction can split the generated electron hole pair and force the current flow through an external circuitry.

PV panels are being constructed by covering all the panel area with the photovoltaic devices made of semiconductor materials having photovoltaic properties. These semiconductor materials are generally expensive and their cost prevents widespread use of them for the electricity generation. In spite of high material cost, they have found lots of applications and their use has increased dramatically in recent years. The total installed PV system has reached 70 GW with an enormous increase in the annual rate.

To increase the utilization of photovoltaic energy converters further, cost barrier has to be reduced even further. One of the ways to pass over the cost barrier is to decrease semiconductor area, which is the main part of the cost, with the help of optical concentrators. These concentrators gather light from a large area and deliver it onto smaller semiconductor area in a concentrated way. By this method it is possible to produce more energy from a unit solar cell.

Concentrating photovoltaic (CPV) systems that are using optical concentrators have potential to perform the electricity generation economically and reliably.[1] CPV can be described as combining high efficiency cells and low cost and abundant materials in a cost effective manner.

Recent studies in the solar cell research result in development of very efficient but expensive solar cells. Silicon solar cells can have an efficiency value up to 25%, whereas newly developed multilayer solar cells can work with efficiencies approaching 45% under concentrated light. Design of new type solar concentrators that have high tracking tolerance and high concentration ratio is becoming important [2] because of these new high efficiency solar cell achievements.

CPV technology is a multi-disciplinary field. This technology needs research and collaboration in fields such as semiconductor science and technology, optical engineering, electrical engineering, thermal engineering and mechanical engineering. A good working CPV solar panel should consider the every aspect of a product to function well for long years. Several different types of CPV panels have been developed to reduce the area of the semiconductor used for conversion of solar energy. Some of the panels have been designed to have very high concentration on the order of 1000x while some of them only have a few times concentration. All of the systems are targeted to reach grid parity but several persisting technical problems prevent their widespread use.

Most of the CPV panels have very bulky structure and needs too much construction material. Moreover high concentration systems have very narrow acceptance angle and needs very accurate sun trackers. The main architecture of the panels and their tracking requirements are determined by the optics. Right optical designs considering several aspects of a CPV panel can solve most of the problems in these systems.

In this thesis study, main focus is on the concentrator optics for concentrating photovoltaic applications. Discovery of more efficient, compact and cheaper concentrator optics can solve the significant problems of the CPV systems and can increase the solar energy utilization in the world. With this motivation, existing concentrator optics and their design principles have been investigated. A new light concentrating method based on horizontally staggered light guides is explored with which we think solar energy systems will become more widespread. We have developed a new system approach for which a patent application (PCT/TR2011/000156) is filed. Main important design parameters are explained in this patent document.

The limits of the horizontally staggered light guides as an optical concentrator part are investigated by optical simulations. Extra concentration features are applied in the simulations and it is shown that high concentration systems are possible with good acceptance angles. Moreover in this study thermal simulations are performed to show the performance of the linear concentration systems. It is shown that linear concentration systems are much more superior to the point focus concentrators with respect to the thermal behavior. A planar aluminum plate touching to the back of the solar cell is enough for heat dissipation in these line focus systems.

The light guide solar concentrator is realized by manufacturing the optical concentrator with medium concentration ratio, using low cost and easy production techniques. Silicon solar cells are positioned at the exit port of the light guide to convert the sun light into electricity. We have shown that the total semiconductor material usage can be reduced to 4% of what is used in an equivalent conventional system. Assembly and testing of the prototype is explained in detail for the future development efforts. Finally, a cost analyses based on the recent manufacturing processes and materials are given to show the feasibility of the method. We believe that this concentrator can decrease the semiconductor area significantly and increase the utilization of photovoltaic solar energy systems in daily life by decreasing the price of solar electricity.

This thesis has been organized as 7 chapters. Chapter 1 is the introduction to the whole study. Chapter 2 summarizes the basic concepts of photovoltaic and concentrating photovoltaic systems. In Chapter 3, optical aspects of the concentrating photovoltaics are given. Chapter 4 presents the design and simulation studies carried out in this work. A thermal analysis of the system is also presented in this chapter. In Chapter 5 the results of system realization are summarized and discussed. Suggestions for the future studies are given here. Chapter 6 deals with a cost analysis. In Chapter 7, conclusions and recommendations for future are given.

CHAPTER 2

OVERVIEW OF CONCENTRATING PHOTOVOLTAIC SYSTEMS

2.1. Introduction

Concentrating PV has a great potential for generating cost effective solutions to the solar energy conversion problems. It is a combination of high efficiency solar cells and low cost and abundant materials.

There are many different types of solar concentrators which all aim to reach highest efficiency at lowest cost. The simple idea of the Concentrating Photovoltaics (CPV) is shown in Figure 1.

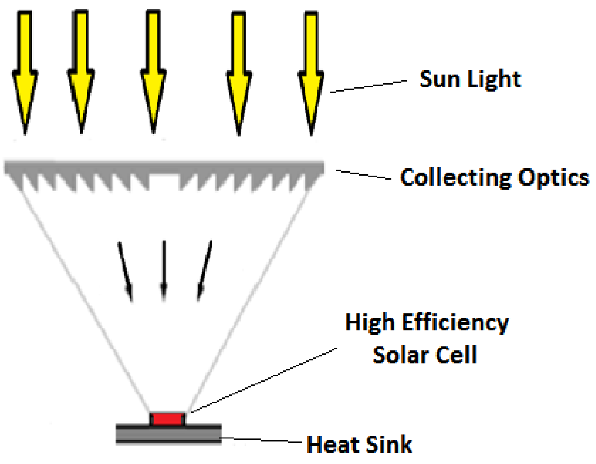


Figure 1: Schematic representation of the CPV method

CPV systems have two important characteristics. First, these systems have high system efficiency and second with CPV systems great potential for cost reduction is possible especially for big solar farms.

By concentrating the light using proper optics, only a small amount of semiconductor material is needed. Depending on the ratio of concentration, 100-1000 times less semiconductor material is required for high concentration CPV systems. Because less solar cell material is needed, high efficiency but expensive solar cells can be used with CPV systems. Although prices of the high efficiency solar cells are still too high, high concentration ratios enables us to use small amount of this cells, and thus cost effective module production is possible.

Using multi junction cells and concentrated light, very high efficiency values are attainable. Multi junction cells under concentration have reached an efficiency value of 44% in recent years. This record breaking cell performance also gives high module efficiencies. DC efficiencies of exceeding 30% have been demonstrated in recent years. This high module efficiency values are not possible with flat silicon PV panels.

In CPV systems, the optical and mechanical parts are made of low cost materials. This means that expensive semiconductor materials are replaced with cheaper materials such as glass, plastics and metals. Most of these materials are recyclable. Therefore at the end of the lifetime, most of the wastes can be used again and some of the investment can return back with the recyclable materials.

CPV systems are using optics to concentrate the light. This concentrator optics can only function if directional light exists. Most of the high concentration CPV systems has very small acceptance angle and therefore needs highly collimated light. This collimated light can be achieved if the sun light directly strikes perpendicularly to these panels. This restricts the use of these systems to high Direct Normal Irradiance (DNI) regions and requires trackers to satisfy near 90 degree angle requirement.

Concentrated solar panels should track the sun during the daytime. Tracking accuracy is important for these systems because accurate tracking systems can dramatically increase the cost. For this reason an optical concentrator which has large tracking tolerance with high efficiency and low cost is desired.

The solar concentrator systems can be distinguished from each other with respect to several features such as concentration ratio, type of optics and tracking requirements. In general these systems are classified by their concentration ratios which also determine the type of optics and tracking tolerances.

2.2. Types of Concentrating Photovoltaic Systems

High concentration (C> 100x)

High concentration systems are developed for use with high efficiency tandem solar cells. These cells have very high conversion efficiency and their efficiencies increases towards 50% under concentrated light.

Tandem solar cells are produced with expensive materials and processes and therefore at least two orders of magnitude more expensive than the crystalline silicon solar cells. Because of this high price, to realize a cost effective solar system, it is required to reach high concentration values of at least 250x.

Medium concentration (10x < C < 100x)

Medium concentration systems are using high quality single junction silicon or GaAs solar cells. Generally cost of the solar cell is not a significant parameter in these systems. These systems need single axis or dual axis tracking to function.

The main problem of these systems is heating. Because of concentration ratio, heat is accumulated fast and temperature of the solar cell increases rapidly. Silicon solar cells used in these systems are so sensitive to heating and their efficiency decreases fast with the temperature.

To overcome the heating problem, active cooling methods or larger heat dissipating fins are used. This kind of efforts increases the overall system cost and decreases the reliability of the systems.

Low concentration (C < 10x)

Low concentration systems generally have more flexibility on tracking requirements. They can work without trackers in a great portion of the day time. Although some examples use trackers, the main motivation behind tracking is to reduce the cosine effect and therefore increase the area looking to the sun. Their concentration ratio is low so that solar cell cost is still be an important factor in these systems. Extra cost parameters such as dicing and diffuser surfaces increase the cost of the systems.

Some of the low concentration systems do not use lenses or mirrors. Instead, they are using diffuse reflectors and Total Internal Reflection (TIR) to transport the light on to the photovoltaic cell. Photovoltaic surfaces and diffuse surfaces are placed side by side and some portion of the solar cell region is replaced with the diffuse coatings, so that cost of the solar panel is reduced.

Commercial examples

CPV research in recent years has led to a rapid commercialization. As a result, many studies sourced from research centers and universities have become a commercial product. In order to understand the present efforts and approaches and draw future research paths, it is beneficial to investigate the CPV systems available on the market. The current situation of the industry is periodically reported by NREL [3]. Avoiding unnecessary repetition and referring the NREL reports for a full coverage, we explain and discuss some representative and successful examples here.

As an illustration to the Fresnel lens based systems, Amonix high concentration system is a good example. It is using PMMA acrylic Fresnel lenses as the primary optics and reflective secondary optics for homogenization and increase the tracking tolerance. Very high efficiency receiver cells are accommodated at the focus of the optics. Amonix is building all factory assembled very large modules to maintain the alignment of the modules as shown in Figure 2. Amonix announced 34% module conversion efficiency in 2012.

Figure 2: Amonix Mega module

Solfocus Company is also building high concentration systems with different optical design. Their optical design based on reflective optics which can eliminate the chromatic aberration and reach higher concentration levels. Furthermore this kind of optics makes it possible to build more compact modules. Optical efficiency of this optical type is reduced by the reflection from the surfaces, cover glass Fresnel losses and obstruction because of secondary mirror. For this system lower than 75% optical efficiency is reported.[4]

Figure 3: Solfocus Company's Mirror based CPV system demonstrated in CPV-8 meeting. (Photo by author)

There are also systems trying to use less structural material like inflated balloons such as the system of Cool Earth Solar Company as shown in Figure 4. A parabolic mirror and a transparent front combined to get a balloon type CPV system. Although the commercial success and long term durability are questionable for this system it represents a good example of novel efforts for CPV applications.

Figure 4: Cool Earth Solar's inflated baloon CPV

Although most of the CPV systems are designed for utility scale applications, there are also small sized systems for home users as shown in Figure 5.

Figure 5: Green & Gold Energy's CPV SunCube module.

2.3. Optical architectures in CPV systems

There are many examples of optics used in the CPV systems. Generally most of the systems can be grouped into smaller sub-groups. The dominant form of the CPV systems are the Fresnel lens based systems. Mirror based and light guide systems are also developed to be alternatives to these systems.

Fresnel lens based systems

Fresnel lens based systems are using the simple idea of collecting the solar radiation and focus it onto the solar cell. If an ordinary lens is used, the lens will be too thick for a commercial system. To overcome the thickness problem associated with the large lenses, thinner Fresnel lenses are used to concentrate the light as shown in Figure 6. These lenses have similar optical properties while require less optical material. With less material usage, these systems are cheaper and lighter than the ordinary conventional lenses.

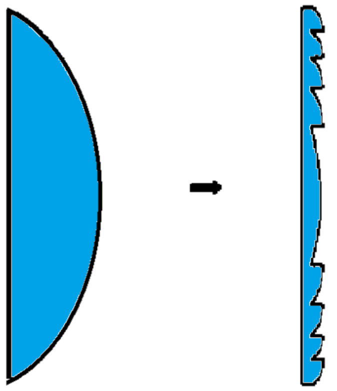


Figure 6: Comparison of ordinary lens (left) and a Fresnel lens (right)

Fresnel lenses were initially produced from glass. The sharp corners of the lenses were problematic because of delicate nature of the glass. Moreover in molding processes, high surface tension of the glass is rounding the sharp edges of the Fresnel grooves and lowering the optical performance. With the development of high quality optical plastics, such as PMMA, Fresnel lenses are now produced from this kind of transparent plastic materials.

Fresnel lenses have many corners because of their faceted geometry as shown in Figure 7. The edges should be infinitely sharp but always a degree of rounding exits in these corners. Tip and valley rounding is an important loss mechanism in these lens type. Moreover Fresnel lenses are produced by using plastic molds. To remove the mold from the material always a draft angle is needed. This draft angle also exists in the final product and causes optical losses. By collecting all the loss mechanisms, Fresnel lenses that are used in CPV systems can have %80 percent optical efficiency while very high quality ones can have a few percent higher than this value.

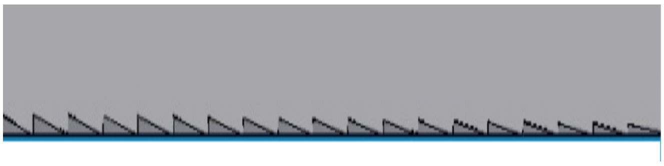


Figure 7: Faceted geometry of Fresnel lenses

The spherical aberration problem of ordinary lenses does not exist in Fresnel lenses. Every faceted ring can be designed separately and therefore non-imaging designs are possible.

There are several variations of the Fresnel Lenses. A normal Fresnel lens has a flat front surface. But if the front surface is curved, than some refractive power can be obtained from this surface, moreover draft losses and edge rounding losses can be reduced by optical design to some extent. Conical Fresnel lenses and Dome Shaped Fresnel lenses are also possible. Classical Fresnel lens and dome shaped Fresnel lens are shown below in Figure 8 for illustration.

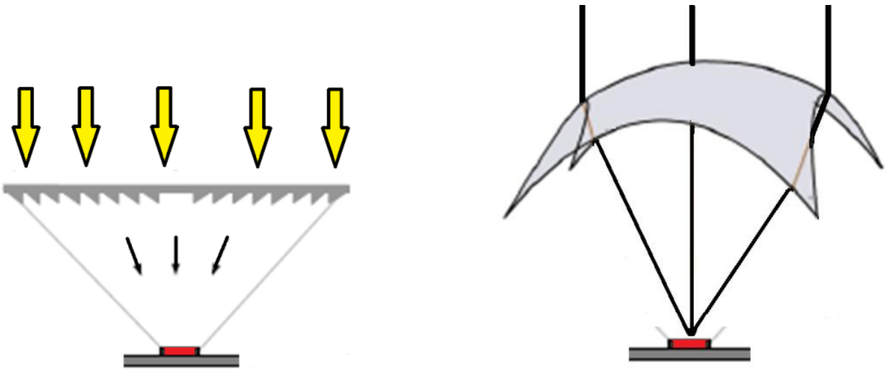


Figure 8: Comparison of classical Fresnel lens and Dome Shaped Fresnel lens.

One of the important variations of the refractive Fresnel lens is total internal reflection (TIR) lens as shown below in Figure 9. A refractive Fresnel lens gets lossy when the lens f-number gets smaller [5]. This is mainly sourced from the Fresnel reflection losses from the facet surfaces. To eliminate this problem, TIR reflection can be included to the design. TIR lens is using internal reflection from facets to concentrate the light. Generally center region is ordinary Fresnel lens because TIR surfaces become too steep if used at the center region. This lens type can reach higher concentration levels as a result of achieving lower f-number.

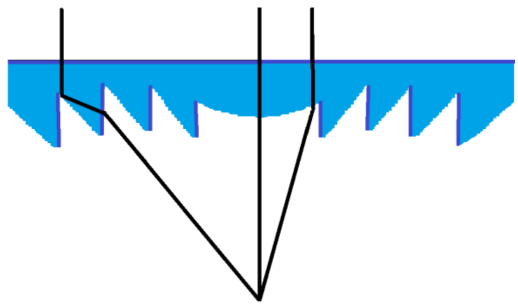


Figure 9: TIR Fresnel lens

Production of the TIR lenses is harder than the ordinary refractive Fresnel lenses because in this lens type two surfaces are functioning to concentrate the light. Facets are steeper and therefore needs sophisticated mold surface production.

Mirror based systems

Optical systems that consist of reflective optical components can also be used as an optical concentrator. Either a single parabolic geometry (Figure10) or a combination of several mirrors can be used for this purpose. This system uses reflection only to concentrate the light, therefore there is no chromatic aberration in this system which enables us to reach higher concentration levels.

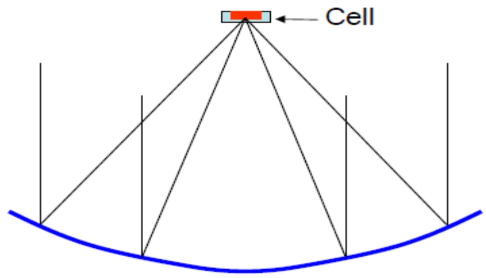


Figure10: Parabolic mirror concentrator

Mirror based systems generally have an obstruction in front of the light. If a single parabolic mirror is used, the obstruction will be the solar cell, support structure and the cooling elements. A better cooling mechanism or stronger support structure will increase the shading losses. By using Cassegrain configuration as shown in

Figure 11 it is possible to locate the solar cell at the back of the solar panel. As a result larger and better cooling elements can be used without obscuring the light. But in Cassegrain systems, secondary mirror will still cause obstruction.

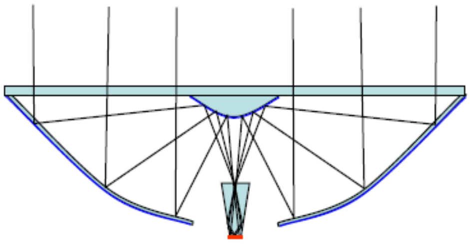


Figure 11: Cassegrain two mirror concentrator with secondary optics

Cassegrain configuration has advantage of folding the light paths and reducing overall system length. As a result, bulkiness of the system can be reduced. In the real operating conditions there are degrading effects on the mirrors. Generally a front cover glass is used to generate a closed solar panel. The front cover glass also been used as the support structure of the secondary mirror. Although there are many advantages of using cover glass, because of adding two more optical surfaces, %8 of the light will be lost from the cover glass if no AR coating is applied.

Light guide based systems

Light guide systems are a newly developing concept. In light guide systems, incoming solar radiation first concentrated by a series of small lenses or concentrating elements onto injection regions of a light guide. The light guide collects and in some cases concentrates the light and sends to a common exit port where the solar cell is located.

The commercial examples are all based on the similar light guide geometry where the light guide steps are towards the thickness of the light guide. Morgan Solar Company is trying to commercialize a light guide concentrator based on circularly rotated form of vertically staggered light guide. This company is trying to realize a high concentration system and their patent applications show that they will also try medium concentration versions of vertically staggered light guide.

Horizontally staggered version of the light guide solar concentrators is studied in this thesis. No prototype or performance related publications have been recorded on this particular approach. We have designed and realized this system during this Ph.D. study. We have materialized a prototype of the system and a patent application has been performed. During our patent applications we found that a simple model based on a similar idea was discussed in a conference paper published by a group from Rochester University.[6] However, this publication did not include many of the features such as optical and thermal simulation, PV performance analysis, and practical realization of the system. We have fabricated and tested a prototype based on this approach for the first time in this Ph.D. study.

2.4. Problems and challenges of conventional point focus CPV systems

Solar cell geometry

Sun has a circular geometry and occupies an angular size of 0.26° on the sky. As a result, the image of the sun at the focused region is circular and light only illuminates circular regions on the solar cell. While the illumination is circular, solar cells are produced in rectangular forms. Geometries of the illumination and the solar cell do not match well and solar cell is not used effectively under such a condition.

Besides wasting of the solar cell, some part of the solar cell is not illuminated and therefore non uniformity losses occur. Efficiency of the solar cells generally drops under non-uniform illumination.

Bulkiness

If a solar module gets thicker, it uses more material to be stiff and getting heavier. In windy days, a thicker module is exposed to more drag force and mechanical structure should compensate this force. Moreover, high module thickness is not good for cost effectiveness because thicker modules require more material usage.

A Fresnel lens can focus the light to a distance equal to its focal length. This is the place where the solar cell is sitting. Therefore the module should be at least as thick as the focal length of the lens. Fresnel lens based systems are generally thicker and called as box type systems. Although mirror based systems diminished this problem, the thickness of the module is still higher than the flat plate silicon panels.

With respect to the panel thickness, the only non-problematic structures are light guide systems. Light guide systems using small focal length lenses, and light guide itself is generally not a thick structure. Therefore they have similar thickness values with the commercial flat plate silicon panels.

Solar cell cost

In high concentration systems, tandem solar cells are commonly used. These cells are too expensive and therefore it is only possible to use them under high concentrations. In spite of high concentration with a small cell area, the cell cost is still an important part of the total module cost.

Tandem solar cells are using rare earth materials and their availability in high volume is questionable. Their production techniques include epitaxial growth and therefore still not very suitable for the mass production.

Overheating

Even a small child with a magnifier knows that focusing the sun light causes overheating and even fires. The solar concentrators also have the same effect because of the highly focused sun light.

Heating reduces the solar cell efficiencies. This effect is high in the silicon solar cells and still significant in the GaAs based tandem solar cells.

Overheating can dissolve solder joints and break the electrical connections. Moreover overheating and uneven temperature distribution can distort the module structure because of thermal expansion and can cause optical misalignments.

Classical point focus systems have over heating problems because of difficulties in heat dissipation. Heat moves in the material with temperature gradients. Linear heat generation is better than the circular generation if the same amount of heat generation area is considered which is shown in Chapter-4.

Available radiation

Most of the high concentration optics can only collect light from a small portion of the sky. CPV optics can transmit light to the photovoltaic cell, if only the light is received from a proper direction. Therefore only the direct portion of the solar irradiation is available. Direct portion of the solar irradiation is only 80-85 % of the total irradiation in clear sky condition. Although high concentration systems can use higher efficiency solar cells, their bad diffuse radiation performance reduces the total output power.

Tracking tolerance

Medium and high concentration systems have to use sun trackers to function well. Although trackers add complexity to the systems, two axis trackers can increase the yearly output power approximately 40%. If the tracker is reliable and cheaper, the tracker requirement of the CPV systems becomes pros of the CPV systems. But this profit can be lost if the tracking tolerance gets tighter like in the very high concentration CPV systems. Tighter tracking tolerance needs stiffer and delicate trackers. Accurate trackers are costly, more prone to errors and can lose tracing with a small breeze.

Optical efficiency

Optical efficiency of the optics is an important factor in the module power outputs of the solar concentrators. Optical concentrators have several loss mechanisms which have already been mentioned. The losses from boundaries, called Fresnel losses, can be reduced by the application of anti-reflection (AR) coatings. AR coating is not widespread in the industry because of high cost of the vacuum coating processes. But recent developments on sol-gel coating methods can solve this problem with low cost methods.

Besides the cost effectiveness of the methods, most of the AR coating methods are not suitable for Fresnel lenses. To apply vacuum AR coating, first of all a dip coating or sprayed hard coating process is necessary for the plastic lenses. The problem comes from the faceted geometry of the Fresnel lenses. Dip coating process is not suitable for such fine structured optics because fluid is not only wetting but accumulates at the valleys of the lens surface.

Summary of problems and future directions

Invention of new optics and their cost effective production methods can lead to revolutionary changes in the CPV systems. For an ultimate success of the CPV idea, low cost modules with mass production of trackers and high efficiency concentrator cells are needed. Upcoming years can be CPV age of solar energy if good solutions are discovered to the persistent problems. The problems of the systems are summarized below which are already mentioned in detail with in this section.

Table 1: Summary of problems for CPV systems

Solar Cell Geometry	Sun image is circular while solar cell is rectangular. This causes inefficient use of solar cell area.
Bulkiness	Modules are very thick. Thicker module consumes excessive material and needs stiffer support structure.
Solar cell cost	High efficiency solar cells are too expensive. Very high concentration ratios are required for cost effectiveness. C > 500x
Overheating	Needs cooling fins and panels are separated from each other to promote air circulation.
Available radiation	Diffuse radiation is lost because of small acceptance angle of high concentration systems.
Tracking tolerance	Expensive solar trackers with stiff construction are needed.
Optical Efficiency	Fresnel lenses are lossy and not possible to use ordinary AR coating directly to reduce losses because of small features of faceted geometry.

2.5. Photovoltaic cells for CPV

Photovoltaic cells are devices that generate electricity using energy of light. The photovoltaic effect was firstly observed by Alexandre-Edmond Becquerel in 1839. His discovery showed that, exposure of light on metal electrodes in an electrolyte solution generates electricity. Following him, in 1877 Adams and Day encountered a similar phenomenon in solid selenium and they built first solid structure having photovoltaic current generation. Following years served for the development of physics behind photovoltaic effect and photovoltaic cells. In 1954 the first single crystal silicon solar cell having 6 % efficiency was developed by Chapin et. al. in Bell Laboratories. This single crystal silicon solar cell is the beginning point of the modern photovoltaic systems that we use today.

In 1950s and 1960s, photovoltaic technology was mostly used for powering artificial satellites. The first satellite to use solar panels was the “Vanguard 1”, launched in March 1958 with solar cells made by Hoffman Electronics. The successful launch and operation of this first satellite created interest in development of new solar powered satellites either for earth observation or communication purposes. This critical application area of solar cells is motivated by funding of research for improved solar cells.

Years of research improved the efficiency of silicon solar cells and also generated new kinds of solar cells such as thin film solar cells, organic solar cells and multi-junction solar cells. The most efficient solar cells developed up to now are multi-junction tandem solar cells and they have an efficiency record of 44% in 2012 from Solar Junction Company.

Architecture of solar cells

A photovoltaic cell is a two terminal device like a diode. Solar cells are constructed from semiconductor materials having artificially generated p-n junction in it. Electrons in this materials move from valance band to the conduction band when they absorb energy from the light.

Figure 12: Excitation of electrons from valance band to conduction band as a result of light absorption

Built in electric field exists inside this solar cells as a result of the artificially generated p-n junction by doping. This electric field separates electron hole-pairs from each other and forces electrons to flow through an external circuitry. The schematically representation of an operating solar cell is shown in Figure 13.

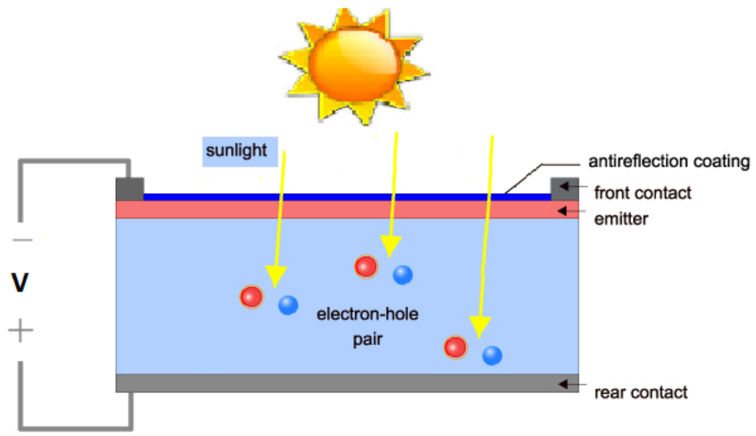


Figure 13: Solar cell model

A single solar cell is a low voltage device and ordinary solar cells can only generate a voltage in a range of 0.5 to 1 V. To construct a useful power generator with a desired voltage and current, several solar cells are connected in series and parallel to form a solar panel.

Photovoltaic device model

Photovoltaic generators can be modeled by a current source in parallel with a diode in ideal conditions. Real photovoltaic cells have also several resistive disturbances which can be generalized in two components, shunt resistance and series resistance. A high shunt resistance and a low series resistance values are desired for a well behaving solar cell. The circuit model of the solar cell is shown in Figure 14.

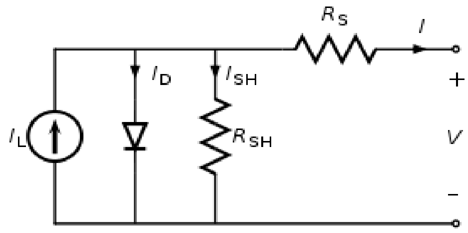


Figure 14: Electrical equivalent of a solar cell

The mathematical representation of an ideal solar cell is an ideal diode in parallel with a light-generated current source and leads to the following expression:

$$J = J_{sc} - J_0 \left[\exp\left(\frac{qV}{k_B T}\right)\right] - 1 \tag{1}$$

Where q =1.602×10^{-19} C is the magnitude of the electronic charge, k_B =1.380×10^{-23} m^2.kg.s^{-2}.K^{-1} is Boltzmann's constant and the temperature T is assumed to be 300 K. When the contacts are isolated the expression for the open circuit voltage can be found as:

$$\mathrm{V_{OC}} = \frac{k_B T}{\mathrm{q}} \ln\left(\frac{J_{sc}}{J_0} + 1\right) \tag{2}$$

The power generated by a solar cell is determined by the incident light level. Generally the incident light level is well defined for testing of the solar panel standards and it is constant. By knowing the incident light level and the power output, the important parameter efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{in}} \tag{3}$$

If the I-V curves of the solar cells have been in a rectangular shape, than the maximum generated power will be the multiplication of the short circuit current with the open circuit voltage. In reality, the I-V curve is not rectangle and the performance parameter "fill factor" defines the shape of the I-V curve of a solar cell. Definition of fill factor is [7]:

$$\mathrm{FF} = \frac{\mathrm{P_{max.out}}}{\mathrm{V_{OC}} \times \mathrm{J_{SC}}} \tag{4}$$

Several important parameters of a solar cell can be extracted from I-V curves as shown in Figure 15. Maximum power point, open circuit voltage and short circuit current can easily be obtained from I-V curves. Moreover series (R_s) and shunt (Rsh) resistances can be calculated. The reciprocal of the slope of the curve where voltages are closer to the 0 gives the shunt resistance. Shunt resistance should be large and it is the main indicator for the edge isolation performance. Similarly the reciprocal of the slope of the curve at the open circuit voltage region indicates the series resistance. The mathematical expressions of R_s and R_{sh} are shown as;

$$R_s = \lim_{V \to VOC} \left(\frac{dI}{dV}\right)^{-1} \qquad R_{sh} = \lim_{V \to 0} \left(\frac{dI}{dV}\right)^{-1} \tag{5}$$

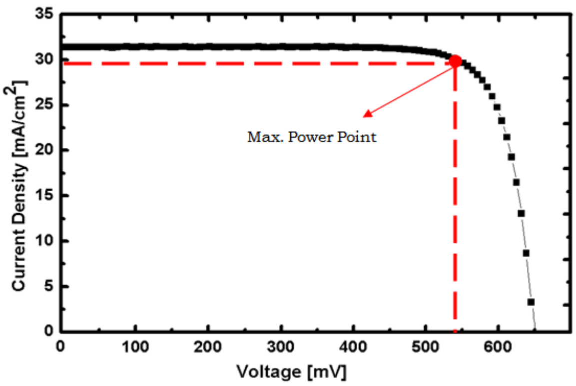


Figure 15: Typical I-V curve for a solar cell

Silicon solar cells: First generation solar cells

Silicon solar cells are first generation solar cells and the most common cell type in the market. They are classified with the quality of the material that they use. In general single-crystalline type has higher efficiency while multi-crystalline have lower cost. These solar cells are produced from silicon wafers that are cut from the larger ingots. Most of the silicon solar cells have screen printed contacts while other metallization schemes also exist in some specific technologies such as in the interdigitated back contact solar cell technology.

Figure 16: Crystalline silicon solar cells

First generation solar cells have an expected life span of 20-25 years and their degradation rates are known for long periods. The silicon industry is a very mature industry today. These cells have the most widespread use and the oldest track records.

Thin film solar cells: Second generation solar cells

Silicon purification and wafer manufacturing processes are not cost effective processes and therefore crystalline silicon materials are expensive. To reduce the cost of the solar energy, several attempts have been made to reduce the semiconductor material used in solar cells.

Thin-film technologies reduce the amount of active material of solar cells considerably. Most thin film solar cells are produced by vacuum coating processes onto the glass or plastics. The majority of the film panels have significantly lower conversion efficiencies. There are several types of thin film Technologies. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (aSi) are major thin-film technologies that have obtained some market share.

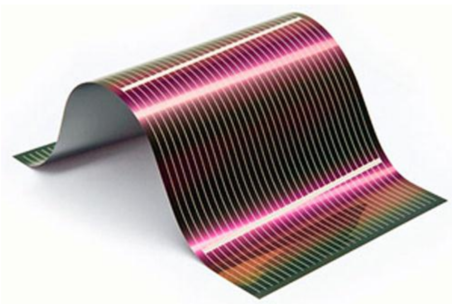


Figure 17: Thin film CIGS solar cell on flexible substrate[8]

Multi-junction solar cells- third generation solar cells

Extensive research on solar energy conversion technologies has generated lots of new kind of solar cells and some of these new solar cells are classified as the third generation solar cells group. These solar cells utilize novel concepts, new materials and nanostructures. Nano-crystalline silicon solar cells, photo-electrochemical solar cells, dye sensitized solar cells, organic solar cells, hybrid (organic-inorganic) solar cells and tandem solar cells are some examples of this generation. Tandem cells or so called multi-junction solar cells made of GaAs family are very important for the CPV systems.

Multi-junction cells are developed to utilize as much of the solar energy as possible by eliminating the band gap limitation. Every layer of the cell is sensitive to different portions of the solar spectrum and designed to maximize the power generation[9]. Multi-junction cells are designed to satisfy current match at every layer and minimum current generating layer is determining the maximum current that can be obtained from the entire solar cell. Band gap and material type of the solar cell is determined with respect to the spectral distribution of the sun light. Therefore these cells are sensitive to spectral content of the light.

Multi-junction cell concept is very successful and their efficiency is continuously improving as shown in Figure 18. These cells are using rare earth materials and also using expensive epitaxial growth processes. Main barrier related to their widespread use is the cost and it limits these cells to be used only with high concentration systems that has concentration ratio higher than 250x.

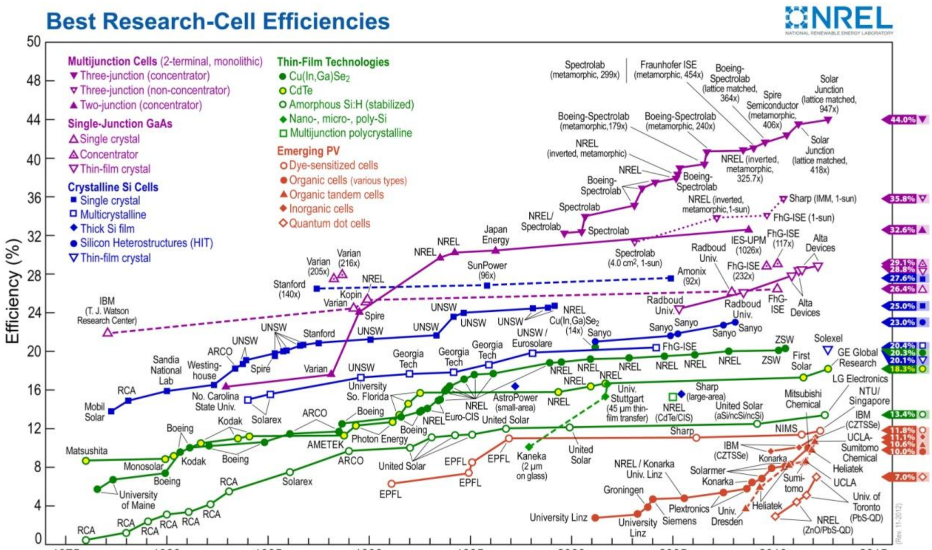


Figure 18 NREL's best research-cell efficiencies chart [10]

Important parameters of solar cells in CPV systems

CPV cells differ from the ordinary solar cells by several aspects. The main differences of these cells are their high current densities at the working conditions. A concentrator cell should be designed by considering that they will receive higher solar flux and therefore generate higher current densities. This current density can be transferred well only if the cell's series resistance allows its flow.[11] Therefore one of the most important parameters for a CPV cell is series resistance associated with the metal connections.

To understand the effect of illumination on FF of the cells, a standard H patterned cell produced at GÜNAM labs is compared with a buried contact solar cell (which is described below). I-V curves of the cells were measured at different illumination levels. The resulting I-V curves are given in the Figure 19.

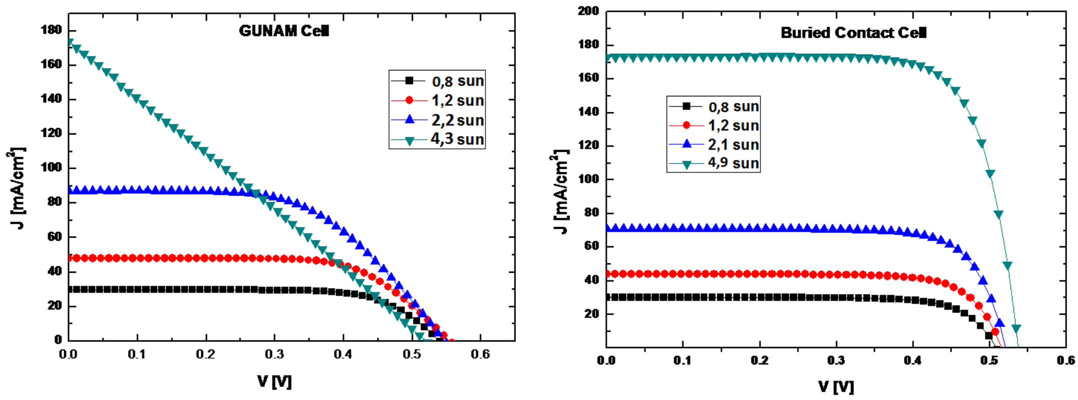


Figure 19: Comparison of I-V curves

It can be seen from the data that the IV curve of the buried contact solar cell is keeping its rectangular shape with increased illumination while screen printed GÜNAM solar cell loses its shape with illumination. This means that screen printed cells has a reduced FF at higher illuminations due to the resistive losses with increasing current densities.

Open circuit voltages are also changing with the illumination and in general increasing with the illumination level, but the open circuit voltage is also very sensitive to temperature changes. These measurements are not performed on a constant temperature environment and concentrated light causes rapid heating of the solar cells. Therefore absolute values of the open circuit voltages that obtained in these measurements should not be taken as a reference.

Low series resistance cells need proper metallization. Screen printed cells are not as good as a concentrator cell, because series resistance is too high for this kind of metallization.[12] Buried contact cells have smaller series resistance because of having larger and better contact region and therefore it is possible to use them in concentrating systems.

There are three different cell type developed in the literature suitable to use with silicon based concentrators. These cells are back contact solar cells, buried contact solar cells and sliver solar cells. Their common property is smaller series resistance and ability to work under high illumination conditions. These cells are explained below in detail.

Buried contact silicon solar cells

Buried contact solar cells are front contact solar cells. Distinguishing property of these solar cells is that their metal fingers are buried into the silicon wafer. This type contact has high area of contact and therefore has low series resistance.

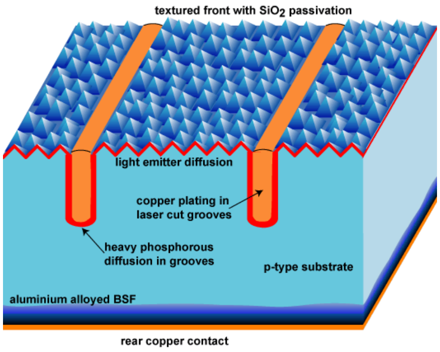


Figure 20: Buried contact solar cell (Source: PVCDROM)

Buried contact cells are first commercialized to be flat plate PV panels. But recent developments in the flat plate silicon panels have destroyed the market opportunities of these type solar cells. Only the company NAREC is producing this technology now in a plot line for the concentrating photovoltaic systems.

Back contact silicon solar cells

These cells are using float zone silicon wafers with high lifetimes. All the metal contacts are at the back of the solar cell. Sunpower Corporation has commercialized these cells as a flat panel PV and reached an efficiency record of 24.2 % on a full scale wafer. Recent collaborations across Europe also try to commercialize this technology. IMEC has showed a prototype achieved 23.4% efficiency for small size cells. Because of the float zone wafers and more sophisticated production methods, these cells are more expensive than the commercial screen printed solar cells.

The best cell type for the silicon concentrator systems are back contact solar cells. These cells have larger contact areas at the back of the cells and therefore have smaller series resistance. Moreover as a result of absence of the front metallization, they don’t have finger shading losses and higher efficiencies can be achieved.

Sliver cells

Sliver cells are using less silicon material for cost reduction. These cells have their metal contacts at the side of the cell as shown in Figure 21. In general cells are very thin and highly efficient. The main limitation of Sliver cells are their small width in the range of 0.5mm to 2mm. They are commercialized as a flat PV panel by arranging many of them side by side.

This technology can be used with the special types of the CPV optics, such as light guide concentrators or luminescent concentrators. This type of solar cell can have efficiencies above 20% at 1 sun and does not have finger shading losses.

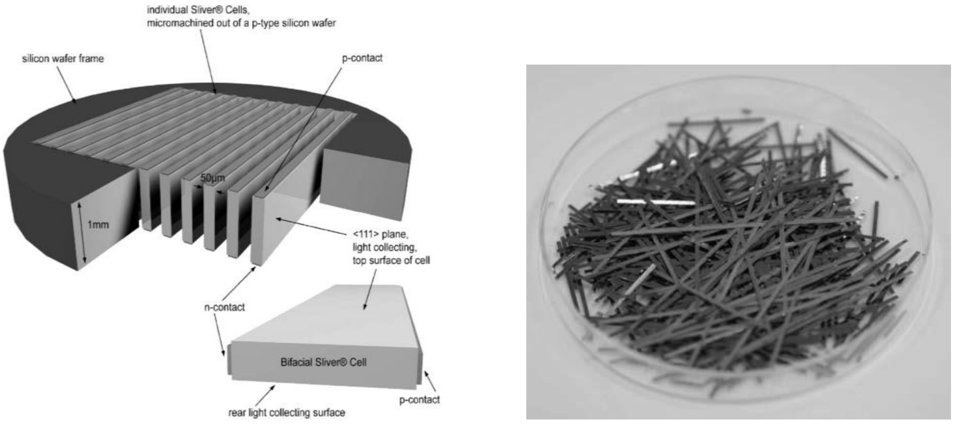


Figure 21: Sliver cells [13]

Effect of light intensity

Efficiency of solar cells tends to increase under concentrated light. With higher illumination levels some of the loss sources remain constant or increase less than the increase of the illumination level. The increase of the solar cell efficiency depends on the solar cell type and design of the solar cell.

The equation below gives the relation between open circuit voltage and the concentration ratio. In the equation m is the ideality index. As shown from the equation, voltage logarithmically depends on the concentration level [14][9].

$$V(T,C) = V(T,1) + \frac{mkT}{e}\ln(C) \tag{6}$$

For silicon solar cells the peak efficiency point can easily be obtained at 30-50x range and can be manipulated with the cell design as shown in Figure 22. For the tandem cells, manufacturers design the cell to have their peak point somewhere close the 500x or that point is specifically designed for the targeted cost effective concentration ratio.

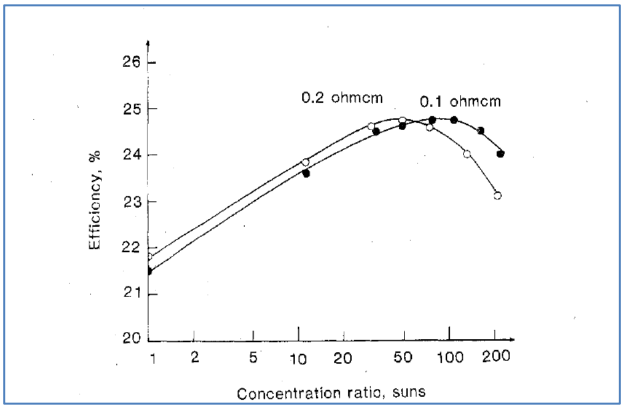


Figure 22: Energy conversion efficiency versus concentration ratio for two different silicon solar cells.[15]

Back contact silicon solar cells are shown to work with an efficiency of 27.5% under concentrated light in 1986 as demonstrated by Stanford University [16] [17].The most efficient solar cell ever produced is 27.6 % from Amonix with a concentration ratio of 92x in 2005. The silicon solar cells generally show their peak efficiency below 100 suns. Silicon solar cells have limiting efficiency lies in the 36-37-percent range under concentration. This limiting value drops to 29.8 percent for non-concentrating cells.[18]

The improved efficiency under concentrated sunlight related to the current and voltage output of a solar cell. The current increases linearly with illumination while the voltage output not staying constant but increases logarithmically. This behavior cause efficiency increase in solar cells. [16] This efficiency increase can partially compensate the optical and thermal losses inherent to CPV systems.

Effect of temperature

Efficiency of solar cells decreases with the increasing temperature.[19] Although the current increases slightly with the temperature, the voltage drop is more significant with the temperature increase and as a result efficiency drops. Under one sun condition most of the silicon solar panels has 0.38 %/°C to 0.50%/°C drop in their conversion performance.

Temperature affects several parameters of the semiconductors. First of all, as a result of temperature increase, band gap of the semiconductors are reduced. This is explained by Varshni's empirical formulation [20] [21][22]:

$$E_g(\mathrm{T}) = E_g(0) - \frac{\alpha T^2}{\mathrm{T} + \beta} \tag{7}$$

Where $E_g(0)$, α and β are material constants. For Silicon crystal, $E_g(0)$ is 1.1557 eV, α is 0.0007021 eV/°K and β is 1108 °K . Values are calculated in the below table for different temperatures and it is shown that the effect of temperature is not significantly influence the band gap and for 30 °C increase beyond room temperature, reduction of band gap is only 0.7% with respect to the value at room temperature. As a result smaller energy photons that have only 9 nm larger wavelength can be absorbed by the material. Therefore short circuit current of the solar cell will slightly increase as a result of temperature increase. [21]

Table 2: Effect of temperature on silicon band gap

T(°C)	E(g)	Change (%)	Corresponding Wavelength (nm)
25	1.112	**0.0**	1115
35	1.109	**-0.2**	1118
45	1.106	**-0.5**	1121
55	1.103	**-0.7**	1124

Besides the band gap of the material, temperature also influence the intrinsic carrier concentration of a material. For solar cells this causes an increase of the back saturation current (I_0). If shunt resistance is high enough, open circuit voltage of a solar cell depends on the back saturation current with the below formulation.

$$V_{OC} \cong \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \tag{8}$$

Increase of the back saturation current as a result of temperature elevation is the main responsible mechanism for the temperature degradation of open circuit voltage.

The ratio of the open-circuit voltage to the intrinsic band gap is the primary predictor of the temperature coefficients of solar cells[23]. Higher efficiency cells with higher open circuit voltages have better temperature response, as an example back contact solar panels have -0.38 %/°C temperature coefficient which is the smallest in crystalline silicon panels.

The level of efficiency loss of solar cells with the temperature is affected by the concentration ratio. The drop per degree is lower in the high concentration region. This effect is also applicable for the silicon solar cells. Temperature dependence of open circuit voltage of the silicon concentrator cells is expected to drop from 2.2mV/°C for one sun illumination and to about 1.8mV/°C under 100x concentrated sunlight.[14] This behavior is shown in Figure 23. Although V_{OC} drops at elevated temperatures, the change is slower at higher illumination values and higher open circuit voltages (V_{OC}) can be obtained under the concentrated light.

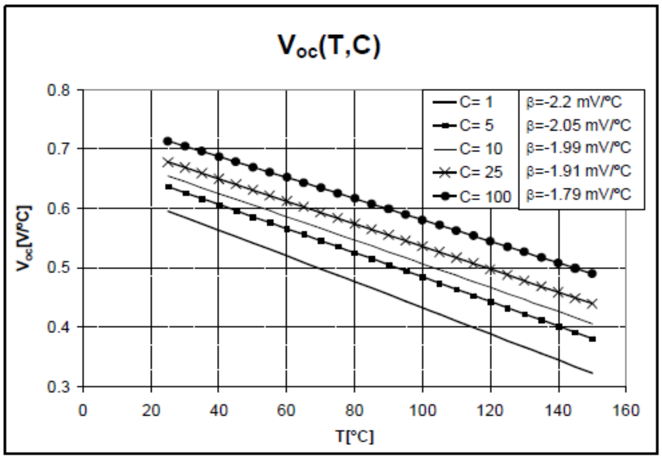


Figure 23: Voc vs. temperature and concentration level [14]

Effect of module geometry- single cell vs. dense array

Most of the concentrator cells are produced from smaller cells that are cut from standard wafers. This increases cell count and number of electrical contacts. But smaller cells receive smaller amount of radiation and thus thermal cooling is easier.

Some CPV designs prefer working more on the heat transfer problems and using bigger cells. In this case sophisticated cooling means are necessary to overcome the thermal issues while electrical connections get simpler. Two systems, one is using dense arrays and other using small single cells are shown in Figure 24.

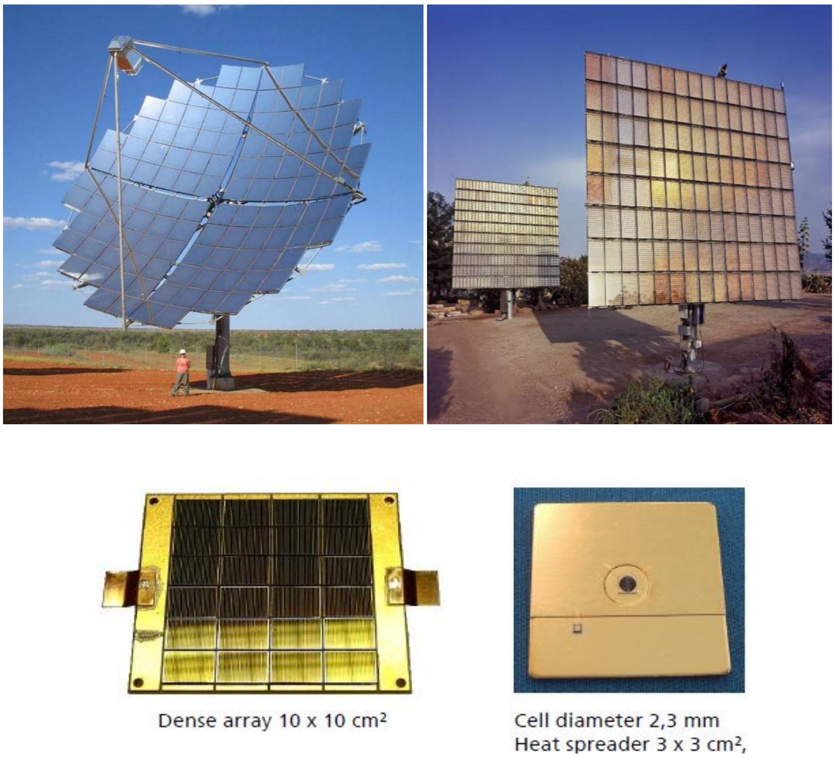


Figure 24: Solar System and Concentrix Solar high concentration systems and dense array vs. small single cell [24]

CHAPTER 3

OPTICS FOR SOLAR ENERGY

3.1. Introduction

There are many different optical configurations that have been used in CPV systems. Although geometries are so different, their design effort created several common design methods. The degree of attainable concentration is an important consideration for the CPV systems. It is of great interest to estimate this value for any particular design.

In the first look, geometric optics does not seem to have any relation with the thermodynamics; in fact concentration level is limited with thermodynamics rules [25]. Concentration limit which is derived from the étendue concept is preventing building optical perpetual motion machines. By knowing the ideal upper levels of concentration, it is possible to judge whether an optical design has further improvement room or not.

Concentration limit is a function of refractive index of material and acceptance angle. Higher concentration levels are possible if the end region is a high index medium rather than a vacuum. Moreover, acceptance angle is inversely proportional with the concentration ratio which also explains the small acceptance angle problem of high concentration systems. The concentration limit can then be expressed as:

$$C_{max} = \frac{n^2}{sin^2\,\theta_s} \tag{9}$$

Where n is the refractive index, θ_s is the acceptance angle.

3.2. Étendue

Étendue characterizes level of spread out of the light in an optical system. The spreading takes into account the spatial distribution and also angular distribution of the light. In an optical system étendue is the integral of the area of the entrance pupil times the solid angle of the source. Integration should be applied to infinitesimally small elements of area and solid angle.

$$d^2G = n^2 dS\,cos\,\theta\;d\Omega \tag{10}$$

Étendue never decreases in any optical system. Concentrators spread angular distribution of the light while the illuminated area gets smaller. Change of étendue is irreversible. A good concentrator system tries to maintain the étendue of the source after light passes from several optical elements.

3.3. Non-imaging optics

In a classical optical system it is generally aimed to have good imaging characteristics and reduce the optical aberrations as much as possible. These constraints are unnecessary if the requirement is the light collection only and aberrations such as distortion or astigmatism are not important.

A simple concentrator lens is designed such that collimated light is come to a single focus. Because the sun occupies a solid angle on the sky, the resulted illumination at the focus becomes a circle. This circular pattern is not coupling well with the solar cells because most of the time solar cells have a rectangular shape. Moreover single lens optics does not have any tracking tolerance. These problems are overcome by applying different principles than the classical imaging optics.

New design principles are aiming to reach better concentration and illumination schemes rather than good imaging characteristics. Because of these, new design principles are called as non-imaging optics. This new optics, using Edge Ray Principle and Simultaneous Multiple Surface Method, is enabling design of better performing optical concentrators.[26][27]

Edge ray principle

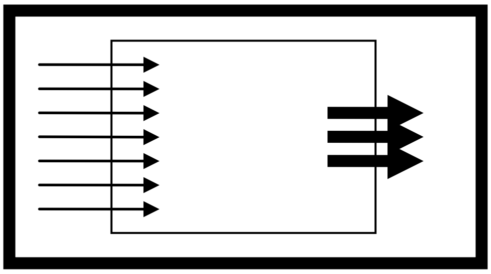
The theory is such that, if edge rays are reaching to the illumination plane, than all the other rays between two edge rays will also reach the illumination plane. As a result, designing a system which only considers the extreme rays will also guarantee the system to collect all the other rays too. Edge ray principle comes into play for the concentrator design as an important design tool of non-imaging optics.[28]

Simultaneous multiple surface design method

Non-imaging Fresnel lenses are designed with the new principles of this non-imaging optics. The primary optics has to be designed on conjunction with the secondary optics. In fact, the designs of both components depend on each other and a technique “simultaneous multiple surface design method” can be applied. By using SMS design method, freeform secondary elements can be designed.

3.4. Concentration and Acceptance Angle Product (CAP)

If all the incoming light exits from the concentrator, than the concentration is the ratio between areas of entrance and exit ports as shown in Figure 25. When the light is concentrated to a smaller area, it is distributed in a larger solid angle as shown in Figure 26.[29]



$$C_{\max} = \frac{A_i}{A_e}$$

Figure 25: Schematically representation of concentration ratio

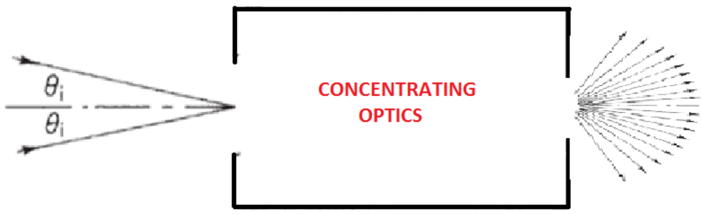
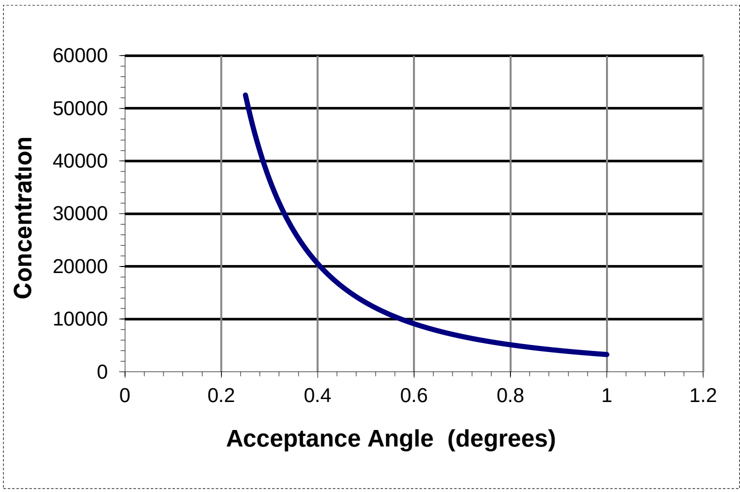


Figure 26: Concentrated light has more angular distribution

When designing a system, higher acceptance angles are mostly targeted. Acceptance angle indicates from how large solid angle does the concentrator collects the light. There is an inverse relation between acceptance angle and the concentration ratio as shown in Figure 27.



$$C_{\max} \propto \frac{1}{\sin^2(\theta_i)}$$

Figure 27: Acceptance angle vs. concentration

To characterize and compare different systems, concentration and acceptance angle product can be used. CAP value is calculated by multiplication square root of the concentration and sine of the half acceptance angle. Maximum allowable CAP value is related with the maximum concentration ratio formula. CAP value is always smaller than the refractive index of the medium.

$$CAP = \sqrt{C}\, sin\, \theta \leq n \tag{11}$$

CAP value can be used to distinguish different optical designs to decide which is better with respect to concentration performance.

3.5. Secondary Optics

Classical lenses have no tracking tolerance and any miss-orientation causes beam walk on the solar cell. To prevent energy loss, solar cell size should be larger. In these systems it is not possible fully illuminate the solar cell. Some parts of the solar cell do not receive much illumination while some parts get too much. For most of the solar cells, this non uniform illumination causes problem and is lowering the conversion efficiency.

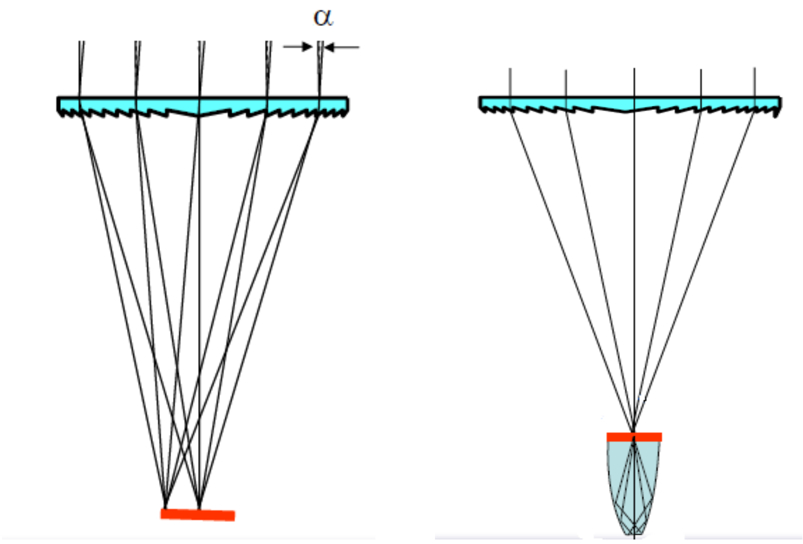


Figure 28: (a) System without secondary optics which has no tracking tolerance, (b) System with secondary optics

Using secondary optical elements, it is possible to increase the tracking tolerance (Figure 29) and homogenize the illumination on the cell. With this addition of optics it is possible to reach higher concentration values and assembly tolerances.

There are many different types of secondary optical elements which can be refractive and reflective type. Most of the reflective types are similar to conical structures, while refractive elements can have very specific surface geometries which are designed in conjunction with the primary optical element.

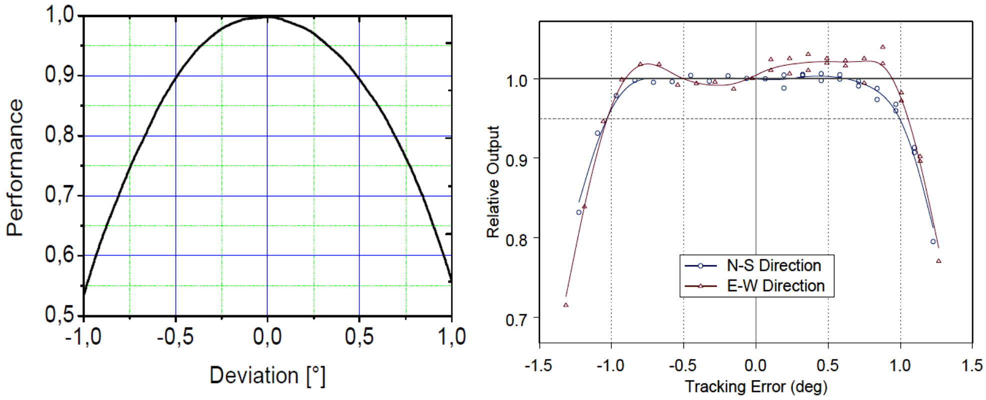


Figure 29: Fresnel lens only (Concentrix Solar) and with Secondary Optics (Daido Steel). Angular tolerance is improved significantly with secondary optics

3.6. Compound Parabolic Concentrator (CPC)

This type of the concentrator is the big achievement of the non-imaging optics. CPC is a good concentrator geometry and all the designing parameters are well documented. It is possible to concentrate light near ideally with this concentrator type. The only problem of this geometry is the requirement for the long construction. In practical applications, it is usually modified from ideal geometry to shorten its length.

CPC geometry is satisfactorily used in this thesis as a final concentrator .The length is not a problem here because the light guide is horizontally placed and input aperture of the CPC is small.

3.7. Fresnel boundary reflections

Even for a geometrically lossless optical system, boundary reflections are an important loss mechanism. When the light passes from one medium to another, some portion of the light is reflected from the boundary like reflecting from a mirror as shown in Figure 30. If several boundaries exist inside an optical system, than the reflection losses will increase.

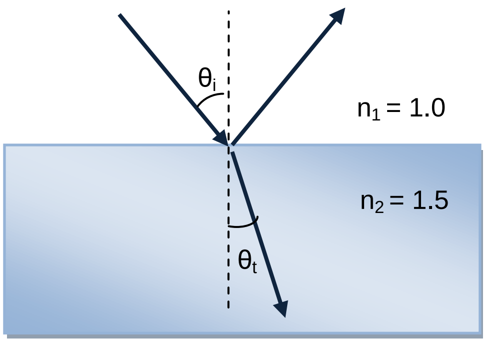


Figure 30: Transmission of light between two medium. Some portion is reflected back into the initial medium.

The physics behind the boundary reflections are explained with the Fresnel formulations. The reflection amount of light depends on the polarization of the incident light and governed by different formulas for different polarization states. Light sourcing from the sun is unpolarized therefore transmission of the light can be found by taking the average of the two polarization states. Fresnel equations for different polarizations are:

$$R_p = \left|\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right|^2 \qquad R_s = \left|\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right|^2 \tag{12}$$

For near perpendicular incidence angles, θ_i and θ_t values become 0° and cosine terms equals to unity. The above formulas for perpendicular and parallel polarizations become equal for the perpendicular incidence angles:

$$R_p = R_s = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2 \tag{13}$$

If the primary lens of a high concentration system can be modeled as a two-sided transparent flat plate with a refractive index of 1.5, for perpendicular incidence Fresnel reflection is approximately %4 for every surface of the plate. Because a lens has two optical surfaces, a total of approximately %8 is lost as a result of boundary reflections. For a small f-number lens, Fresnel reflection losses increase because of the steep angle of the exit ray and the facet surfaces. These losses can be reduced by the use of antireflection coatings or by applying nano-texturing antireflection surface treatments.

For oblique incidence, reflections should be calculated by considering the different polarization states. Ray tracing optical design software such as ZEMAX can include the effect of Fresnel reflections precisely by applying the equation to the every traced light ray.

Transmission vs. incidence angle is shown for the oblique incidence in Figure 31. Graph shows the incidence from air into glass medium. P polarization vanishes at a certain angle. This angle is called as Brewster’s angle and after this angle both of the components are increasing rapidly.

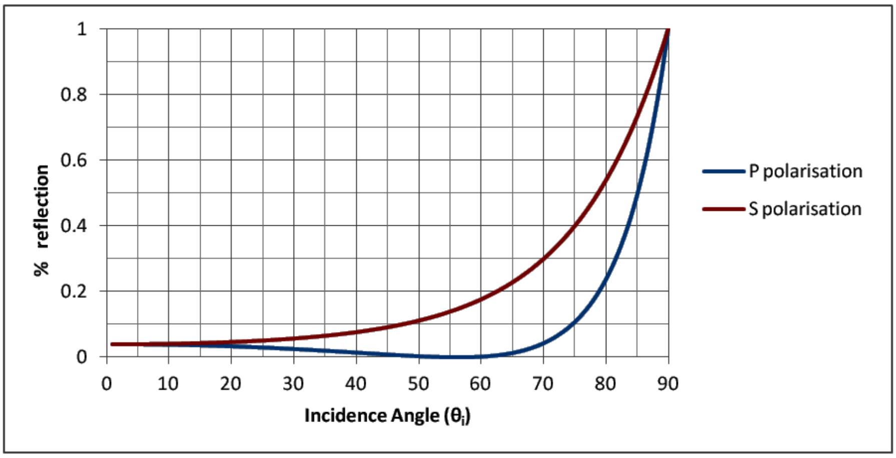


Figure 31: Fresnel reflection from air to glass (n=1.5)

The situation is somewhat different for transmission from glass to air as shown in Figure 32. After the critical angle of incidence no light is passing to the second medium and all the light reflects back into the medium. This is called as total internal reflection and is the key mechanism that enables the light guide systems.

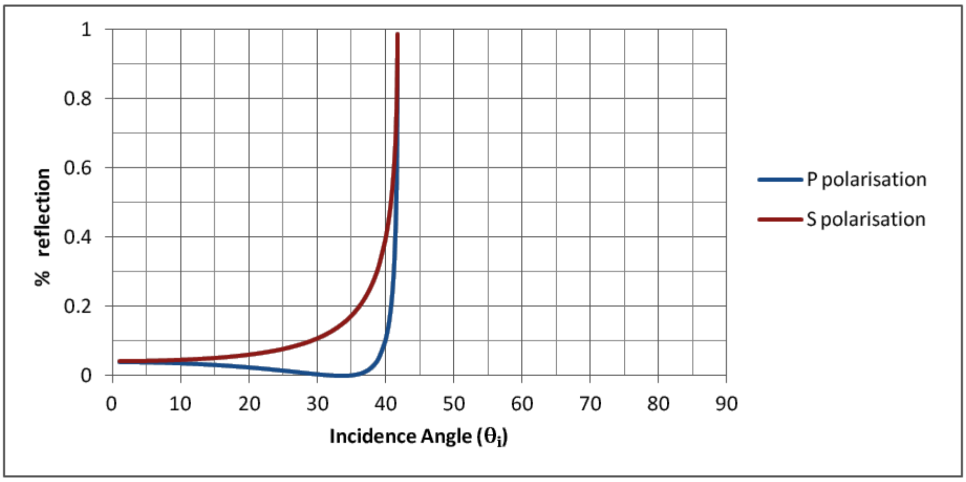


Figure 32: Fresnel reflection from glass (n=1.5) to air

3.8. Optical waveguides (Light guides)

Optical waveguides are reflective structures which restricts light into its volume and transporting it along a direction. If the light guide is a high index medium, the reflectivity from walls can be obtained by total internal reflection (TIR).

For refractive systems light obeys Snell's Law and this law determines the transmission of light from one medium to other with different refractive indexes. When light pass from a high index medium to a low index medium, light is refracted such that the angle between the refracted light ray and normal of the surface increases.

$$n_1 sin\, \theta_1 = n_2 sin\, \theta_2 \qquad \text{(Snell's Law)} \qquad (14)$$

When the angle of the ray hitting to the boundary surface increases, after a certain angular value the light cannot pass to the second medium instead starts to reflect back into the first medium. This reflection from boundary is called as total internal reflection (TIR) and the angle when TIR starts is named as critical angle. Light can be guided inside a light guide if the angle is larger than the critical angle.

$$\theta_c = sin^{-1}(n_2 / n_1) \qquad \text{(Critical Angle)} \qquad (15)$$

For the light guide solar concentrators the materials are either glasses or plastics. These materials are generally have a refractive index of close to n_1 = 1.5. By assuming the surrounding medium is air with a refractive index n_1 = 1, critical angle becomes 42 degrees. Air surrounded light guides can only guide light if the light is hitting to the surfaces with angles larger than this critical angle, 42 degrees.

TIR reflection is used in several practical applications such as fiber optics in communication systems, reflectors in automobiles and backlights in LCD screens. The newly developing area of light guide concentrators will also be one of those examples.

Fiber-optics systems are using TIR for long distance transmission of light. A fiber-optic cable has a high index core which is generally surrounded with a low index cladding. Light travels along and inside the fiber with TIR reflections because of this refractive index difference. TIR is a lossless reflection method and light signal can be transmitted to long distances inside the glass core with high efficiency. Fiber optic light guides in communication systems generally have very small core structure and their computation require electro-magnetic calculations. While in some applications the core of the fiber optics is larger and geometrical optics can be used for the explanation of the behavior inside the fiber. Fiber optics systems do not affect the angular distribution of the light, as a result while transmitting the light across the fiber optics, étendue is not changed.

Backlights in LCD screens are also using TIR to generate uniform illumination across the screen. Planar light guide in backlights carry the light that sourcing from series of LEDs by TIR reflections and distributes light uniformly as a result of intentionally generated surface defects. In this systems étendue is not intended to be conserved and increases significantly because light starts from a small area and distributed to a large area of the screen, moreover it is angularly distributed to reach a wide view angle.

3.9. Properties of the sun light

Sun continuously moves in the sky throughout the day. The maximum elevation angle, sun rise and sun set places and length of the day change day by day in a year and also changes with the location on the earth.

Sun occupies ±0.26 degrees angular size on the sky. Most of the light reaching to the ground is coming from this angular cone and this radiation is called as direct solar irradiation. In most of the measurements the direct component of the light is measured together with the ±5 degrees circumsolar radiation. This circumsolar radiation is the forward scattered radiation in the atmosphere and the most powerful part of the diffuse radiation.

Diffuse radiation is the combination of scattered radiation in the atmosphere and reflected radiation from the ground. Atmospheric content such as water vapor and aerosols affects the amount of the diffuse radiation. Increase of diffuse radiation means in general decreasing the direct component of the solar energy because diffuse radiation results from the scattering of the direct radiation.

The amount of the total irradiation is the main parameter for a flat PV panel. Flat modules are characterized under standard $1000W/m^2$ AM1.5 condition which includes direct and diffuse components of the sun light.

CPV modules can only collect radiation from their acceptance angle which is generally on the order of a few degrees. Optical systems cannot concentrate diffuse radiation satisfactorily. Any radiation coming out of acceptance angle is either rejected or absorbed by the structure and couldn't be converted to useful power. Because of this, CPV systems are generally specified to work at 850 W/m^2 direct normal irradiance and power output of the CPV module and efficiency of the module are calculated under 850 W/m^2.

For the CPV systems the most important component of the sun light is the direct component of the sunlight. Because of that, CPV systems are working better where the sky is open and direct component of the sun light is available. The measurement for the yearly energy coming from the direct component of the solar radiation is called as Direct Normal Irradiance (DNI) and CPV systems are useful in high DNI regions.

Diffuse component of the sun light depends on the atmospheric conditions and also the angle with respect to the sun position. The graph shown in Figure 33 indicates how the diffuse component of the radiation is changing with the angle with respect to the sun position. It indicates that higher acceptance angle is beneficial because it is possible to collect an important amount of the diffuse radiation with high acceptance angle optics [3].

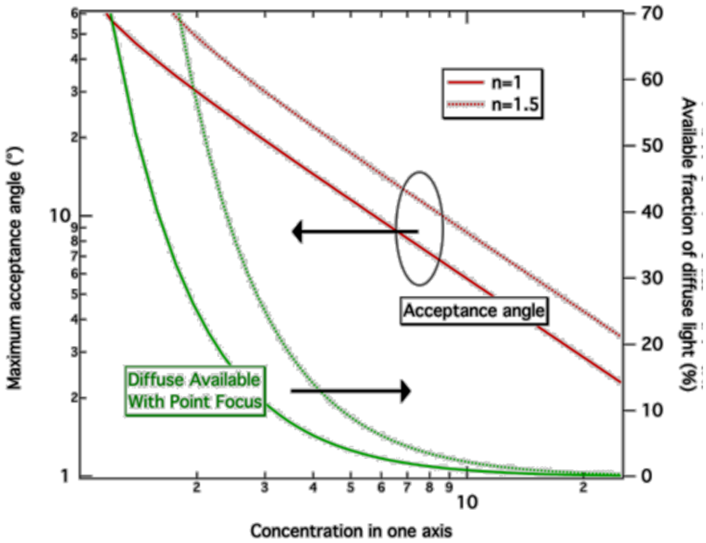


Figure 33: The theoretical maximum for the acceptance angle (red curves; left axis) that can be achieved as a function of linear concentration and the fraction of diffuse light that can be collected theoretically (green curves, right axis) assuming that the diffuse light is isotropic.(Source: NREL [3])

Spectral distribution of the sun light is also important for the photovoltaic power generation. Sun behaves like a blackbody source and has a spectrum from ultra violet to far infrared. Extraterrestrial spectrum is modified by the absorption and scattering of gases in the atmosphere shown in Figure 34. ASTM G173 is the most accepted reference spectrum for the photovoltaic calculations. This reference spectrum assumes light is passing from air mass 1.5 with clear sky conditions.

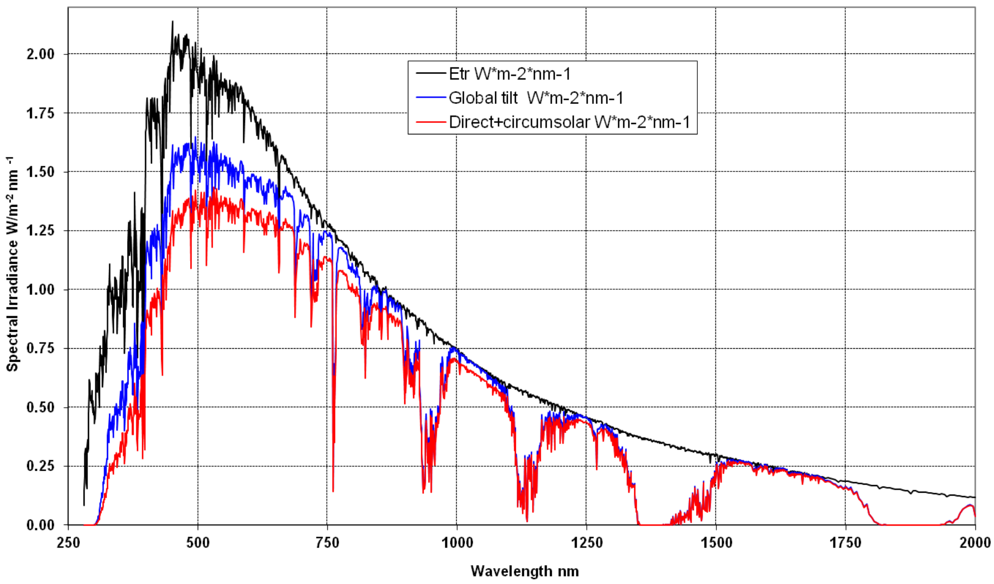


Figure 34: ASTM G17-03 Reference Solar Spectrum

CHAPTER 4

THE HORIZONTALLY STAGGERED LIGHT GUIDE SOLAR CONCENTRATOR CONCEPT

Parts of this chapter have been published in Optics Express, Vol. 20, pp. 19137 (2012), O. Selimoglu and R. Turan.

4.1. Introduction

When the thickness of a point focus CPV module gets thinner, it needs very tiny solar cells and very high assembly tolerances. Many small size solar cells need to be connected accurately and therefore module gets complicated as shown in Figure 35. Moreover these tiny solar cells should be placed with tighter spatial tolerances.

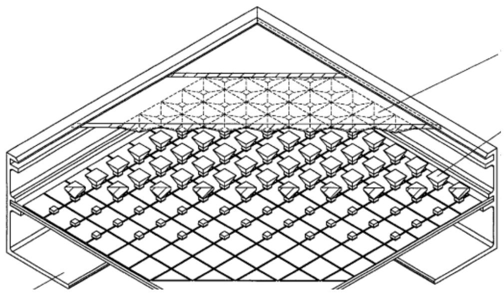


Figure 35: Thin CPV module with very small cell sizes.[30]

In order to reduce complexity of CPV systems with a more robust construction, light guide solar concentrator systems have been proposed [31]. In this approach, the incoming solar radiation is collected by several primary concentrators and directed to a single PV cell through a light guide vertically located with respect to direction of the solar radiation. Light guide solar concentrators can be divided into two main classes as “lossy and lossless” [32]. As the names indicate, lossy systems lose some of the collected solar radiation through injection points or directing surfaces [32]. Because of their architecture, they tend to have smaller loss if the tracking tolerance is made tighter. On the other hand, the lossless systems do not have geometrical decouple loss, while they still have some losses due to Fresnel reflections from boundaries and material absorption. In order to achieve a completely lossless system, a volume increase at injection points are necessary [32]. In some of the recent studies [33] [34], the volume increase has been applied towards thickness direction resulting thicker light guide construction as shown in Figure 36.

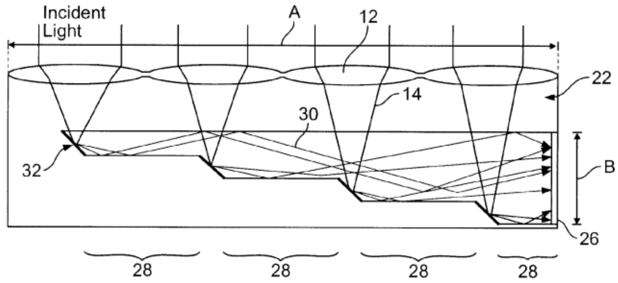


Figure 36: Light guide concentrator with increasing light guide thickness[34]

Many of the proposed light guide concentrators implement linear exit ports which have low concentration level. For the lossless cases, this is a consequence of having long directing surfaces that couples well to line focus primary concentrators. To achieve high concentration in these systems, they need to be designed in circularly symmetric geometry (Figure 37) with a point focus like circular exit port [33][34]. The lossy systems also need secondary concentration geometries to reach high concentration levels [35]. But this extra concentration feature sacrifices continues and also linear exit port geometry to achieve high concentration levels and reaches discrete exit ports similar to the point focus systems. In order to overcome the problems encountered in previous concentration approaches, horizontally staggered light guides can be used. This kind of staggering does not increase the thickness of the light guide and this light guide well couples to the point focus primary concentrators [6]. This design has a potential for reaching high tracking tolerance with high concentration ratios while satisfying the cost effectiveness required by a CPV system.

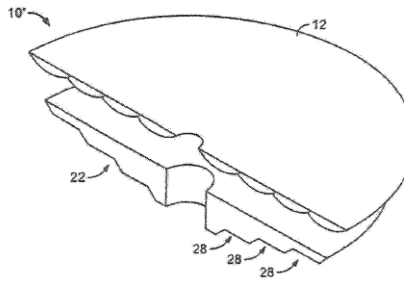


FIG. 4

Figure 37: Circularly symmetric lossless light guide solar concentrator[34]

In this study, we investigate the effectiveness of the horizontally staggered design for very high concentration levels up to 1000x. D. Moore et al., have recently reported general structure and basic properties of this approach for medium concentration systems.[6].

4.2. Method of concentration

The concentrator investigated in this study is an arrangement of a lens array and a horizontally staggered light guide. As shown in Figure 38, light guide stays below the primary concentrating lens array. Light directing surfaces, light transmitting media and the exit port of the concentrator are actually features of the horizontal light guide structure. A photovoltaic cell will be attached at the exit port of the optical concentrator to finalize the system. The components of the optical system, design parameters and their effects on the optical performance are discussed below in detail.

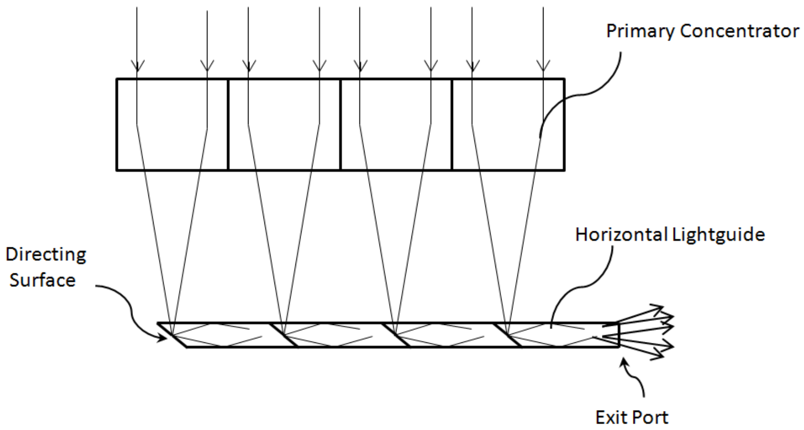


Figure 38: Solar concentrator that using light guide

4.3. Parts of the concentrator

Lens array

The primary concentrator array is focusing the light onto points of a rectangular grid. These focused points will be the injection points (acceptance region) of the light guide. The rectangular grid of the injection points is shown in Figure 39(a).

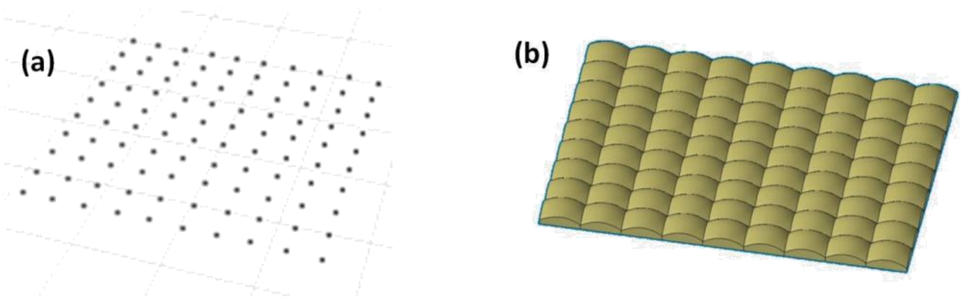


Figure 39: Primary concentrator array, (a) Rectangular grid of focal points, (b) Lens array.

The primary concentrator array can be constructed from several different types of point focus concentrators such as fly eye lens array, array of Fresnel lenses, Compound Parabolic Concentrators (CPC), diffractive concentrators, Cassegrain systems or combinations of lenses and mirrors. In the optical design and simulations, ordinary simple lens array is chosen for simplicity as shown in Figure 39(b). The primary concentrator focuses the incoming light onto the light directing surfaces which is a part of the light guide structure. Because the light directing surface is small, to achieve maximum acceptance angle the directing surface should be at the focus of the primary concentrator array where the beam width is the smallest.

The vertically staggered lossless light guide solar concentration systems are best coupled with line focus primary concentrators. These line focus primary optics squeeze the incoming collimated light only in one dimension, and if circularly symmetric form is not used, they are generally low concentration systems. In horizontally staggered light guides, instead of line focus lenses, point focus systems or specifically ordinary lentil type lenses can be used. This type of lens squeezes the beam in two dimensions, and as a result, the diameter of the incoming beam is reduced. This has an important advantage compared to the line focus systems. If the line focus primary concentrator concentrates the light with a concentration of C, than the ordinary lentil type lenses approximately can give a concentration ratio of C^2. Because of this rule, horizontally staggered light guide solar optics can easily reach very high concentration values.

The focal length of the each focusing element in the primary concentrator array defines the main thickness of the total structure. The focal length also defines how big the sun image will be at the focus point, which is a design parameter for directing surfaces and also for the light guide thickness.

The aperture of the each lens element is also important together with the focal length. The f-number (focal length to aperture ratio) is a measure of the brightness of the image at the focus. If the f number gets smaller, than some light rays coming to the focus is too angled. This angle is an important parameter for the directing surfaces and should be properly designed to achieve Total Internal Reflection (TIR) at the directing surface and from the walls of the light guide structure. If the angle of the incident light gets excessively large, some of the incoming light rays will not satisfy the TIR conditions so decouple loss can be significant.

Excessively angled rays also cause optical path length elongation. If the rays move more in the material, depending on the material selection, internal absorption may cause significant transmission losses. These too angled rays also make too many TIR reflections from the surfaces of the light guide, resulting in more interaction with the optical surface irregularities such as surface roughness.

Low index media

In order to satisfy TIR condition inside the light guide, a low index region between the light guide and the lens array is compulsory. This low index medium can be an air gap in the simplest case or it can be a low index transparent material that fills the region between the light guide and the lens array.

Fresnel boundary reflections result from the refractive index changes at the boundaries. If the low index media between the light guide and lens array is properly selected, the Fresnel reflections can be minimized and increases the optical efficiency. The refractive index of this medium should be low enough to satisfy TIR in the light guide, while it should be high enough to reduce Fresnel reflection losses sourced from index differences.

Using low index materials instead of an air gap has some mechanical benefits such that the primary concentrator will support the light guide and no extra support structure is needed. On the other hand, the use of an air gap brings some design advantage in reaching very high concentration values. At higher concentration levels, the light traveling inside the light guide hits the boundaries with steeper angles. Therefore at the very high concentration regions such as the exit part of the light guide, it is beneficial to use an air gap as the low index medium. This approach is used in the simulated design to reach very high concentration levels.

Light guide

The light guide is responsible for transferring the light to the end of the concentrator. As illustrated in Figure 40(a), it collects the light from different lenses and, when properly designed, gives extra concentration to the travelling photon beam. It is best visualized from the top view shown in Figure 40(b).

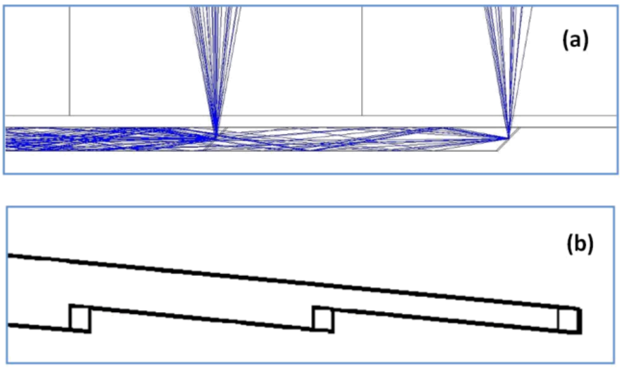


Figure 40: Horizontally staggered light guide (a) Light guide collects light from different lenses. (b) Stepped structure of the light guide (top view).

The length of the light guide is restricted by several parameters. At a certain length, when new lenses are added to the system, adjacent light guides start to overlap. This overlapping prevents addition of new steps to the horizontal light guides and determines the concentration limits of the optical system.

The absorption of the light guide is also important and it can significantly affect the final efficiency of the system. As the light travelling considerably longer distances inside the light guide, the absorption by the light guide material becomes important. Therefore, a low absorbing material should be used to fabricate the light guide of the system.

Light directing surfaces reflect the light into the light guide with an angle such that reflection from the light guide surfaces satisfies the total internal reflection (TIR) condition. If the refractive index of the light guide material is high enough, no reflective surface coating is needed.

4.4. Further concentration methods inside the light guide

Side cutting surfaces

In order to reach higher concentration levels, the side of the light guide can be cut with specifically calculated surface orientations such that overlap of the adjacent light guides can be avoided. The surface compresses the light to a smaller volume and provides additional concentration as shown in Figure 41(a).

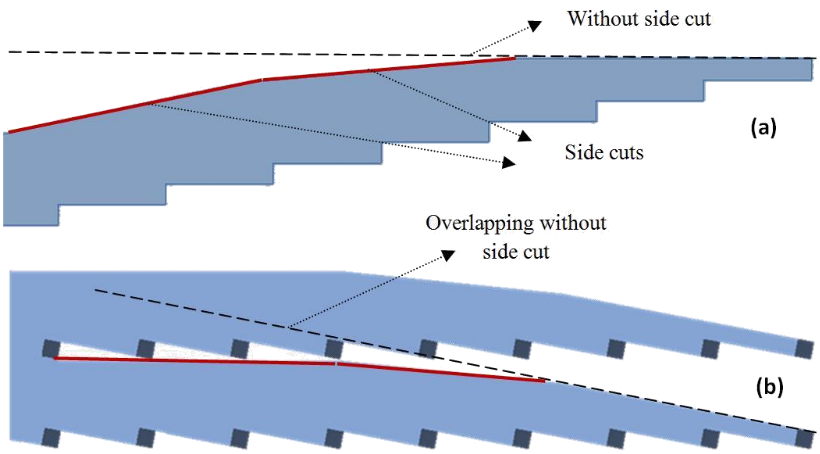


Figure 41: Side cutting of light guides (a) Side cutting makes the exit port smaller and gives extra concentration. (b) Side cutting can postpone overlapping of adjacent light guides

Side cutting can eliminate overlapping to some extent as shown in the Figure 41(b). This side cutting gives extra concentration and therefore the light rays hitting to this surfaces start to move with steeper angles inside the light guide. After a certain length of the light guide the extra concentration surfaces cause the rays to move with excessively steeper angles and causes violation of TIR requirements inside the light guide. If a ray violates the TIR requirement, it starts to leak from the light guide and efficiency of the light guide reduces. Therefore the side cutting surfaces and the length of the light guide should be properly designed.

In our studies, to determine the side cutting geometry the rays that enters farthest from the end region and has the steepest angle is traced until it reaches to the exit port. The length of the light guide and the geometry of the side cut are iteratively determined to always preserve the TIR condition inside the light guide while keeping the length of the light guide as much as possible. Further study can suggest an equation or a generating algorithm to fully determine more effective side cutting geometries.

End cutting- final concentration region

In accordance with the concentration required at the end of the light guide, the end part of the light guide is designed to squeeze the light beam to a smaller region. This region can be either a separate part and then cemented to the light guide or be just the end geometry of the light guide. In the latter case, the end of the light guide can have a two dimensional conical or two dimensional Compound Parabolic Concentrator (CPC) type shape as shown in Figure 42.

The CPC can further concentrate the light and reduce the PV area considerably. Concentration in the CPC geometry is defined by the input aperture and its acceptance angle. To collect all the light efficiently, the CPC input aperture should be equal or greater than the light guide output aperture.

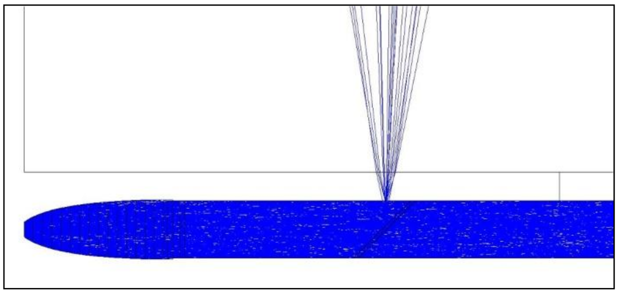


Figure 42: End region of the light guide with a CPC type extra concentration element

The concentrated light meets to the PV cell at the end of the final concentrator region. In most of the CPV applications, the image of the sun is generally circular while the PV cell is rectangular or square[36]. This incompatibility prevents the optimum use of PV cell area because of the inhomogeneous distribution of the light on the active PV cell area. However in the present light guide solar concentrator, the end geometry of the concentrator is rectangular which provides an excellent match with the rectangular PV cell geometries.

Multiple reflections inside the light guide have a homogenization effect on the travelling beam. Uniformity of the light at the exit port is very good if no end cutting region is used. When an end cutting region concentrator geometry applied, the distribution of light can change and the uniformity can be disturbed. Effect of non-uniformity on the solar cell should be investigated for specific applications. If the uniformity is so important for the solar cell used, a homogenizer region can be added to the end of the light guide. This homogenizer region can just be a simple planar light guide or a modification of end concentrator geometry.

4.5. Concentrator simulations

For the simulation of the solar concentrator, we have used the ZEMAX ray tracing software. The input parameters are adjusted to reach a 1000x geometric concentration and ±1 degree of tracking tolerance. The wavelength range is including visible and near infrared bands up to 1.1 microns.

In the designed system, one of the most common optical glass material, BK7 (n_d: 1.516) is selected for the lenses and light guide structure. Lenses are aspheric lenses and the defining equation of the aspheric surface is shown below. In this equation Z is the surface sag, R is the radius of curvature, k is the conic constant, s is the distance from the center of the lens and A_4 and A_6 are the aspheric terms.

$$Z(s)=\frac{(\frac{1}{R})s^2}{1+\sqrt{1-(1+k)(\frac{1}{R})^2 s^2}}+A_4 s^4+A_6 s^6+\ldots \qquad (16)$$

Lens surface is specifically designed with ZEMAX software to reach system level targeted optical specifications. This designing process requires several iterations and optimization runs. ZEMAX software has embedded optimization algorithms and it is also possible to interactively determine the parameters by user inputs. These algorithms and designer's insight are used to reach the targeted acceptance angle and concentration ratio. Lens is not designed separately but designed with considering light guide and directing surface properties. Lens surface geometry is selected to have an aspheric property by adding a conic constant term. This conic constant term is used for reducing aberrations to reach good focusing ability with a single lens.

As a result of designing efforts, lens surface geometry is defined with radius(R): 4.715 mm, conic constant (k): - 0,433 and 5mm x 5mm square aperture. Further aspheric terms are not used. Back surface of the lens is flat. Thickness of the lens is selected to be 13.4 mm. Lens array has a MgF_2 AR coating of 150 nm on the out looking face (front surface). A low index medium with a 0.2 mm thickness and refractive index of 1.48 is inserted between the lens array and the light guide.

The light guide has a 0.4mm x 0.4mm step increase for every injection point and this step increase is performed on a horizontal plane. The primary concentration level is defined by the ratio of the lens aperture to the step increase. Therefore the primary concentration is 156.25x with this selected geometry. The light guide has 45 degree reflective surfaces, which are assumed to be ideal reflectors. TIR (Total Internal Reflection) criterion is satisfied both at the light guide region and at the CPC end region. The only non TIR surface is the 45 degree light injecting surfaces.

The 45 degree light injecting surfaces are assumed to be ideal reflecting surfaces for clearly pointing the issues related to the design and prevent intervening of the reflective surface type technologies which are so broad and continuously improving. First of all, the surface reflectivity can be selected by accommodating several different reflecting surfaces such as silver, aluminum or dielectric mirror coatings. Second, the 45 degree reflecting surface can be eliminated if a material with a higher refractive index is chosen as the light guide material. Therefore adding a real reflective surface may interfere with the purpose of this study.

Effect of the reflective coating on the 45 degrees surfaces is very predictable. The effect of the non-ideality of the coating will be limited and real coatings will only alter the efficiency a few percent because every light ray is hitting to the reflective 45 degrees surfaces only once. Reflected rays will never encounter any of the other coated surfaces again. Therefore, after the first reflection the light rays will only exposes to the TIR reflections and this brings us that, the effect of the any selected reflective coating on these surfaces are easily predictable. The calculated efficiency will be multiplied by the reflectivity to get the efficiency of the system with a selected realistic coating.

Furthermore, the real reflectivity of the materials has spectral reflectance curves. If this spectrally behaving real coating were applied to the simulations, it will not be possible to simply predict the effect of the reflective coatings on to the overall efficiency.

A side cut and a CPC end region are added to the light guide to reach a high concentration level of 1000x. A side cut is realized with a one step straight line cut which is parallel to the virtual line passing from the injection surfaces. To prevent any overlapping with the adjacent light guides, width of the light guide is selected to be slightly smaller than the width of the primary lenses which is 5 mm. The width of the light guide is selected to be only 50 microns smaller than 5 mm to prevent touching of the adjacent light guides to each other. As a result of these parameters side cutting reduced the exit port dimension from 8 mm to 5 mm. Therefore the concentration is increased %60 inside the light guide as a result of side cutting feature.

A 2D CPC region is used as an end cut region and this CPC region is a solid structure that using the same material with the light guide which is BK7. All the reflections inside the CPC satisfy TIR. The exit port dimension and the acceptance angle fully define the 2D CPC geometry. The exit port has a 0.1 mm width and the acceptance angle is 14°. Therefore end cutting region increases the concentration level 4 times by reducing the exit port thickness from 0.4 mm to 0.1 mm.

In the simulation study, we used 20 lenses with corresponding reflective surfaces in the light guide. The total thickness of the structure is 14 mm and it is a very thin structure with respect to conventional CPV systems. The described geometry of the simulation is given as a graphical illustration in Figure 43 and Figure 44.

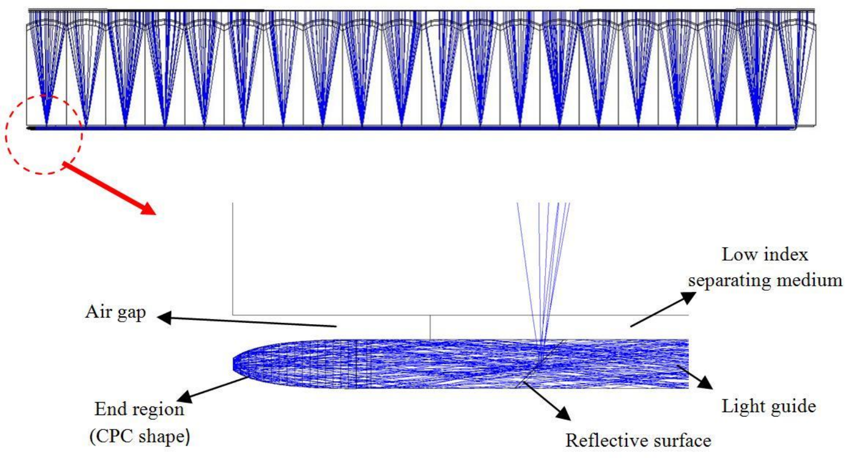


Figure 43: Cross sectional view of the concentrator

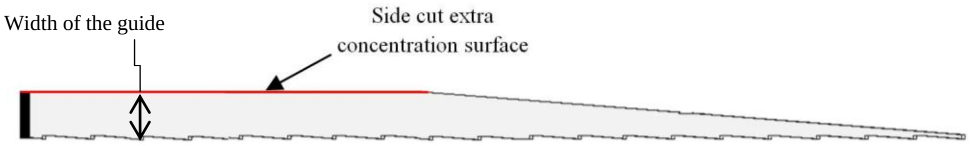


Figure 44: Top view of the light guide with a single side cut extra concentration surface

4.6. Simulation results

Optical efficiency

The optical efficiency, which is simply defined as the ratio of the output power to the input power, is a function of reflection and absorption losses. With the system parameters given above, the system efficiency is found to be 96.5 % including absorption and reflection losses. If no AR coating is applied, then the total system efficiency drops to 94.4%.

The reflection losses occur at the boundaries where the light passes from one region to the other with different refractive indices. Although we assumed an AR coating on the surface of the lens array, the highest loss occurs here. The reflection loss is 2.1% from this region if all the wavelengths are assumed to have the equal weight. It is clear that a single layer AR coating is not sufficient to prevent boundary reflection because of broad wavelength distribution of the solar spectrum. By properly designing the AR coating with a multilayer structure, the reflection from the surface can be further reduced to below 1%.

Refractive index change is very small at the boundaries of the low index medium therefore the total reflection loss at the two boundaries of the low index medium is 0.03%, which is not significant.

The absorption loss occurs in the lens material and inside the light guide because of the absorption in the BK7 glass. In our design the lens array and the light guide have absorption of 0.2 % and 1.2 % on the average, respectively. Absorption loss becomes important if the light guide is made longer to reach thicker light exit regions.

Field of view (FOV)

FOV of the concentrator is defined as the angle where efficiency drops by %10. As the light guide gets thicker and the horizontal step is made larger, the focused light from the primary lens has more place to move without decoupling from the light guide. Therefore enlarging volumetric increase of light guide while keeping the primary concentrator size similar, gives better tracking tolerance. Increasing the acceptance angle reduces the concentration permanently. Decreasing tolerance to its half increases the concentration more than 4 times. In the simulated system we studied, simulations show that the FOV is more than +-1 degree as shown in Figure

45. This acceptance angle along with a 1000x concentration is not achievable with basic Fresnel lens and secondary optics combinations. This result demonstrates the advantage of the presented system in terms of concentration performance which is comparable with the sophisticated CPV optics such as Fresnel-Köhler concentrator. [37]

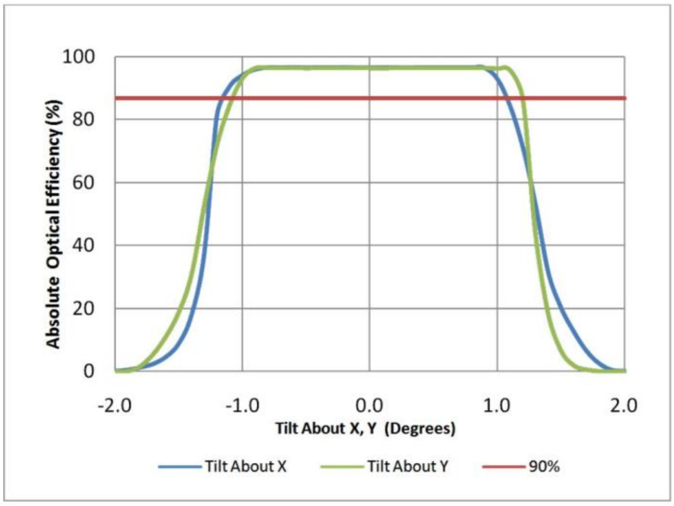


Figure 45: Transmission efficiency vs. tilt angle

Concentration

Concentration is mainly a ratio of input and output apertures. The width of the input aperture is 100 mm and the width of the output aperture is 0.1 mm. The ratio of two dimension shows that system has a geometric concentration ratio of 1000x.

PV cell geometry

Exit port geometry of the light guide is a long thin strip. The small width of the exit port can be problematic because of increased assembly tolerances and small width cell sizes. It is possible to increase the small width of the exit port by putting several light guides on top of each other [6]. This method can increase the exit port width. But the dimensional increase will cause the elongation of the light guide too. Although the light guide utilizing low absorption materials and very smooth boundaries, too much elongation of the light guide can significantly degrade the optical transmission because of absorption and scattering losses.

Although 0.1 mm cell dimension required for 1000x concentration is small and it might bring some manufacturing difficulties, it is achievable with the GaAs based solar cell technology [38]. Moreover, this small width may be an advantage for extracting large current densities from the solar cell.

4.7. Design Variations:

While developing the horizontally staggered light guide concentrator concept, several design variations are investigated and worth to mention here. It is possible to apply some variations to the primary optical design for either improving the manufacturability or system efficiency.

Separate reflecting surfaces

To reach the limits of this light guide CPV design it is necessary to have 45 degree directing surfaces. This angle does not change the etendue while coupling the light into the light guide. But available materials has low refracting index and cannot satisfy the TIR from the directing surfaces with a 45 degree angle. Without a reflecting coating, it is obligatory to deviate from the 45 degree requirement and therefore it is not possible to reach the limits of this concentration method. Coating of directing surfaces with a high reflectivity material is required but coating process of the directing surfaces is not an easy task. Coating the directing surfaces only with a very high reflecting material with a cost effective method needed to be developed. It is possible to stick some reflecting parts to the directing surfaces but it is also a time consuming and unreliable method.

Here we recommend using separate mirrored surfaces which is staying just behind the unsatisfactory directing surfaces. As a result, light rays will first reflect by TIR and some of the light will pass through the directing surface. Rays which escapes from the directing surface will encounter reflecting second surface and couple into the waveguide.

Although method is simple, it can eliminate bonding requirement of the reflecting surfaces. Moreover even a good mirror coating has some absorption loss. In this configuration, some portion of the light rays will reflect by TIR and only the remaining portion will be reflected from the mirror. Therefore absorption at the non-ideal mirror will decrease because not all the light interacts with it. As a result, the final reflecting efficiency is higher along with easier production.

Spectral splitting with band gap filtering

Light is a combination of different colors as shown in the Table 3. If a single band gap silicon solar cell is used only, for the violet-blue range approximately 40 % of the energy can be converted. Rest of the energy will be converted to heat. Similarly for the yellow-green band 50% and for the red band % 60 of the energy can only generate electricity. As the energy of the specific color gets closer to the band gap of the semiconductor, the photovoltaic process gets more efficient.

To increase the conversion efficiency spectral splitting can be used. If different colors of solar light are converted with suitable band gap solar cell, it is possible to improve the system level conversion efficiency. This method is being used with tandem solar cell approach. But available lattice matched solar cell materials and production methods are problematic.

Table 3: Light conversion performance of silicon solar cells for different colors

	Wavelength (nm)			**Energy (eV)**			**Convertible portion of energy with silicon solar cell (band gap 1.11eV)**
	min	max		max	min		
Violet-Blue	400	500		3.1	2.5		36 - 45 %
Yellow-Green	500	600		2.5	2.1		45 - 54 %
Red	600	740		2.1	1.7		54 - 66 %

If light is optically separated from each other, than it is possible to use separate solar cells without lattice matching constraint. Spectrally splitting of the light to different color bands and converting energy of different colors with different solar cells can be a solution. But in this case dichroic filters are necessary.

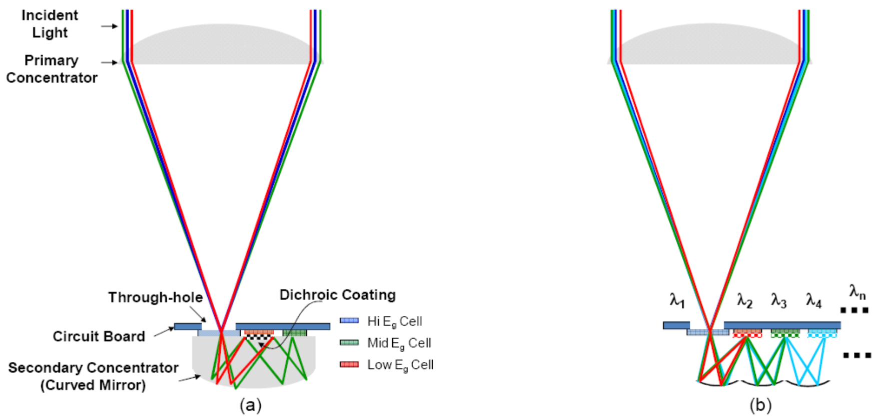


Figure 46 : Common-plane spectrum-splitting concentrator unit cell concept: (a) 3-cell structure (b) multi-cell structure [39]

Dichroic filters are suitable for collimated light and not so good with concentrated light which has an angular distribution. To eliminate color filter requirement, band gap filtering method is investigated. Semiconductor materials are generally transparent to the photons if their energy is less than their band gap material. With this method, the solar cell itself can perform spectral selection. Different band gap solar cells will be placed next to each other, so that light rays first hit to the high band gap solar cell. If the light rays are not absorbed by the solar cell, they will reflect from the solar cell and then hits to the next solar cell as shown in Figure 47. With this approach some conversion efficiency increase is expected. But the production of this system with a cost effective manner should be further investigated.

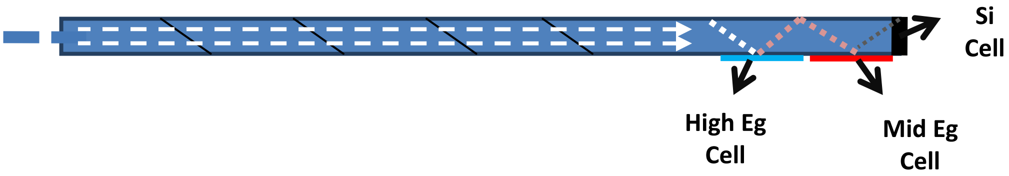


Figure 47: Band gap filtering method in light guide solar concentrators

Light trapping in waveguide

The properties of the solar cells that are used in the concentrator systems are also investigated. Carrying light trapping property from cell to the light guide and its benefits has been investigated.

Solar cells have high refractive indexes. Silicon solar cells have a refractive index of 4 on the average. This causes very high reflection from the front surface of the solar cell. To eliminate this problem, solar cells are using texturing and AR coating on their front surfaces.

Silicon solar cell efficiency has saturated in recent years, limited primarily by surface recombination.[40]. Although texturing increases surface recombination, it is now an industry standard, because efficiency of the cell increases as a result of more light is going into the solar cell.

Two important problems can arise from texturing. The first is the increasing the surface area of the solar cell. Bigger surface area can have more recombination centers. Second, texturing generates surfaces that have higher recombination rates. Normally silicon wafers have {100} surfaces. Texturing generates pyramidal crystal surface and this pyramids has {111} surfaces. {111} surface has higher recombination rates than the {100} surfaces.

To reduce the surface re-combinations, passivation is applied to the solar cells. But these processes cannot totally eliminate the re-combinations. Moreover stress induced during oxide growth can also become a recombination source.[41]

Surface texturing and AR coating can be eliminated if light trapping is achieved by the light guide. It is possible to generate multiple reflections by using a light guide as done with the texturing. This configuration preserves the effect of light trapping while eliminates the surface recombination losses from the textured surfaces. Light trapping with light guide can also recycle the finger losses in the front contact solar cells. A total increase of conversion efficiency can be expected with this method.

There are two different quantum efficiency measures in solar cells. External quantum efficiency is a measure of the electrons generated per shining light on the solar cell while internal quantum efficiency only takes into account the absorbed light. Because light trapping can recycle unabsorbed light, high internal efficiency solar cells should be used with light trapping configurations.

Several configurations can be used for light trapping. Light trapping performance increases with size of the solar cell. In CPV systems bigger solar cells means lower concentration ratio. Therefore, while increasing the conversion efficiency with light trapping, economics of the system should also be considered.

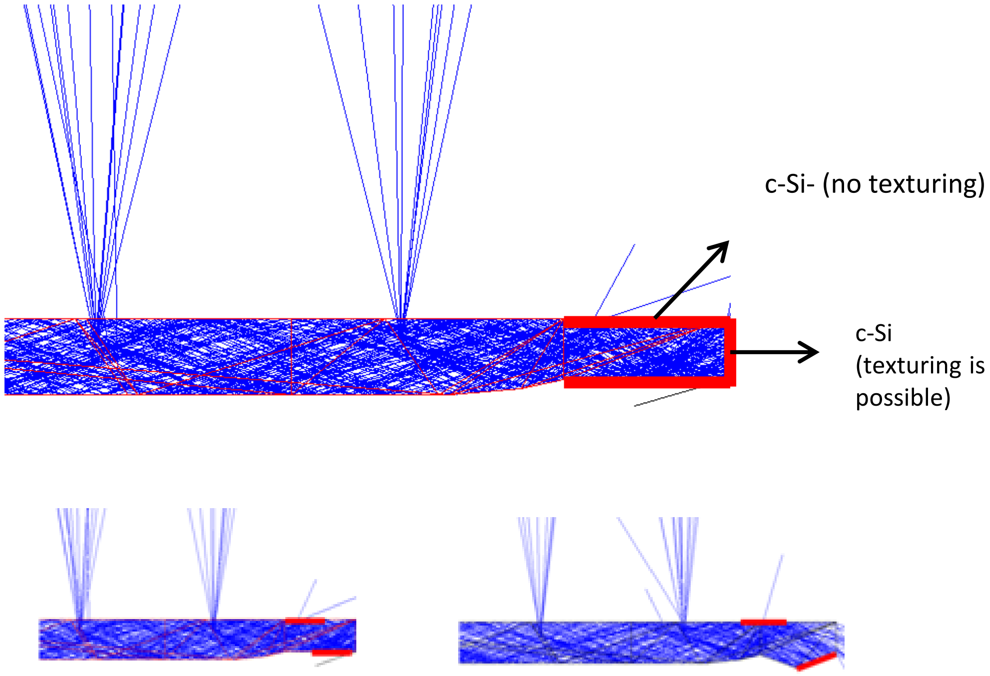


Figure 48: Different cell configurations for light trapping

Turning of light exit regions

In light guide systems, light exit region is at the side of the light guide. This can be problematic for cooling and supporting of solar cell. Therefore in some cases it is beneficial to turn the exit region towards the back of the module.

Turning of the module is investigated and shown that without any reflective coating, it is possible to turn the light downward as shown in Figure 49. This operation reduce concentration ratio dramatically but it can give simpler module integration and can be beneficial in some commercial applications.

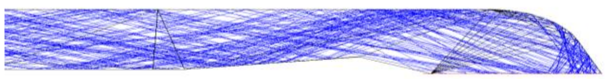


Figure 49: Turning the light exit region downward

Composite guide material

There is always absorption in the wave guide. This loss may become important if the length of the waveguide increases. Generally glasses are very brittle while plastics are not. But plastic materials can soften with temperature increase while glass materials can stand very high temperatures.

It will be good if we produce the waveguide from high transparent glasses. But the glass is hard to form. Therefore a composite structure which is a glass core with a plastic cover can be considered as shown in Figure 50. Glass core will have a high transmittance. The plastic region can be easily shaped. Therefore it will give the chance of combining high transmittance of the glass with easily formable properties of plastics.

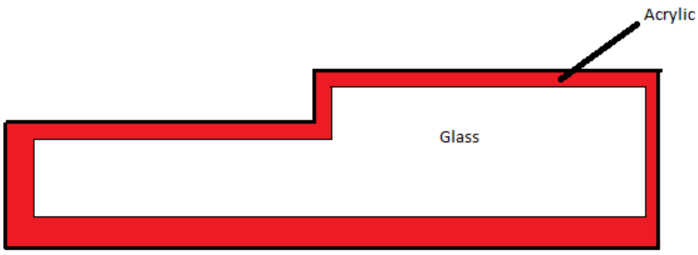
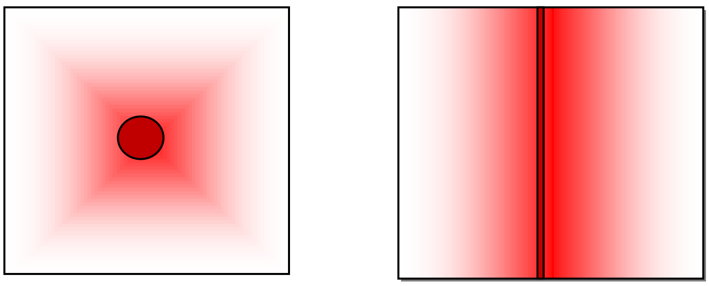


Figure 50: Composite light guide

4.8. Thermal considerations

In traditional point focus CPV applications cooling is a troublemaking issue at high concentration levels. Sophisticated active and passive coolers are needed to remove the heat generated by the focused sun light at high concentrations. The proposed concentrator has an important geometrical advantage for the cooling as shown in Figure 51. Because the PV cell is spread to a line, heat generation is also spread in one dimension. Therefore smaller temperature gradients are enough to spread the heat to the cooling plate. As a result lower temperatures are expected in the line focus systems than the point focus systems.

Heat dissipation using a passive cooling plate could be easily integrated to the photovoltaic cell. Moreover, if an active cooling is selected for cooling, a simple water circulating pipe touching to the back side of the PV cell would be sufficient to remove the heat accumulated in the cell.



a) Point focus   b) Line focus

Figure 51: Schematically representation of; a) point focus system, b) line focus system

Passive cooling

To understand the passive heat dissipation behavior and numerically prove the superior properties of line focus systems, a basic thermal model is developed. An aluminum sheet is attached to the PV cell which is also the back cover of the module as shown in Figure 52. This aluminum back cover isolates inside of the module from outside weather. Although the plate has two sides, one face is looking inside of the module. The air inside the module has a higher temperature than the ambient and trapped inside the module. Therefore plate is losing considerable amount of heat to the ambient air from only the out looking face because only this face has direct contact with the ambient air. In the steady state response, the air inside the module has an elevated temperature and the temperature gradient in between is not significant. Therefore heat transfer between lens and the plate can be disregarded to simplify the problem. The simplified problem is shown in Figure 53.

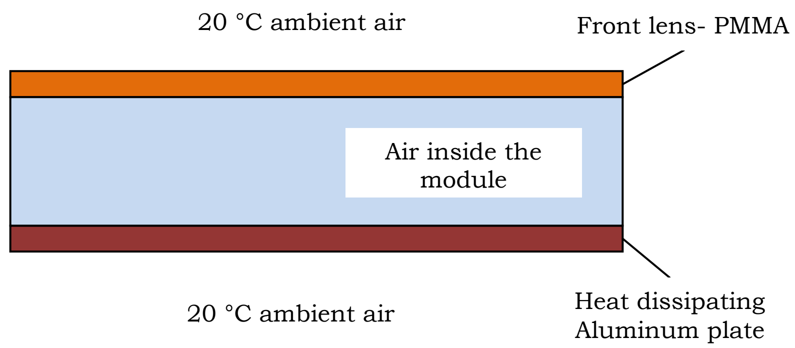


Figure 52: CPV module with back aluminum sheet and front cover lens

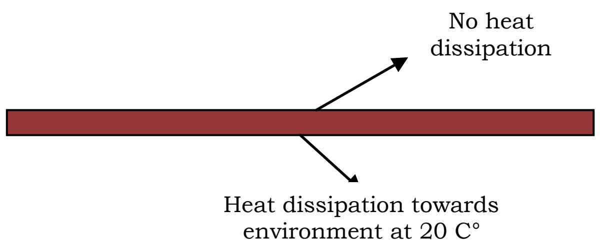


Figure 53: Simplified heat transfer problem

There are three heat dissipation mechanisms in this setup. Conduction is responsible from the diffusion of the heat all over the aluminum sheet. The convection mechanism transfer heat to the ambient air and radiation is sending heat as an infrared radiation to the cooler surrounding surfaces.

Conduction occurs in solid mediums as a result of vibration of atoms, diffusion of electrons and phonons. Conductive heat transfer is a result of diffusion and internal heat energy flows from high energy density towards the low energy density regions. The conductive heat transfer rate depends on the steepness of the temperature gradient within the body and also the material type. In one dimension, conductive heat transfer can be written as:

$$\frac{\Delta Q}{\Delta t} = -k.A\frac{\Delta T}{\Delta \mathrm{x}} \tag{17}$$

Here k is the thermal conductivity, A is the area of heat flow and T is the temperature and Q is the heat energy. Every material has its own thermal conductivity (k). Metals in general have very high thermal conductivity and several thermal conductivity values are shown in Table 4. Copper is a very good thermal conductor and is used in many heat extraction applications. Although having superior thermal conductivity, copper can easily oxidize, it is heavy and expensive. Because of these aluminum is also popular for the heat conduction applications.

Table 4: Thermal conductivities of common materials [42]

	Thermal Conductivity ($W.m^{-1}.K^{-1}$)
Copper	401
Gold	318
Aluminum	237
Silver	430
Iron	80
Glass	0.9
Acrylic	0.2

Because the light converted to the heat at the photovoltaic cell, the heat should be transferred to the heat sink via conductive heat transfer to keep the solar cell temperature low. When light falls on a solar cell, higher energy photons release some portion of their energy as heat which is the energy exceeding the band gap of the semiconductor material. At operating condition, most of the heat is expected to be generated at the front side of solar cell because higher energy photons are absorbed there. Therefore for cooling purposes, generated heat has to be transferred to the back side where the cell is touching to a heat sink. Photovoltaic cells are crystalline semiconductor materials and these materials generally have high thermal conductivity values. As a result of having high thermal conductivity and thin cross section, this heat transfer does not require high temperature gradients as shown later in this chapter.

Table 5: Thermal conductivities of common semiconductors

	Thermal Conductivity ($W.m^{-1}.K^{-1}$)
Silicon	130
GaAs	55
Germanium	58

When a body is surrounded with a fluid, than convective heat transfer is an important heat transfer mechanism. CPV modules are surrounded with ambient air and transfer its heat to the cooler outside air with convective heat transfer. The convective heat transfer depends on the temperature difference between the body and the surrounding air. Moreover the type of the fluid, velocity of the fluid and properties of heat dissipation surface is important and convective heat transfer coefficient takes into account all these variables. The mathematical representation of the convective heat transfer is shown below. In the equation, "h" shows the convective heat transfer coefficient; "A" represent the area of the contact region and ΔT is temperature difference between the material and the surrounding fluid.

$$\frac{\Delta Q}{\Delta t} = -h.A.\Delta T \tag{18}$$

Radiative heat transfer is also important for the heat transfer calculations of CPV modules. Every object radiates with respect to its temperature. Radiative heat transfer from one surface to another is equal to the difference of thermal radiation entering to the surface and the radiation leaving the surface. In an ordinary day sky has lower temperature than the ambient air and surrounding air has lower temperature than the module. As a result module loose heat towards the sky and towards the surrounding. Radiative heat transfer depends on the absolute temperatures and depends on the properties of surface which is characterized with the emissivity. Emissivity (ε) shows how closely resemble is the surface to a blackbody. Radiative heat transfer depends to the 4^{th} power of the absolute temperature. If the outside temperature is lower than it will radiate more than it received, as a result cooling will occur.

$$\frac{\Delta Q}{\Delta t} = \varepsilon.\sigma.A.\mathrm{T}^4 \tag{19}$$

In the equation "σ" is the Stefan-Boltzmann Constant, σ = 5.670 10^{-8} (W/m^2K^4), "ε" is the emissivity of the surface, "A" is area and "T" is the absolute temperature of the surface.

Conduction, convection and radiation equations defined above are the main defining equations of the heat transfer calculations. If we apply these equations into a real problem, we can encounter complex geometries and non-uniform temperature gradients throughout the system. Because of this, most of the real problems do not have simple analytical solutions and numerical finite element methods are necessary to solve this kind of problems. With these methods, bodies and surfaces are break into smaller regions and every region is assumed to have uniform properties. With the help of software codes it is possible to reach high fidelity results throughout the large and complex structures by applying simple heat transfer equations. In this thesis heat transfer problems are handled with the Ansys Wokbench software because of non-uniform temperature gradients on the cooling plate.

To demonstrate the thermal success of the line focus systems, a thermal simulation study was performed with the same parameters for line focus and point focus systems. In the simulations Ansys Workbench software is used. Both systems are assumed to have a 1000x concentration with a 500W/m^2 portion of the solar irradiance converted to heat on the photovoltaic surface. In both cases the area of the PV cell is selected to be 1 cm^2 for comparison. PV dimension of point focus system is 10mm x 10mm. The line focus system has a PV dimension of 0.32mm x 31.6cm. Both PV cells are touching to a 2 mm aluminum heat spreading sheet that has the same area as the collecting lenses (31.6cmx31.6cm). The heat is assumed to dissipate only from the bottom surface of the aluminum sheet via convection with a convection coefficient of 5W/m^2.C° and via radiative heat transfer with an emissivity of 1.0 to the ambient with a temperature of 20 °C. The parameters are summarized in below table.

Table 6: Thermal simulation parameters

	Point focus	**Line focus**
Concentration	1000x	
PV dimension	10mm x 10mm	0.32mm x 31.6cm
Collecting Lens Area	31.6cmx31.6cm	
Heat flux	500W/m2	
Convective Heat Transfer	20 °C ambient temperature Convection coefficient : 5 W/m2	
Radiative heat transfer	20 °C ambient temperature Emissivity : 1	
Heat dissipating surface	Aluminum plate : 31.6cmx31.6cm Heat dissipating from only one face.	

The simulation results are shown in Figure 54. It is shown that heat transfer is much more superior in the line focus system than a point focus system.

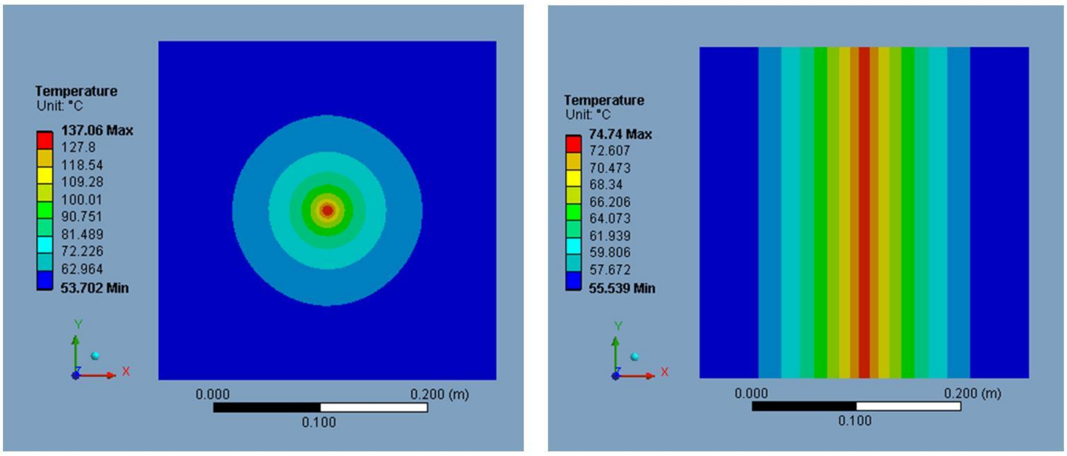


Figure 54: Thermal simulation results of point focus and line focus systems

The maximum temperature for the point focus system is obtained to be 137 °C from simulations. This value is too high for the solar cell operation and needs additional cooling means such as heat dissipation fins or active cooling systems. But for the line focus system, the maximum temperature on the cell is found to be 75 °C. This value is acceptable for high efficiency cells and therefore does not require any special cooling mechanisms. Thus, a passive cooling attachment like the one used in the simulation is sufficient to realize the high concentration light guide concentrator systems. Also, this maximum temperature is far below the glass transition temperature of plastic optics produced from PMMA (T_g=108°C)[43][Appendix A] and therefore low cost PMMA plastic material can be used instead of glass as the light guide material.

Simulations are not considering the thickness of the solar cell and heat is directly generated on the heat sink surface. This assumption is performed because GaAs solar cells can have a very thin cross-section which can only be a few microns. By having very small thickness and high thermal conductivity, assuming heat is directly generated on the heat sink is reasonable.

Silicon solar cells are generally thicker than the GaAs solar cells. For silicon solar cells, it is easy to understand the effect of the larger solar cell thickness on the thermal behavior by using heat conduction equation. For example, for silicon solar cells thermal gradient that require for transferring energy from front side to the back side of the solar cell can be calculated by the heat conduction equation. In the calculations it is considered that heat flux on the solar cell is similar to the simulated case (1000x) and thickness of the solar cell is 250 microns.

$$\frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}} = -k \cdot A \cdot \frac{\Delta T}{\Delta \mathrm{x}} \tag{20}$$

1000 times concentrated light is falling onto the solar cell and 500W/m^2 portion of the incoming solar radiation is converted to heat, and then the total heat flux on the solar cell is calculated by multiplication of the heat flux density with the area of the solar cell as follows;

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta q}{\Delta t} \cdot \text{ Area} = (1000 \cdot 500\text{W/m}^2) \cdot \text{ Area} \tag{21}$$

Thermal conductivity (k) of silicon solar cell is 130 W/m·K and thickness of the solar cell is taken to be 250 microns, then;

$$\Delta T = \frac{\frac{\Delta q}{\Delta t} \cdot Area \cdot \Delta x}{k \cdot Area} = \frac{\frac{\Delta q}{\Delta t} \cdot \Delta x}{k} = \frac{5x10^5 \, W/m^2 \, \cdot \, 250x10^{-6} \, m}{130W/m \, \cdot \, K} \tag{22}$$

$$\Delta \text{T} = 0.96 \ ^\circ K \tag{23}$$

Result show that, a temperature gradient of approximately $1°K$ is enough to transfer the heat across a 250 microns silicon solar cell under 1000x concentration. If similar thickness value is assumed, this temperature gradient is approximately $2.3^\circ \ K$ for GaAs and Ge solar cells. Therefore ignoring solar cell thickness does not have a significant effect on the thermal simulation results. Moreover this additional temperature increase should be considered for both line focus and point focus systems, and therefore temperature difference between two cases will be preserved.

Active cooling

Active cooling systems are also very suitable for the line focus systems. A pipe is a linear cooling element and can easily be attached to the back of the PV cell. Water circulating in this pipe can carry heat away from the cell and heat can be used for heating purposes. As a result a PV-T system is easily realizable with the actively cooled line focus systems.

Water cooled systems are also favorable in the very hot climates. In these places passively cooled water in night time can reduce the temperature of the PV to even lower temperatures than the ambient.

Passive cooling systems are relying on the convection from air and convection coefficient is changing with the orientation of the module which is continuously changing in a day. Active systems can give more trustable cooling which is independent of the module orientation. Moreover circulation speed of the cooling fluid and its type can be adjusted. As a result cooling performance and temperature of the heated liquid can be intentionally changed.

CHAPTER 5

REALIZATION OF HORIZONTALLY STAGGERED LIGHT GUIDE SOLAR CONCENTRATOR

Parts of this chapter have been submitted to Progress in Photovoltaics for publication, with authors O. Selimoglu, F. Es, O.Demircioglu and R. Turan

5.1. Initial efforts

Initial theoretical studies are shown that horizontal concentrating light guides are an important opportunity for the concentrating photovoltaic systems. Because no prototype study is reported before, in this thesis study, we investigated every available production methods and materials for the realization of horizontally staggered light guide solar concentrator and measure its effectiveness in real conditions.

The initial efforts were manufacturing the lenses and light guide from optical glass. But as a result of several attempts for production, it is understood that light guide has very sharp corners and not suitable to produce from glasses. When alternative materials are investigated, plastic materials such as PMMA are found more suitable to produce the light guide. This material is also used for sharp faceted Fresnel lenses and this previous use is encouraged us to use it as the light-guide material. Optical transmission of this material is shown in Figure 55. As shown PMMA has very good transparency in the visible and near infrared regions.

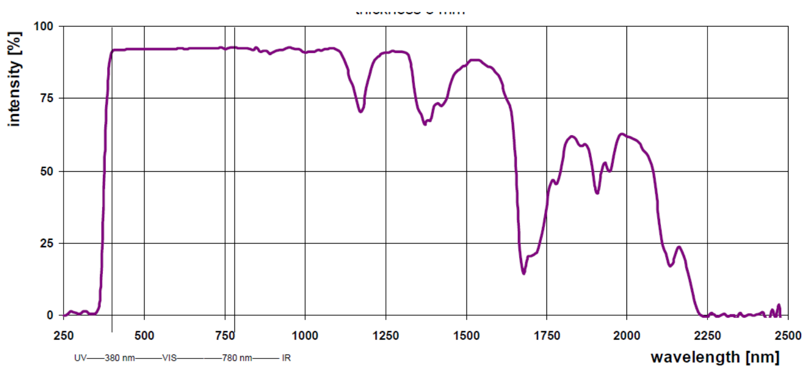


Figure 55: Light transmission of 3 mm PMMA from Evonik (PLEXIGLAS® 8N)[44]

Initially CNC machining considered for the production of light guide from the PMMA. The produced light guide surface was too rough and light guiding was not satisfactorily achieved. Then for better surface quality, a simple mold with a hand polishing is produced. The first partially working light guide is manufactured by this mold as explained in the next section.

5.2. Conceptual prototype studies (Prototype-1)

For this prototype, a simple optical design is performed. The lenses are selected from commercial lenses. Aspheric concentrator lenses from Thorlabs are used as the primary lens array. Lenses were having a 40 mm focal length with a 50 mm diameter. Circular lenses are shaped to have a rectangular geometry by using water jet cutting as shown in Figure 56. The length of the smaller side of the lens is 32mm and the longer side is 38mm.

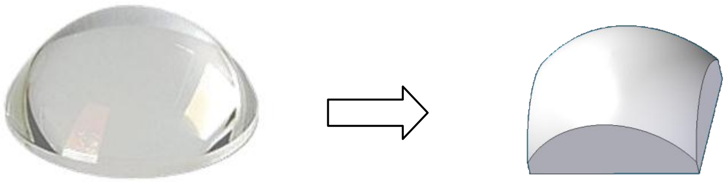


Figure 56: Commercial lenses is cut into rectangular geometry

Light guide is designed without any extra concentration features as shown in Figure 57. The thickness of the light guide is 3 mm. Distance between two directing surfaces is 32 mm and directing surfaces has 50 degree inclination. Waveguide has four horizontal steps and every step has one directing surface. Every directing surface will be registered to a primary lens.

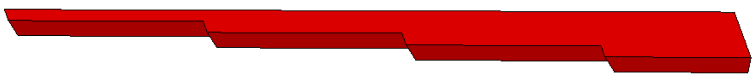


Figure 57: Four step light guide

Optical design of the conceptual prototype is shown below in Figure 58. Every lens corresponds to different directing surfaces and acceptor regions of the light guide are sitting at the focal points of the lenses.

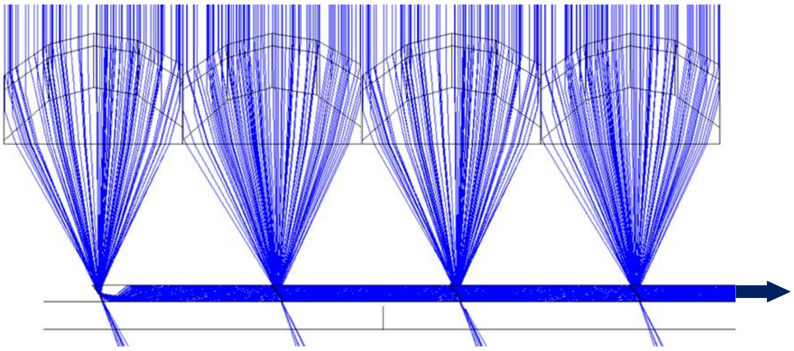


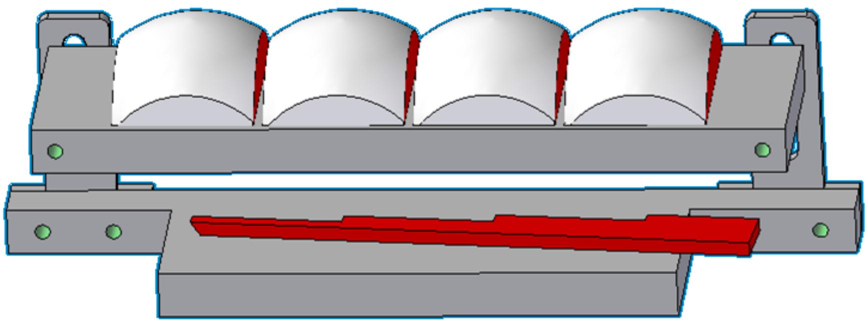
Figure 58: Optical design of conceptual prototype

Because of violation of TIR at the directing surfaces and because directing surfaces does not have any reflective coating, some of the extreme rays are partially leaking from the light guide. Light rays confined to the light guide are travelling to the right, towards the exit of the light guide. Geometric concentration ratio expected was calculated by dividing lens area to the area of step increase and obtained to be 135X.

$$C = \frac{Area\ of\ lens}{Area\ of\ branch\ increase} = \frac{32\ mm\ x\ 38\ mm}{3\ mm\ x\ 3\ mm} \tag{24}$$

$$C = 135\ X \tag{25}$$

Efficiency of the optics is expected to be 86% without considering manufacturing errors and material absorption. Therefore maximum real concentration ratio is 116x for ideal case. When uniformity is investigated via ray tracing, all the light is found totally uniform across the exit port. A mechanical holder is designed for holding 4 lenses and light guide together. Light guide is placed at a proper position below the lenses.



The prototype is tested under non collimated solar simulator although it is not so suitable for testing CPV systems. The main result of the prototype was lots of light is going out of the light guide with a concentration ratio of higher than 15X. Most of the light was leaking from the walls of the light guide because of surface roughness. The walls of the light guide were shining because of leaking of light. This prototype showed that concept is satisfactorily concentrating the light and encouraged the research team to further generate a better prototype which has better surface quality and more suitable for serial production. Further studies are investigating the optical materials, production methods, testing methods and design rules of this light guide concentrator concept by developing a second prototype.

5.3. Second prototype design- HORCON module

From the success of the initial prototype, the main motivation was to realize a system with high optical efficiency and cost effective serial production features. Moreover extra-concentration features should also be added to further show the benefits of the extra concentration elements. Because of including horizontal light guide concentrating features, this prototype is named as Hor-con module.

Solar cell selection

To decide the optical parameters, first of all solar cell type should be selected. Initial efforts were to obtain triple junction and GaAs type solar cells. After investigating the cost parameters, a medium concentration system with silicon solar cells become more favorable and easily realizable. Therefore silicon concentrator solar cells are selected to be used.

Silicon solar cells are easy to acquire with high volumes and has a mature industry. The efficiency of these cells are generally peak at a concentration level of 30x-50x range with respect to their design. If back contact solar cells will be used as a receiver, than an efficiency of 25% at a concentration level of 45x is a realistic value. The back contact silicon solar cells were not available from the market for a prototype level study. Therefore Laser Grooved Buried Contact solar cells were selected although they have lower efficiency than the back contact solar cells. With this selection of solar cell the high module output will not be achieved but optical system will be fully characterized.

Output geometry of the light guide was planned to be approximately 3 mm wide. To cover all the area with the solar cell, active area of the solar cell should be bigger than the exit port of the light guide. Moreover some assembly tolerances will also be needed. Therefore solar cells are decided to have an active area width of 4 mm. LGBC solar cells with an active area dimension of 4x121 mm from NAREC Company is procured. These cells are specifically designed for this concentrator study and design of metallization to obtain these cells from a complete wafer is shown in Figure 59.

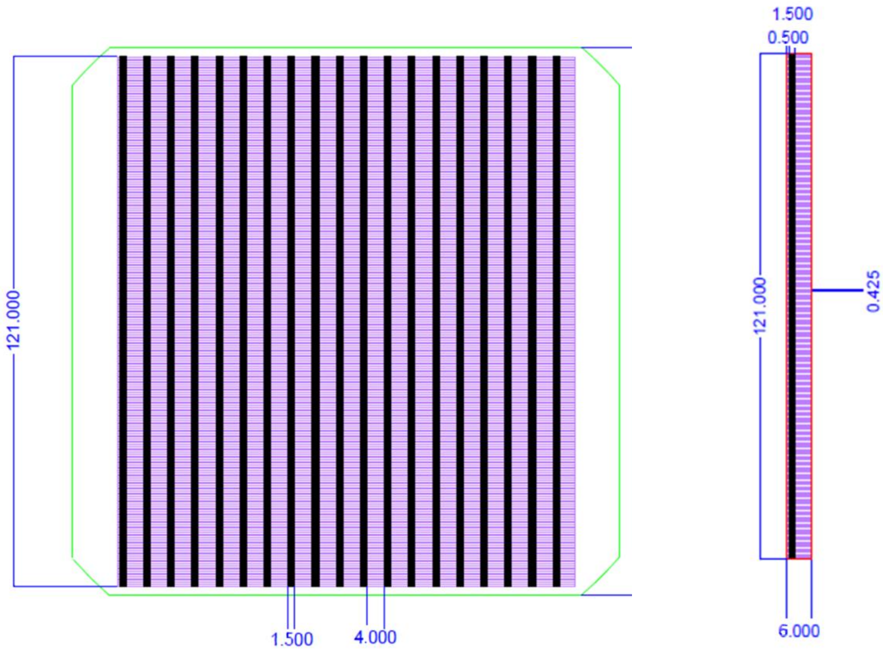


Figure 59: Buried Contact Solar Cells are used from NAREC. Their geometry is specifically designed for this prototype.

Optical design

Optical design is targeted to generate a medium concentration module that using high quality silicon solar cells as the receiver. Light guide concentrator is developed with the principles in [45] and schematically shown in Figure 60.

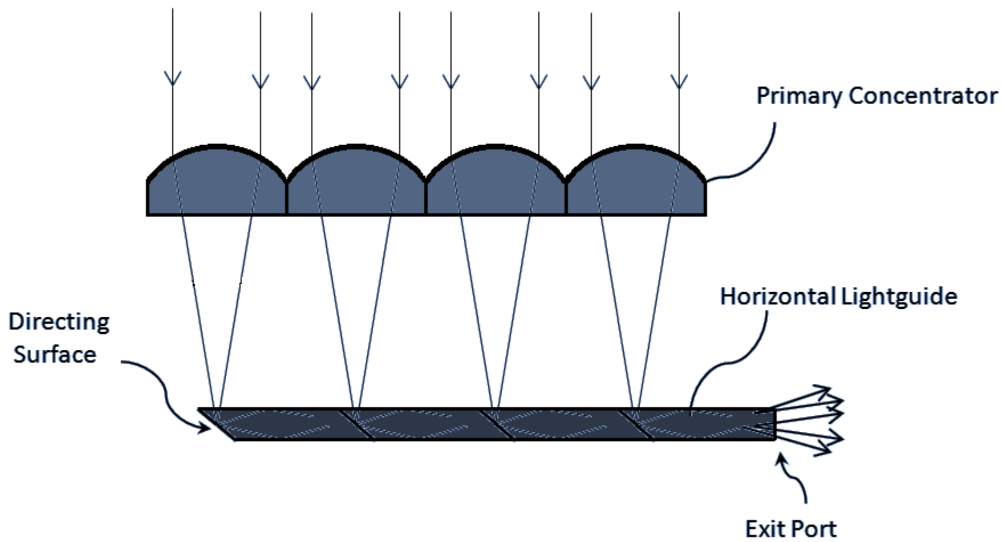


Figure 60: Solar concentrator that using light guide

Efficiency of the system is targeted to be 80% which is equivalent to the Fresnel lens based systems. The loss mechanisms are mainly Fresnel reflections from boundaries. The boundary reflection loss is approximately 4% from every surface and therefore by having 3 surfaces, it will cost approximately 12%. The remaining 8% loss budget will compensate for the absorption losses mainly in the light guide and scattering losses sourced from manufacturing defects.

Primary optics is an aspheric lens array made from PMMA. The lenses have a square aperture of 16 mm x 16 mm. The front surface of the lens has 15.46mm radius of curvature. Conic constant of the surface is -1.348 and A_4 coefficient is 0.0000272. The back of the lens is flat and the distance between two surfaces is 6 mm. As a result of these parameters, lens can able to focus light to a distance of 28 mm from its back surface and has an effective focal length of 32 mm.

Light guide is designed to collect and concentrate the light that coming from the primary lens array. Initially the exit port of the light guide is designed to be 3 mm. But discussions with the manufacturer, CPC geometry of the exit port are changed to be one side flat and other side with a 2 step angled surface to build a cheaper and reliable injection mold. By changing the end cutting geometry, the exit port is updated to be 3.2 mm wide as shown in Figure 61.

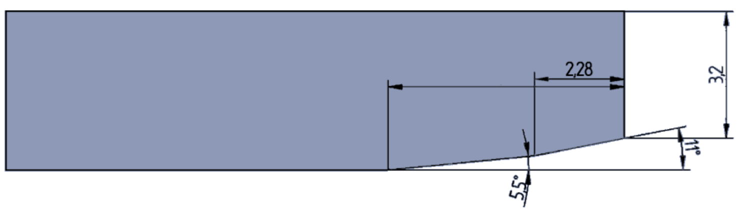


Figure 61: End cutting geometry

Prototype-1 was having leaks from the directing surfaces. In this prototype, directing surface angle is increased to 55 degrees to prevent losses from directing surfaces. Directing surfaces are placed 16 mm away from each other so that every directing surface is registered with a primary lens.

Light guide is formed from 9 branches. Every branch is collecting light from 9 primary lenses. Light guide has 4 mm thickness. This thickness is constant until the final concentration region. Final concentration region is thinning the light guide to achieve an exit port width of 3.2 mm and increases the concentration ratio by 25%.

Side cutting surfaces are also applied in this prototype. Side cutting surfaces are giving an extra concentration to the traveling beam. The geometry of the side cuts is calculated by ray tracing. Every branch increase is 3 mm in the light guide. Without side cut the exit port will be 27 mm wide, but side cutting surfaces reduce this exit port to 16 mm and increase the concentration by 69%. Design limits were not intended to reach with this prototype because this is the first time application of side cutting geometry and achievable manufacturing tolerances were unknown. The side cutting geometry is shown in Figure 62-a. Side cutting surfaces are 5° and 10.8° tilted surfaces with respect original side surface.

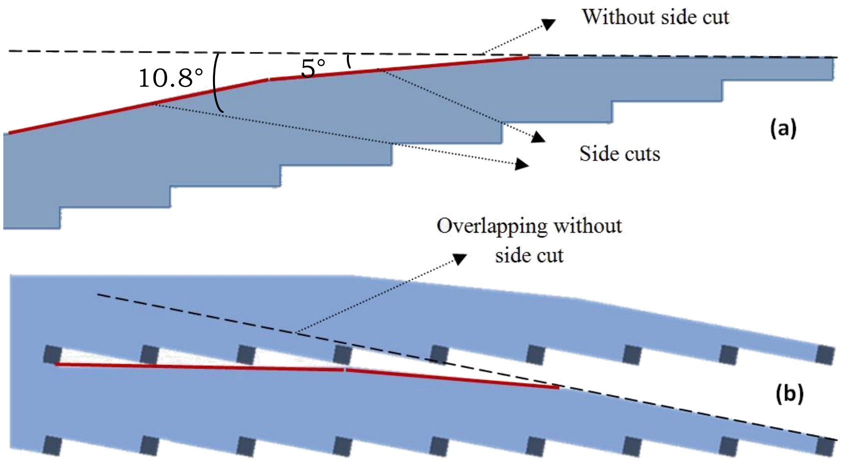


Figure 62: (a) Side cutting surfaces. (b) Relative placement of two branches without overlapping.

The resultant optical design is shown in Figure 63. The legs were designed for alignment and supporting purposes but excluded at the production stage for the sake of optical quality.

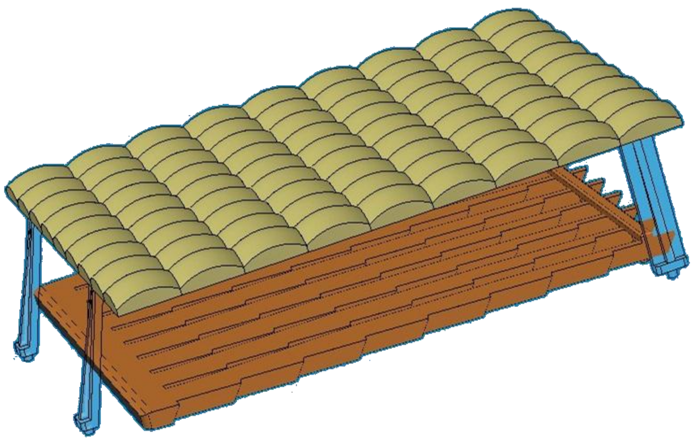


Figure 63: Hor-con optics

Design for manufacturability

Manufacturability is an important concern if it is necessary to realize the theoretical work. To get a manufacturable design we added 3 degree draft angles to the every vertical side of the mold to make it suitable for the injection molding. This change is simulated and verified that this modification is not causing a significant light loss. This angle makes it easy to remove the part from the mold, prevents mechanical stresses and increases the mold life time.

Support structure and mounting pins are added to the light guide structure. The place of the support structure is chosen such that from that region no light reflects internally and so the transmission efficiency of light guide is not affected.

The material injection region is very important for the injection molds. Injection region is important for the successful production and its place on the product should be analyzed with the mold flow simulations. In a light guide structure this plastic injection region can have a very destructive effect on the light transmission. Injection regions generally result deformed and highly rough surfaces. Therefore injection regions should be designed such that light does not interact with that region.

For the Hor-con light guide the only region for the material injection is the exit port of the light guide. This region will be attached to the PV with an adhesive and surface defects will be absorbed by the adhesive region. As a result the injection region will not have any effect on the final assembled module.

Module design

Geometric concentration ratio and the module thickness are obtained as a result of optical design of the module. The primary goal of this design is the realization of the concentrator. With a further design study it is possible to push the geometric concentration ratio to even higher levels while keeping other values constant. Hor-con solar module has the following design parameters as shown in the Table 7.

Table 7: HOR-CON Design Specifications

Acceptance angle	+- 2 degree
Geometric concentration	45x
Optical efficiency	%80
Absolute concentration ratio	30.6 x (With respect to 1000W /m^2)
Module thickness	4 cm
Module efficiency	%13.6 (with 17% cell efficiency under concentration)
Output power	115.6 W/m^2 (under 850 W/m^2 direct radiation)

Concentrator systems mainly use direct component of the solar irradiation. 850W/m^2 direct solar irradiation is assumed for module power estimations.

The power output of the module is estimated to be 116 W/m^2. It is calculated by multiplication of incident solar power with the optical efficiency and PV cell conversion efficiency as shown in Figure 64. The targeted optical efficiency can further be improved by accurate mold production and applying antireflection coatings.

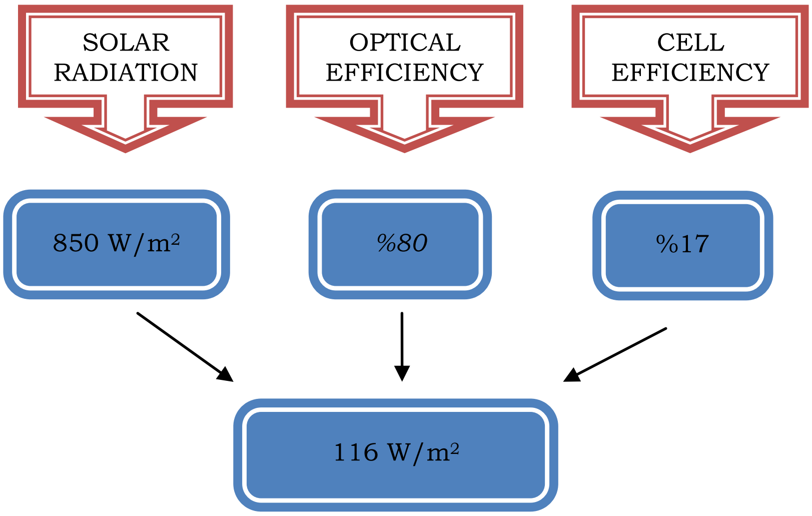


Figure 64: Power calculation of the solar concentrator module.

Mechanical design of Module

To hold the lens and the light guide in a proper position a test mechanics is needed. For the alignment of lens array and the light guide a rigid mechanical structure is designed as shown in the Figure 65. This mechanical structure will be produced from aluminum and it will also be used for heat dissipation purposes.

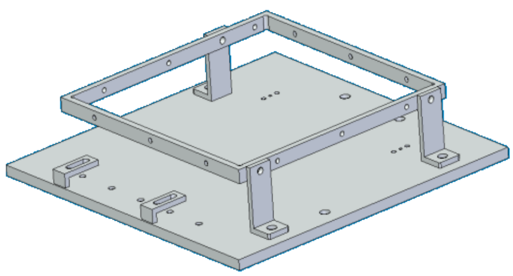


Figure 65: Test mechanics

Light guide and photovoltaic cell will be attached to each other by using a transparent adhesive. At the working condition the cell will be heated up as a result of high level (45x) of solar irradiation. Therefore a copper cooling rod will be bonded to the back side of the cell with epoxy adhesive and down side of the copper rod will bonded to the bottom aluminum plate to transfer the heat. All the parts will be assembled to generate the prototype as shown in Figure 66.

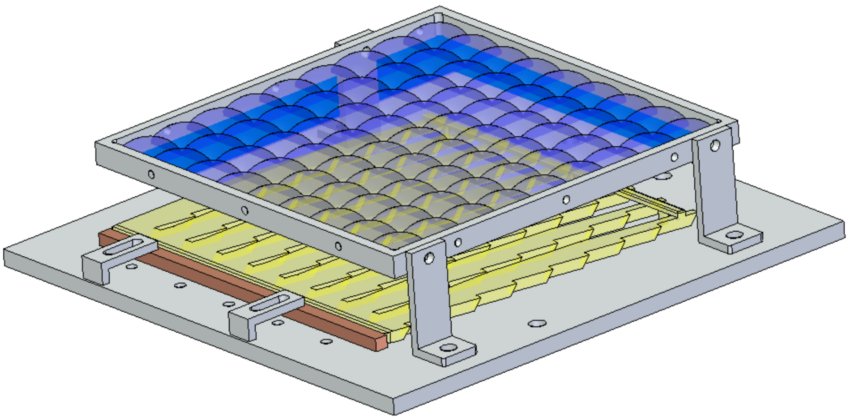


Figure 66: Hor-con test module- Prototype-2

5.4. Optical manufacturing

We have produced a prototype of the Hor-con-45X solar concentrator to verify the manufacturability of the concept. PMMA is used for both lens array and the light guide.

PMMA materials are available from several manufacturers on the market. Although there are many materials, pure PMMA is not easily accessible. PMMA types generally have several chemical additives mixed into it. These additives are used to change the flow rate, improve UV resistance and change the glass transition temperature of the PMMA resin. Most of the used chemicals destroy the light transmission property of the PMMA while improving some other properties of the material.

Lens array is open to the atmosphere and therefore UV resistant PMMA should be used for its manufacturing. Light transmission property is important for getting high optical efficiency. For the material selection, light transmission property of the materials should be checked especially at the blue and infrared region of the spectrum. Mold manufacturer should agree with the flow rates which is important for the mold design. PMMA material from Evonik with a name of 8N is used for the manufacturing of the lens array.

For the light guide material much more attention is needed. Because light path is longer in this material, light guide material should have very high purity for better transmission. High transmission generally prevents using UV resistance additives. In general spec-sheets from the suppliers are not good enough to understand the behavior of the material. The best thing for the measurement is long light transmission property of the material. Very thick samples such as 100 mm thickness should be used for the optical transmission tests. For the manufacturing of light guide high purity light guide grade PMMA from Evonik is used with a name of POQ66.

For the production low cost injection molding method is used. Runner and ejector pin designs are performed as shown in the Figure 67. Runner is the guide of molten plastic to the mold cavity. Ejector pins are used for separating optical components from the mold. Both runner and ejector pins are important for the success of production.

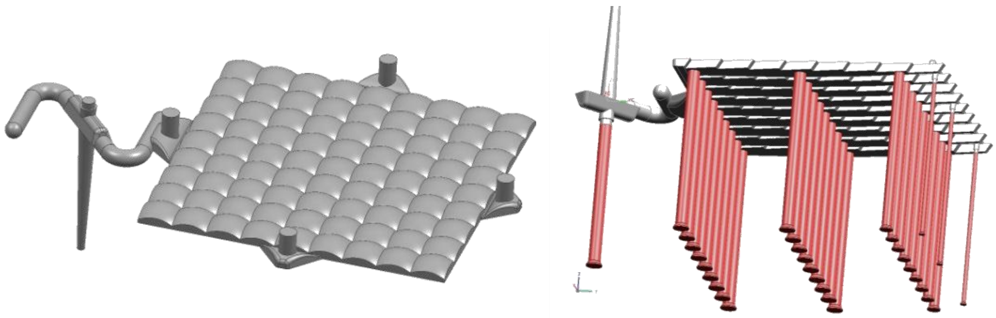


Figure 67: Primary lens array and light guide as they come out of the mold. Ejector pins used for de-molding the light guide is also illustrated (red parts)

The mold used for the production is shown in Figure 68. As seen from the picture both of the optical components are produced in the same mold for cost effectiveness. The left side cavity is the primary lens and the right one is for the light-guide.

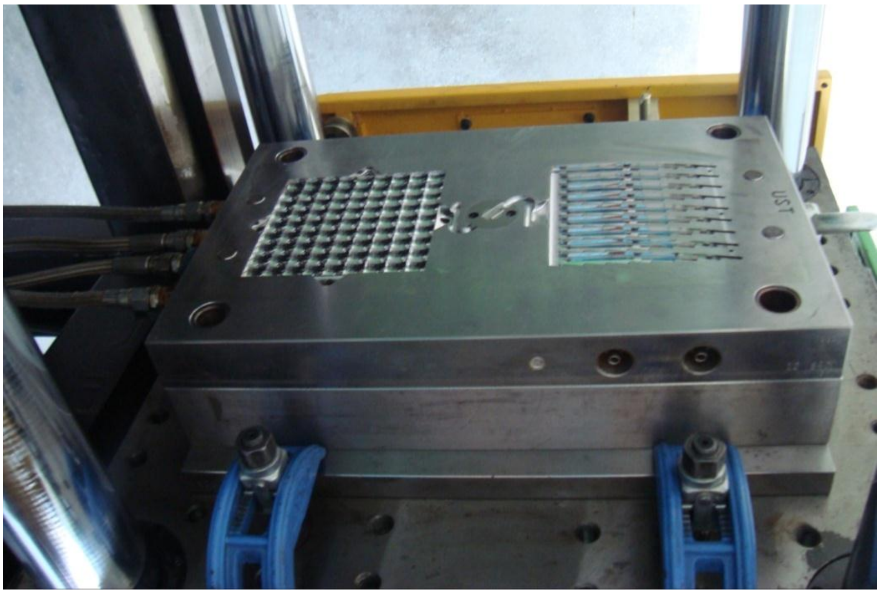


Figure 68: Mold for production

5.5. Quality checks

Initial quality checks are shown that there is waviness on the light guide, which will cause some deviation from the design performance. Surface qualities at side surfaces are not good as shown in Figure 69 and this is also validated by the tests under solar simulator. The most of the light loss was expected from side walls as a result of these quality controls.

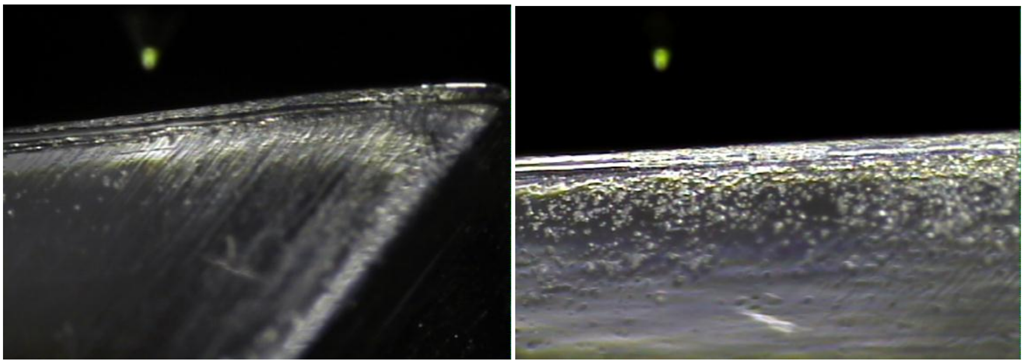


Figure 69: Side surfaces of the light guide. Polishing marks and rough surfaces are shown.

Quality check under the solar simulator is done also to understand the optical behavior of the produced components and determine the defected regions. Solar simulator in GUNAM is used for the optical quality checks. The collimation of the source is not good and therefore instead of a small spot at the focal point, a larger spot is obtained at the focus of primary lens array. Lamps of the simulator can be seen from the image produced by the primary lens array as shown in Figure 70.

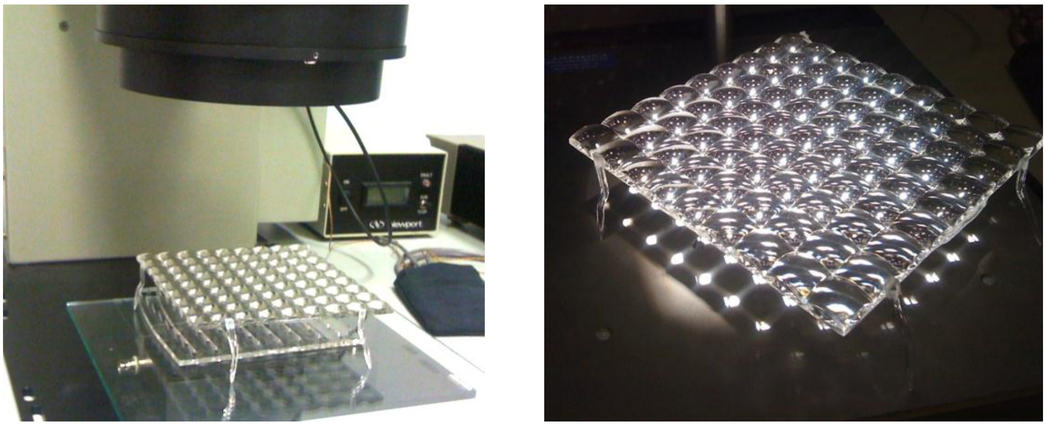


Figure 70: Lens array under the solar simulator.

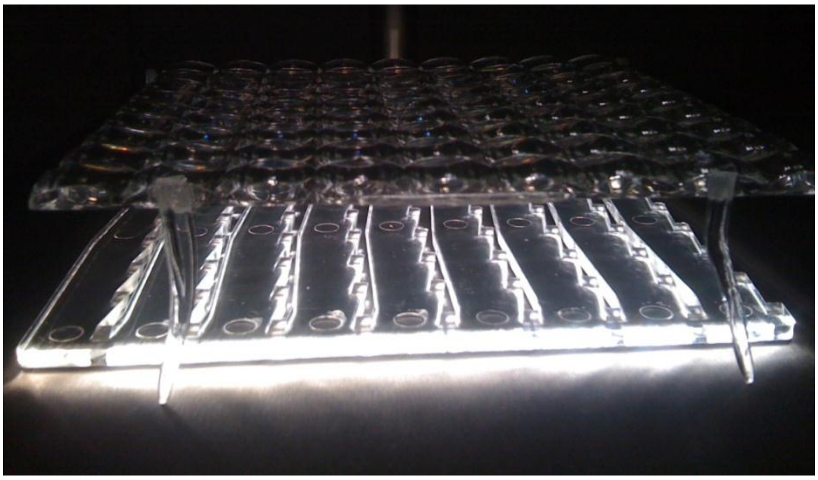


Figure 71: All the optical system is tested under solar simulator. Escaping light indicates the defected regions.

All the optical system is tested under solar simulator as shown in Figure 71. The most of the light loss occur from the side surfaces of the light guide. Light escaping regions are easily detectable because those regions are illuminated by the escaping light as shown in Figure 72.

To eject the produced optical components from the injection mold, several ejector pins were used. These ejector pins are pushing against the optical surfaces and damages these surfaces. The circular light loss regions seen at the down side of the light guide are from the ejector pins. The mold used for production is a simple and low cost mold. It is possible to remove these ejector pin marks at the serial production mold.

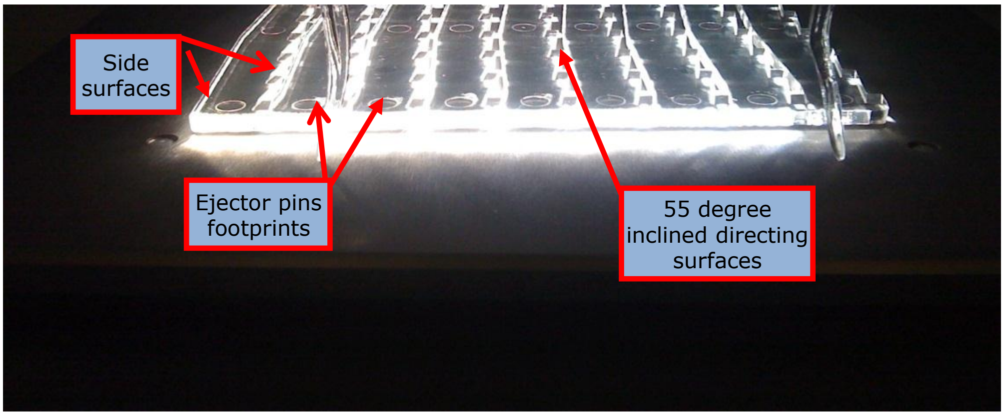


Figure 72: Light escaping regions

As a result of under solar simulator quality checks, mold cavity polishing is repeated 4 times and surface qualities were improved. Because of limitations of hand polishing, side walls and narrow regions cannot be polished well.

5.6. Assembly

Assembly is an important step for the success of the prototype. Suitable materials should be used for combining parts and good alignment is necessary. At the integration stage several problems are occurred and solutions are developed. The experience gained is worth to note here for further studies. Integration procedure is explained in detail. Work is divided into steps for accurate prototype manufacturing and repeatability.

Step 1:

Integration start with the quality checks of optics. It is important that there are no defects or impurities in and on the optics. Because this is a prototype manufacturing, production quantity is not much. Generally small chips of materials could exist from the previous running of the injection molding machine. Although great attention is given for the cleanness and several idle runs are performed to clean the machine, sometimes impurity problems can occur. Therefore optics should be checked to be free of any impurities.

While holding the acrylic optics it is important to use clean gloves. Oil from the human skin can permanently damage the surfaces of the optics.

Step 2:

Optical components are manufactured together with ejector and material injection regions. These extra regions should be removed by tooling. The best method for removing these parts is using grinding tools. These tools can remove the unnecessary parts accurately while keeping flat surfaces. After this machining operation dust accumulated on the optics are removed by washing them with the purified water and dried by the filtered pressurized air.

Step 3:

Solar cells are prepared at this step. Busbars of the solar cells are too thin and does not have ability to carry high currents because of high resistance. In fact this busbars are combination of very thin finger geometries produced by electroplating as shown in Figure 73. Closely placed fingers are building the busbars.

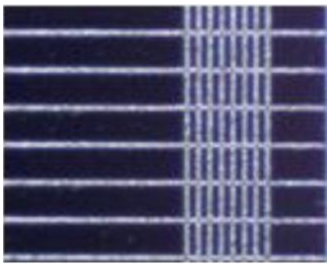


Figure 73: Busbar of the LGBC cell from NAREC

To reduce the grid resistance of the solar cell to carry high current levels, tabbing wires have to be soldered to the busbars. Because of unmatched coefficient of thermal expansion between silicon and copper, the cell with wire is curved like the bimetal strips when cooled after the soldering process. This curvature prevents integration to the optics and increases the fracture rate of the solar cell. For the prototype work soldering of the tabbing wire is abandoned and busbars of the cells are coated with thick solder layer. After that two wires are connected to the front and back contacts of the cell to carry the generated current to the measurement device.

The wires are needed further attention to keep the series resistance low. Because high current densities are generated, thin wires can prevent current flow and prevent power delivery from the device. After the soldering processes short checks and resistance measurements are performed between two soldered wire to control the correctness of the soldering process and misconnections. Furthermore, solar cells are checked under the solar simulator and their 1 sun performance results are noted.

Step 4:

Cooling rod is attached to the solar cell with an epoxy adhesive. Epoxy region should be kept thin to promote heat transfer by reducing the thermal resistance.

Step 5:

The most important step is the combining light guide and solar cell. Transparent UV cured adhesive is used at this stage. Both of the parts are covered with a thin layer of adhesive. Parts are aligned and kept in contact position mechanically. After being sure light guide and solar cell is aligned properly, adhesive is cured with a UV torch. It is possible to use UV cured adhesives in this step because light guide is transparent to the UV light.

We used several different kinds of adhesive types to reach the correct assembly method. Initially cyanoacrylate based transparent adhesives are used for combining light guide and the solar cell. But this solvent based adhesive shrinks when it dries and voids occur in the adhesive layer. If the adhesive layer is so thin, this effect may not be significant but in this prototype adhesive should fill the space generated by the front fingers of the solar cell. Therefore with solvent based cyanoacrylate adhesives good coupling surfaces were not achieved.

Transparent silicone and EVA sheets also evaluated but their sticking on the PMMA material is not adequate. Although some recent studies are exist to use special EVA sheets for the PMMA glasses, these EVA types were not accessible through market at the time of study.

UV cure acrylic based adhesives found to be the most suitable materials for combining light guide and the PV in Hor-con module. These adhesives have a very good purity and gives opportunity to the alignment of the components. After being certain that everything is in place and aligned, a small UV light can cure the adhesive with a very small shrinkage.

NOA-61 adhesive from Norland is used in the final prototype. This adhesive has a refractive index of 1.56 on the average and has a very high light transmission. Transmission graph of the NOA61 is shown in Figure 74.

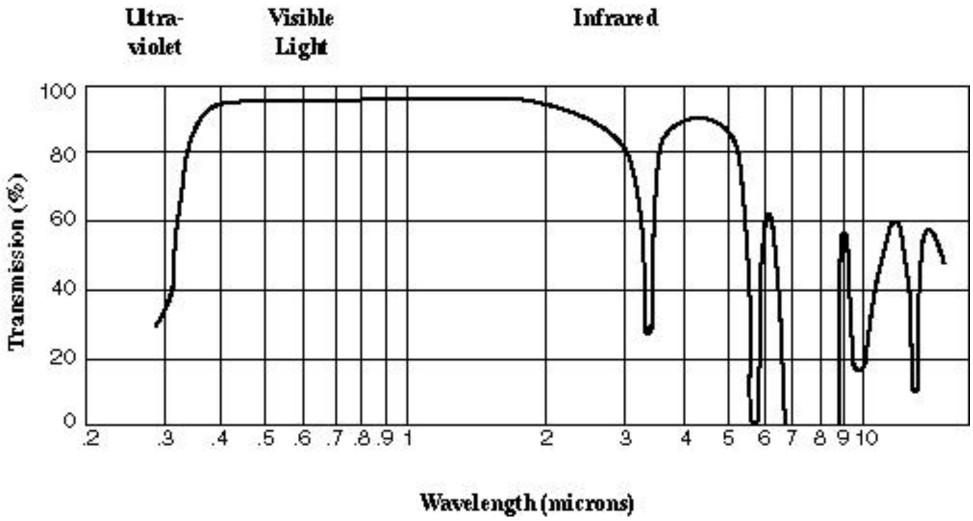


Figure 74: Transmission of NOA 61 adhesive from Norland Products[46]

Step 6:

Finally lens array and light guide assembly is combined with the mechanical structure and aligned. In most of the cases accuracy of the mechanical structure is enough. Alignment can easily be checked under collimated light or under real sun light. Focused light from the primary optics should be matched with directing surfaces of the light guide. Any misalignment is easily detectable with the human eye.

5.7. Testing

Buried contact solar cells have been shown to work with efficiencies greater than 20 % under concentrated light [47]. Optical design in this prototype requires long and narrow cells. As a result of the geometry of the cell, the recombination edge is longer in comparison to active area [48] and un-illuminated area is high because of the busbar. As a result, a little lower efficiency is expected with respect to the square cell geometries.

In this study, the main target is demonstrating the performance of the optical concentrator. Detailed characterization of the cell under concentrated light is not performed because the cell used in this prototype will be replaced by back contact solar cells in the next step. For several measurements under one sun illumination, an average of %80 FF is measured for the LGBC solar cells and this 80% FF is assumed to be stay constant under higher illumination levels, which is acceptable in the literature.[49]

For the measurement of optical performance of the solar concentrator, a cell is characterized under the solar simulator and a SCC: 32.9 mA/cm^2, VOC: 550 mV and a FF: 80% is obtained. As a result 14.48% efficiency is achieved under one sun condition as shown in Figure 75.

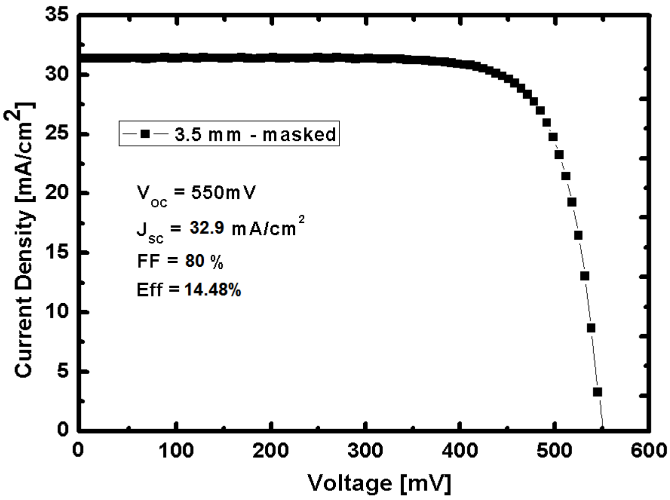


Figure 75: I-V measurement of test cell

SCC will increase proportionally with the illumination level and will be used for the performance measurement of the solar concentrator. Efficiency of the cell will increase with the concentration as a result of increase in the VOC under higher illumination condition. The fill factor of the solar cell is assumed to be constant with the increasing concentration level in the further system efficiency calculations. In fact, a few percent improvements can be expected in the fill factor up to a certain concentration level in some designs [49] with proper solar cell optimization.

Most of the measurements are carried on under real Ankara sun. Because of the changing outdoor conditions, solar flux is also measured with a sun photometer. SCC and VOC of the cell are measured during the tests with multi-meter setup. SCC is used to determine the illumination level on the cell as it is the main indicator of the photon flux. VOC is also affected by the illumination, but it is mainly used to understand the efficiency increase of the cell. VOC also used to estimate the temperature of the cell and monitoring it can prevent occurrence of thermal damage to the system at the initial test phases.

After characterization is performed under the solar simulator, solar cells bonded to the light guides with a transparent adhesive. The tests under the sun have given following results shown in Table 8 for three different integrated prototypes. First integrated prototype was not satisfactory enough. Solar cell alignment was not well established and there were bubbles inside the adhesive layer which affected the optical transmission. Moreover contamination was a problem for the first prototype and next prototypes were developed with the experience gained from the first prototype.

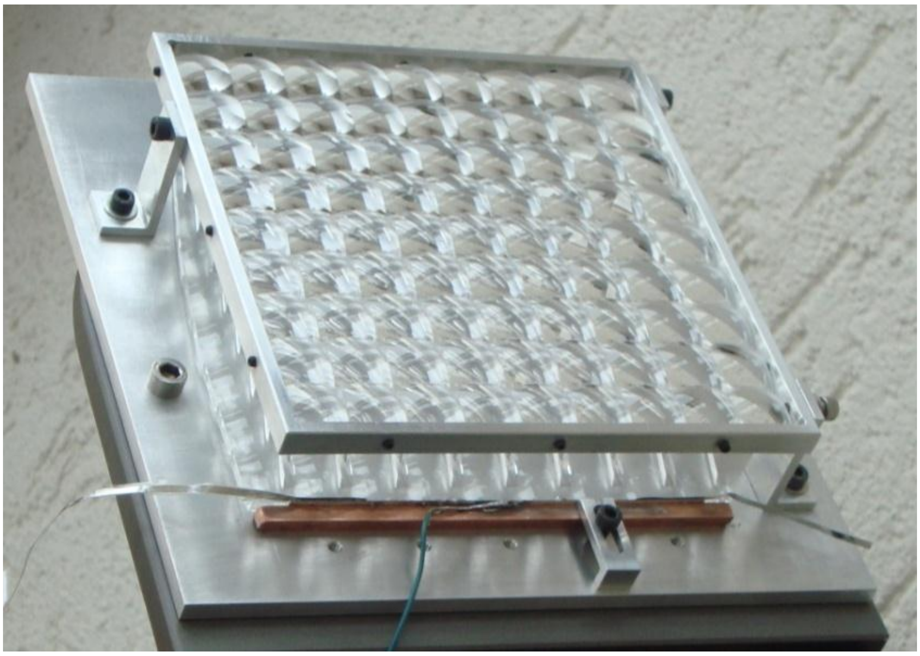


Figure 76: Assemble of optics and test mechanics.

Table 8: Three different integrated prototype measurements under sun

Test date: **30 September 2012**	**1. Integration**	**2. Integration**	**3. Integration**
Short Circuit Current	2940 mA	906 mA	1620 mA
Open Circuit Voltage	645 mV	655 mV	650 mV
Area of the cell	3.2 x 121 mm^2	3.2 x 32 mm^2	3.2 x 57.5 mm^2
Short Circuit Current Density	759 mA/cm^2	885 mA/cm^2	880mA/cm^2
SCC under 1000W/m2 (no concentration)	33.1 mA/cm^2	32.9 mA/cm^2	32.9 mA/cm^2
Direct Solar Irradiation at the test time	800 W/m^2	820 W/m^2	800 W/m^2
Optical Efficiency	**%64**	**%73**	**%74.3**

The best test results are shown in the Table 9. When the cell is attached to the light guide concentrator, the short circuit current density was increased from 32.9mA/cm^2 to a value of 880mA/cm^2. For the short circuit current density calculations active area is taken similar to the illuminated area by the optics which has a width of 3.2mm. Length of the active area is the same as the length of the solar cell. By considering the 800W/m^2 direct solar irradiation, the optical efficiency estimated to be %74. This result is lower than the targeted %80 optical efficiency but acceptable because of several identified defects on the light guide.

Table 9: Measurements under one sun and under concentration (best results)

Test date: 30 September 2012	**Characterization under 1000W/m2**	**Measurement with the concentrator optics**
Short Circuit Current Density	32.9mA/cm^2	880mA/cm^2
Reference Solar Irradiation	1000 W/m^2	800 W/m^2 (direct) 940 W/m^2 (total)
Geometric Concentration	1x	45x
Open Circuit Voltage	550 mV	650 mV
Fill Factor	%80	%80
Efficiency of the cell	%14.5	%17.1

Under concentrated light VOC increased to 650 mV for the initial seconds of light exposure. This is an improvement of %18 with respect to 1 sun characterization. Therefore efficiency of the cell becomes %17.1 under this concentration level with the assumption of FF is 80%.

With this measured optical efficiency and the attached LGBC cells it is possible to achieve a solar panel with a 107 W/m^2 output as shown in the Figure 77.

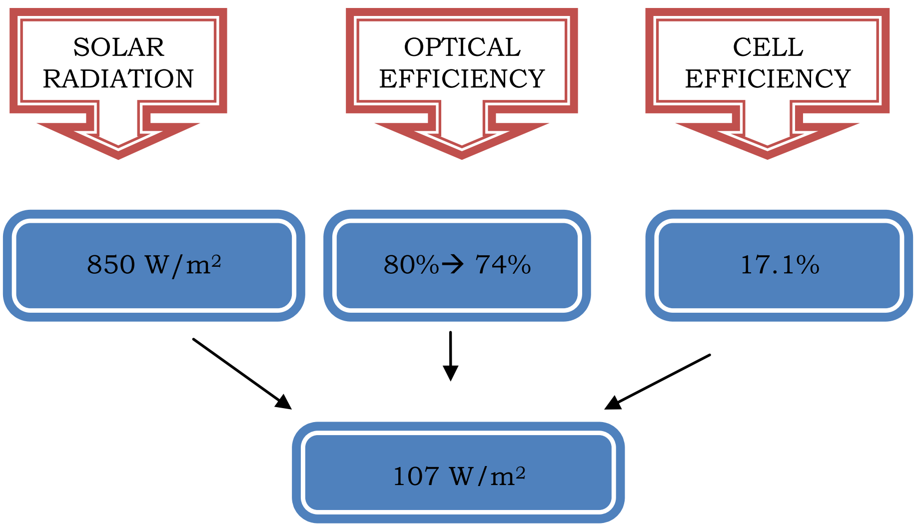


Figure 77: Power calculation of the prototype module.

To figure out the problems, we measured the optical efficiency from different portions of the light guide. A mask is used to prevent reaching of the light to the light guide. Mask is positioned just above the light guide and light is closed step by step from every lens. The optical transmission test results are shown schematically in the Figure 78.

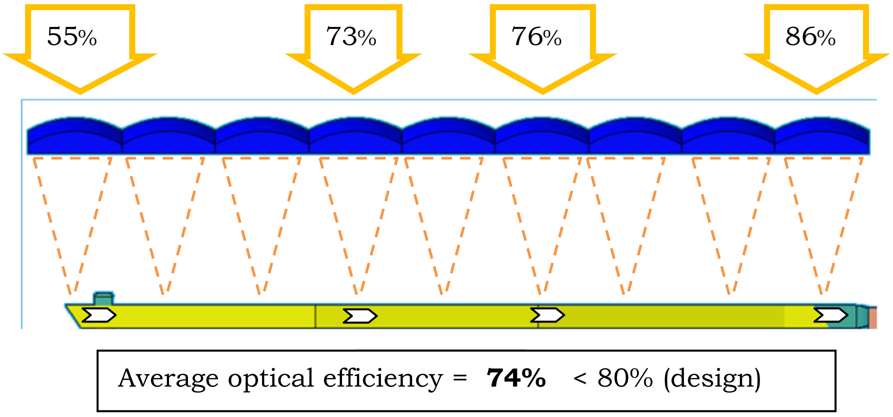


Figure 78: Optical transmission values for different portions of concentrator.

Light coming further away from the cell has to pass longer paths to reach the solar cell. Therefore comparing different light paths gives information about the optical performance of the light guide.

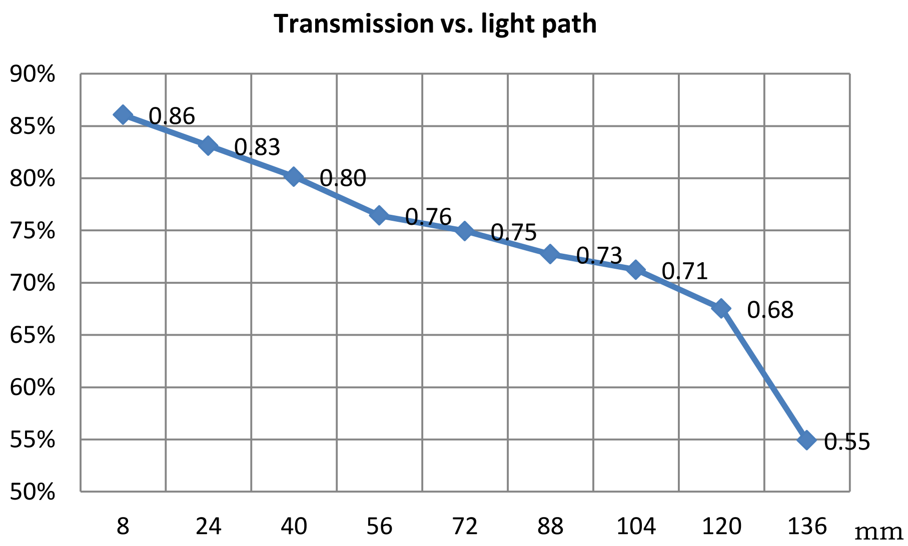


Figure 79: Transmission values for the light rays entering the light-guide from different distances.

By investigating the graph shown in Figure 79, it can be concluded that light coming further away from the cell experiences higher loss. The closest portion has smaller optical path and light only hits to the angled directing surfaces. Therefore scattering and absorption losses are small. An optical efficiency of %86 is measured in this portion. It is close to the theoretical maximum of 88% and losses should be sourced from mainly the scattering losses at the surface of the lens and at the angled injection element. If we go further away from the PV cell, the losses become significant and efficiency drops to 55%. By looking to graph, the losses increase with the length of the light guide monotonically but at the last two portions the losses further increases. This was an expected result because mold couldn't be polished well in the last two step of the light guide. This is a result of hand polishing used for mold manufacturing. If we extract these two defected portions, the main change will be the geometric concentration ratio, which will become 35x. By recalculating the optical efficiency, we can reach %78, which is very close to our targeted 80% optical efficiency.

If we cancel defected first two narrow regions:

Geometric concentration ratio: 45x → 35x

Average optical efficiency = **78**% < 80% – nearly acceptable

Thermal behaviour of the Hor-con module is also inspected at the testing studies. The module is heated 15 degrees beyond ambient temperature in first minute and than temperature difference from the ambient gradually increase to 30 degrees in ten minutues. This result is for the best module integration. The values increase if the adhesive layer between the solar cell and copper rod is thicker or has some voids.

The temperature flactuations occured when wind speed increased. The effects of the unstable outdoor conditions were occilating the open circuit voltage as a result of temperature variations.

This module has a very thick back plate with 5 mm thickness and larger and commercial modules can not use such a massive cooling plate. Moreover this module is an open sided module and heated air inside the module easily leave the module and reduce the panel temperature. Finally, a small module and larger module will have totaly different heat transfer behaviour because convection heat trasfer coeffient is depending on the area of the module. Therefore thermal measurements are specific to this small sized prototype and larger modules will have different thermal behaviour.

5.8. Future Work

This prototype results show that, the Hor-con concentrator optics can be realized with proper mold manufacturing. Mold used in this study has some defects and can be further improved to increase the optical performance of the system. By manufacturing a new mold an optical efficiency greater than 80% can easily be achieved.

To get a better module power output, better efficiency cells are also needed. In this prototype work LGBC cells with 17.1% efficiency under concentration are used and in the future work back contact solar cells are the closest candidate to replace these cells. Back contact cells can easily reach more than 25% efficiency under concentrated light. Therefore with 80% optical efficiency and 25% cell efficiency, a module efficiency of higher than 20% can be achieved. This efficiency corresponds to more than 170W/m^2 module power output.

5.9. Environmental considerations

When a land covered with the solar modules, light reaching to the ground is prevented. Without light, vegetation cannot grow and the land cannot be used for farming. The situation is not that dramatic for the systems that using trackers. Systems that using trackers are elevated from the ground and their shadows are not continuous. This property gives opportunity to establish solar farms on ordinary farms.

Moreover it is possible to generate a system with partially transparent properties. CPV systems are only using direct and close to direct portion of the solar radiation. Therefore the diffuse part of the radiation can pass to the back side of the module and illuminate back side land. This is possible if the heat transfer plate does not cover all the back of the module.

Module recycling is also an important aspect of the solar modules. Hor-con systems are produced from plastics, aluminum, silicon crystal and steel. Nearly all the module and tracker system are recyclable. In this module type, plastic materials have high purity therefore can be recycled by low cost processes.

CHAPTER 6

COST ANALYSES

Solar energy research is mostly a cost driven research area. The projects and ideas focuses to increase the efficiency and decrease the material consumption, so to reach less $/W module price.

Flat solar panels can use all the irradiation without directional selectivity, while CPV panels can only use direct solar irradiation. Moreover CPV systems have to use solar trackers while flat panel systems can be fixed. Therefore their cost analyses are using different parameters. But at the end, cost of the CPV systems can be compared with the flat panel systems.

$$\frac{\textbf{cost}}{\textbf{energy}} = \frac{\textbf{solar cell} + \textbf{optics} + \textbf{mechanics} + \textbf{sun tracker} + \textbf{inverter} + \textbf{other costs}}{\textbf{solar radiation x efficiency}}$$

Concentration decreases the amount of cell requirement while adding other cost items such as optics and trackers. Therefore to reach a lower cost/energy ratio ($/kWh), a complete cost analyses should be performed and design decisions should be made accordingly.

6.1. Cost analyses of the light guide CPV module

Cost analyses of the system are shown here and assumed that solar panels will be manufactured in large amounts. With this assumption, injection mold is assumed to be used all its life time and high efficiency cells are available and produced specifically for this module manufacturing. Price of the module will be calculated with a $\$/m^2$ so that other cost parameters can easily be added to get a system level cost afterwards.

Optical material cost

Inside the module two different optical materials are used. One is the transparent UV resistant PMMA for the primary lens array and the second one is high transmission optical grade PMMA.

The amount of material consumption values are taken from the medium concentration solar concentrator module development, Hor-con module. The solar concentrator in this system has 144x144 mm^2 area coverage. We assume that bigger solar panels will have similar characteristics with the smaller ones and the module area cost will be calculated by the projection of values obtained from smaller modules.

Hor-con sub-module is using a lens array which is an arrangement of 81 small lenses. This lens array has a weight of 118 grams and produced from UV resistant PMMA plastic. Weight of light guide is 62 grams and produced from optical grade PMMA. Summing two values, 180 grams of optical material is needed per sub-module. Prices of the materials are obtained from Evonik for large amounts. The material cost is calculated as shown in Table 10.

Table 10: Material Cost Estimation

	Material	Area (WxL) (mm^2)	Mass (kg)	Mass/area (kg/m^2)	Price ($/kg)	Price ($/$m^2$)
Lens array	UV resistant PMMA	W: 144mm L: 144mm	0.118	5.69	2.85	16.22
Light guide	Optical Grade PMMA	W: 144mm L: 144mm	0.062	2.99	3.25	9.72

Price of mold

For the production of the optics two molds, one for lens array and one for light guide are necessary. Generally injection mold systems are produced for 1 million cycles. Professional molds are expensive systems, but for high production amounts the cost becomes unimportant. For ordinary injection molding machines a 0.5 m x 0.5 m size is feasible at one cycle. Therefore it is assumed that 250000 m^2 panel area will be manufactured with these molds.

Table 11: Injection mold cost estimation

Mold price for lens array	100000$
Mold price for light guide	100000$
Area of module produced per cycle	0.5m x 0.5m
Life time of mold	1.000.000 cycle/mold
Cycles needed for 1 m^2 production	4
Mold price /m^2	0.8 $

Cost of injection molding

Injection molding machines can be rented for daily bases from the industry with fix prices, including energy and maintenance costs. The nominal price for the daily usage of one machine is 200 $ per day. Amount of production depends on the cycle duration. If a faster mold is used, more optics will be produced per day with a fix price. Cycle duration is given to be 1 minute for the calculations.[50]

Table 12: Injection molding cost

Price of injection molding machines (two machine)	200 \$/day *2 machines = 400\$ /day
Number of hours per day	8 hours
Number of cycles per day	8x60 = 480 cycles
Daily production (4 cycle→1 m²)	120 m²
Price per m²	3.33 \$/m² (400\$ / 120m²)

Solar cell cost

In 2012 production cost of the solar modules is dropped to 0.5-0.6 $ /W range. High quality back contact solar modules from Sunpower has similar trend and their price is less than 1$/W. Therefore we can estimate high quality silicon solar cell price of 1 $/W including dicing costs. High quality panels have 20% efficiency under 1000W/m^2 standard test conditions. Therefore 1 m^2 area solar cell can be purchased from 200$.

Hor-con solar concentrator sub-module has a width of 144 mm and a cell width of 4 mm. Therefore with respect to cell dimensions 36x concentrations is achieved. Therefore 1 m^2 solar panel can power 36 m^2 Hor-con panels.

Table 13: Solar cell cost

Back contact solar cell price	200 \$/m²
Dimensional concentration	36 X
Cost of solar cell per panel area	5.56 \$/m²

Mechanical parts

Back side of the module will be aluminum. This part will be used as a heat dissipation surface and back cover. Aluminum sheet will have a thickness of 1 mm.

Table 14: Back sheet cost

Price of Aluminum	3\$/kg
Weight per m² (1 mm aluminum sheet)	2.7 kg
Cost of back sheet	8.1 \$/m²

There will be also stiffness elements and electrical connections. 10 $/m² for stiffness elements and 10$/m² for the electrical connections are estimated. Adhesives are used for connecting parts. A cost of 5 $/m² is estimated. Finally labor will assembly everything and 10$/m² is estimated for the labor.

Table 15: Other cost items

Stiffness Elements	10 $/m²
Electrical Connections	10 $/m²
Labor	10 $/m²
Adhesives	5 $/m²

Cost of panel

By adding all the cost parameters, total cost of the panel is found to be 78.73 $/m². This panel can produce 170 W/ m² with proper mold production and high efficiency cell utilization.

Table 16: Cost estimation of solar panel

	Price ($/m²)	**Share in the cost (%)**
Lens array	16.22	21%
Light guide	9.72	12%
Mold	0.80	1%
Injection	3.33	4%
Cell	5.56	7%
Back Sheet	8.10	10%
Stiffness	10.00	13%
Electrical connections	10.00	13%
Adhesives	5.00	6%
Labor	10.00	13%
TOTAL	**78.73**	**100%**

Price per Watt

Price per watt is estimated by dividing panel cost to the power output of the module. This calculation gives a cost estimation of 0.46 $/Watt. This value can further be reduced by using thinner front lens, higher efficiency solar cells and utilizing antireflection coatings on the optical surfaces.

Table 17: Price per Watt estimation of solar panel

Price of Module (1 m^2)	**78.73 $**
Power output	**170 W**
$ /W	**0.46 $ /W**

6.2. Energy price calculations

Tracking

Tracking increases the available radiation per day and a relatively constant output through the day can be achieved. CPV systems have to work with trackers. Without a tracker, optics cannot concentrate the light. Tracker cost of 100$/m^2$ is achievable for medium concentration systems.

Inverter prices

Inverters are necessary to connect the electricity to grid. Inverter prices are approximately 0.25 $/Watt. Therefore, with a 170 W power generation per square meter, inverters will cost 42.5 $/m^2$.

Energy generation

For the calculation of yearly energy generation of CPV systems, DNI values are used. As an average value, 2000 kWh/(m^2.year) is used for calculations. Panel efficiency is 20% and therefore 400 kWh/(m^2.year) energy production is achievable from one meter square panel.

Cost of electricity

Cost of electricity for solar systems is 13.3 cents per kWh in Turkey and for the calculations this value will be used. 10 year investment return period is estimated for $/kWh calculations. Land cost, labor cost for installation and maintenance are pretty unknown and not included in the calculations.

With this price analyses, 4.16 year investment return time and 5.53 cents/kWh electricity production cost is estimated. These values show that solar energy prices are competitive with the other energy production methods and grid parity is achieved.

Table 18: Energy price estimation

Panel cost(1 m²)	78.73 $
Tracker Cost (1 m²)	100 $
Inverter cost (170 W)	42.5 $
TOTAL COST	221.23 $
Price of Electricity produced (400kWh/m²)	53.20 $/year
Return of investment	4.16 year
Price of electricity (10 year pay back)	5.53 cents($)

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Almost 85% of the total energy need of the world is supplied by burning fossil fuels which have limited resources. Climate scientists are warning the world community for catastrophic climate effects of fossil fuel burning due to the excessive amount of CO_2 emission into the atmosphere. It is our responsibility to replace the environmentally dangerous fossil fuels with more clean and renewable resources. As a clean, abundant and reachable energy resource, solar energy is the most promising candidate as the primary energy source of human kind in the future.

In this work we have studied one of the photovoltaic solar energy conversion systems with the aim of reducing the cost of electricity while keeping the efficiency high. Chapter-1 introduces the solar energy as an important renewable energy source and its indispensable nature for the future of the humanity. Cost problem of flat plate solar systems and CPV concept as a solution to this problem is discussed. A short summary of the efforts in the thesis to develop a solar concentrator is also given in this chapter.

In Chapter-2 an overview of the CPV systems are given. High concentration, medium concentration and low concentration systems are explained. A summary of the main optical concentrator architectures are presented to comparatively explain the efforts in the world in CPV systems. Moreover problems of the CPV systems are determined to guide the studies in direction of the solutions to overcome these problems. Photovoltaic cells are explained and important parameters of the solar cells for CPV systems are emphasized.

Optical concentrator design is the main focus of this thesis study. In Chapter-3 optical techniques and important concepts for the design of concentrators are explained. Main performance parameters such as CAP, concentration ratio and acceptance angle are defined here. Moreover physics behind the light guides are explained. Spectral and spatial distribution of sunlight is given here.

In Chapter-4 horizontally staggered light guide solar concentrator concept is explained in detail. Design methods and parts of the concentrator are explained. A high concentration system is designed and simulated with 1000x concentrator geometry. In this simulation study side-cut and end-cut geometries are successfully employed and results go beyond the expectations in the literature by achieving 1000x concentration ratio, more than +- 1 degree acceptance angle and an optical efficiency of 96.5%. In the theoretical studies, several design variations are developed. These variations can generate the future research paths and can also ease the production of the optical concentrator.

One of the important problems of the classical CPV systems is overheating. The concentrator system studied in this thesis has a line focus type exit port. This geometry has advantage with respect to the heat transfer. Thermal simulations are performed to prove the superior properties of the line focus systems over point focus systems.

In Chapter-5 realization of the light guide solar concentrator is explained in detail. Initially a conceptual prototype is designed and it is shown that the theoretical design is functioning well and can be realized with real materials.

After conceptually showing that concentration method is functioning well, a medium concentration system is targeted with this concentrator architecture. Optical design is performed with real materials and also by considering real manufacturing methods. Design is modified several times to improve manufacturability and simulations are repeatedly performed to validate the design changes. This design is manufactured by low cost injection molding technique and mold surfaces are polished several times to reach a good surface quality.

Specially designed solar cells are used to test the efficiency of the prototype optics. Solar cell is combined with the light guide with a highly transparent optical adhesive. A cooling rod is attached at the back of the solar cell and all the components are aligned with a specially designed mechanical structure which also serves as a cooling element. A telescope mount is used as a sun tracker at the tests and current-voltage values under the sun are recorded with a multi-meter setup.

Test results confirm an optical efficiency of 74% while the target was %80. By investigating the optical transmission with respect to the length of the light guide, 86% optical efficiency is measured for the smallest light path while 55% efficiency is measured for the longest path. Except from the Fresnel losses and the absorption losses, all the unexpected losses are sourced from the insufficient surface quality of the mold. By manufacturing a new mold, it is possible to achieve higher transmission efficiencies.

A supplementary benefit of the realization of the solar concentrator is that manufacturing methods and their costs are investigated in real manufacturing environment. In Chapter-6 cost analyses of the solar concentrator is performed in detail and cost of the CPV module based on this concentrator optics is estimated.

This prototype study is used very low cost methods for the production of injection mold. Injection mold surfaces, especially side surfaces, could not be polished well because of the limitation of hand polishing. One of the further studies can be performed to improve the optical efficiency by producing a new injection mold with a better surface quality.

In this prototype LGBC cell are used and their efficiency is not sufficiently high. A second improvement can be using back contact solar cells as the receiver. This can improve the panel efficiency dramatically.

Finally to improve the optical efficiency anti-reflection surface treatments can be used. These treatments such as AR coatings or submicron surface textures can reduce the Fresnel reflection losses and optical efficiencies exceeding 90% is achievable.

REFERENCES

[1] R. M. Swanson, "The Promise of Concentrators," *PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS,* no. 8, pp. 93- 111, 2000.

[2] M. McDonald, S. Horne and G. Conley, "Concentrator design to minimize LCOE," in *Proc. SPIE 6649, High and Low Concentration for Solar Electric Applications II*, San Diego, 2007.

[3] S. Kurtz, "Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry," NREL, 2012.

[4] S. Horne, G. D. Conley and D. K. Fork, "Progress in the development of modular reflective concentrators for large-scale deployment," in *Proc. SPIE 6339*, San Diego, 2006.

[5] A. Davis and F. Kühnlenz, "Optical Design using Fresnel Lenses," *Optik & Photonik,* no. 4, pp. 52-55, 2007.

[6] D. Moore, G. Schmidt and B. Unger, "Concentrated photovoltaic stepped planar light guide," in *International Optical Design Conference, OSA Technical Digest(CD), paper JMB46P*, 2010.

[7] D. Mbewe, H. Card and D. Card, "A model of silicon solar cells for concentrator photovoltaic and photovoltaic/thermal system design," *Solar Energy,* vol. 35, no. 3, pp. 247-258, 1985.

[8] "Global Solar," [Online]. Available: http://www.globalsolar.com/. [Accessed 08 02 2013].

[9] G. Zubi, J. L. Bernal Agustin and V. G. Fracastoro, "High concentration photovoltaic systems applying III–V cells," *Renewable and Sustainable Energy Reviews,* no. 13, pp. 2645-2652, 2009.

[10] "NREL," National Center for Photovoltaics, [Online]. Available: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg. [Accessed 28 11 2012].

[11] M. Wolf and H. Rauschenbach, "Series Resistance Effects on Solar Cell Meausurements," *Advance Energy Conversion,* vol. 3, pp. 455-479, 1963.

[12] M. Pasquinelli and D. Marakel, "Serial resistance effect on p-type and n-type silicon concentrated solar cells," in *Clean Electrical Power (ICCEP)*, Ischia, 2011.

[13] E. Franklin, A. Blakers, K. Weber, V. Everett and P. Deenapanray, "Towards a Simplified 20% Efficient Sliver Cell," in *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, 2006.

[14] I. Antón, G. Sala and D. Pachón, "CORRECTION OF THE VOC VS. TEMPERATURE DEPENDENCE UNDER NON-UNIFORM CONCENTRATED ILLUMINATION," in *17th European Photovoltaic Solar Energy Conference and*

Exhibition , Munich, 2001.

[15] M. A. Green, Z. Jianhua, A. W. Blakers, M. Taouk and S. Narayanan, "25-Percent efficient low-resistivity silicon concentrator solar cells," *Electron Device Letters, IEEE,* pp. 583-585, 1986.

[16] Z. J. A. W. M. T. A. S. MARTIN A.GREEN, "25-Percent Efficient Low-Resistivity Silicon Concentrator Solar Cells," Vols. EDL-7, no. 10, OCTOBER 1986.

[17] R. Sinton, Y. Kwark, J. Gan and R. M. Swanson, "27.5-Percent Silicon Concentrator Solar Cells," *IEEE ELECTRON DEVICE LETTERS,* Vols. EDL-7, no. 10, pp. 567-569, 1986.

[18] M. A. PATRICK CAMPBELL, "The Limiting Efficiency of Silicon Solar Cells under Concentrated Sunlight," Vols. ED-33, no. 2, 1986.

[19] D. S. Schultz, S. Ghosh, C. S. Grimmer and H. Mack, "A CPV Thesis," in *Proc. SPIE 8108, High and Low Concentrator Systems for Solar Electric Applications VI*, San Diego, 2011.

[20] Y. Varshni, "Temperature Dependence of The Energy Gap in Semiconductors," *Physica,* no. 34, pp. 149-154, 1967.

[21] B. V. Zeghbroeck, "Principles of Semiconductor Devices," Colorado Uni., 2011. [Online]. Available: http://ecee.colorado.edu/~bart/book/eband5.htm. [Accessed 03 02 2013].

[22] D. Wolpert and P. Ampadu, "Temperature Effects in Semiconductors," in *Managing Temperature Effects in Nanoscale Adaptive Systems*, Springer, 2012, pp. 15-16.

[23] C. Honsberg and S. Bowden, "PVCDROM," PV EDUCATION.ORG, [Online]. Available: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature. [Accessed 03 02 2013].

[24] J. Luther and A. Bett, "Progress in High-Concentration Photovoltaic Systems," Fraunhofer Inst. for Solar Energie, 2007.

[25] G. Smestad, H. Ries, R. Winston and E. Yablonovitch, "The thermodynamic limits of light concentrators," *Solar Energy Materials,* vol. 21, pp. 99-111, 1990.

[26] R. Leutz, A. Suzuki, A. Akisawa and T. Kashiwagi, "Shaped non-imaging Fresnel lenses," *J. Opt. A: Pure Appl. Opt.,* no. 2, pp. 112-116, 2000.

[27] W. Welford and R. Winston, High Collection Nonimaging Optics, San Diego: CA:Academic, 1989.

[28] A. Luque, "Non-imaging optics in photovoltaic concentration," *Phys Technol.,* vol. 17, pp. 118-124, 1986.

[29] R. Leutz, H. P. Annen and L. Fu, "Optical tests for reliability and efficiency of photovoltaic concentrators," in *Proceedings of the SPIE,eliability of Photovoltaic*

Cells, Modules, Components, and Systems, San Diego, 2008.

[30] R. P. Corio, "Fly's Eye Lens Short Focal Length Solar Concentrator". Albuquerque, NM (US) Patent US 2008/0185034 A1, 7 8 2008.

[31] J. H. K. a. J. E. Ford, "Planar micro-optic solar concentration using multiple imaging lenses into a common slab waveguide," ().," in *Proc. SPIE 7407, 74070D*, 2009.

[32] E. T. a. J. E. F. J. H. Karp, "Planar micro-optic solar concentrator," *Opt. Express,* vol. 2, no. 18, p. 1122–1133, 2010.

[33] J. Anton, O. Ligero, D. Molini, E. Martinez and S. Caparros, "Light collection and concentration system". Patent WO 2010/056405, 2010.

[34] S. Ghosh and D. Schultz, "Compact optics for concentration, aggregation and illumination of light energy". Patent WO 2009/035986, 2009.

[35] J. Karp, E. Tremblay, J. Hallas and J. Ford, "Orthogonal and secondary concentration in planar micro-optic solar collectors," *Opt.Express,* vol. 19, pp. A673-A685, 2011.

[36] D. G. Jenkins, "High-Uniformity Solar Concentrators for Photovoltaic Systems," in *Proc. SPIE 4446, Nonimaging Optics: Maximum Efficiency Light Transfer VI*, San Diego, 2001.

[37] A. Cvetkovic, R. Mohedano, P. Zamora, P. Benitez, J. Minano, J. Chaves, M. Hernandez and J. Vilaplana, "Characterization of Fresnel-Köhler concentrator," in *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition- EU PVSEC*, Valencia, 2010.

[38] C. Algora, "Determination of optimum solar cell size," in *Concentrator Photovoltaics*, Springer, 2007.

[39] T. Gu and M. W. Haney, "Commona Plane Spectrum Splitting Concentrating Photovoltaic Module Design and Development," in *Renewable Energy and the Environment, OSA Technical Digest (CD)*, Austin, Texas, 2011.

[40] A. Blakers, "Silicon concentrator solar cells," in *Concentrator Photovoltaics*, Springer, 2007, p. 54.

[41] K. R. McIntosh and L. P. Johnson, "Recombination at textured silicon surfaces passivated with silicon dioxide," *Journal of Applied Physics,* vol. 105, no. 12, 2009.

[42] D. R. Lide, CRC Handbook of Chemistry and Physics, Florida: CRC Press, 2003.

[43] E. Industries, *PLEXIGLAS® Optical POQ66 Data sheet- MC139-E v0160,* 2011.

[44] E. INDUSTRIES, *Transmission in the UV-, VIS- and IR- area, PLEXIGLAS® 8N,* 2010.

[45] Ö. Selimoğlu and R. Turan, "Exploration of the horizontally staggered light guides for high concentration CPV applications," *Optics Express,* vol. 20, no. 17, pp. 19137-19147, 2012.

[46] N. P. INCORPORATED, "Norland Optical Adhesive 61," [Online]. Available: https://www.norlandprod.com/literature/61tds.pdf. [Accessed 11 02 2013].

[47] C. Morilla, M. Vivar, R. Russel, J. Fernandez and G. Sala, "Developments in the Optimisation of Laser Grooved Burried Contact Cells for use in Concentration Systems," in *22nd European Photovoltaic Solar Energy Conference and Exhibition*, Milan, 2007.

[48] A. Cole, I. Baistow, L. Brown, S. Devenport, K. Drew, K. Heasman, D. Morrison, T. Bruton, L. Serenelli, S. De luliis, M. Izzi, M. Tucci, E. Salza and L. Pirozzi, "Silicon Based Photovoltaic Cells For Concentration-Research and Development Progress in Laser Grooved Burried Contact Cell Technology," in *AIP Conf.Proc. 7.TH INTERNATIONAL CONFERANCE ON CONCENTRATING PHOTOVOLTAIC SYSTEMS(CPV-7)*, Las Vegas, 2011.

[49] A. Cole, K. Heasman, A. Mellor, S. Roberts and T. Bruton, "Laser Grooved Buried Contact Solar Cells for Concentration FActors up to 100x," in *IEEE 4th World Conference on Photovoltaic Energy Conversion*, 2006.

[50] J. T. Mäkinen and R. d. Schipper, "How can plastics injection molding help driving down the cost of photovoltaic concentrators?," in *International Workshop on Concentrating Photovoltaic Power Plants, Optical Design and Grid Connection*, Marburg, 2007.

[51] R. Z. LLC, *Zemax 12 - Optical Design Program - User's Manual,* 2012.

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Publications:

1. Ö. Selimoğlu, F. Es, and R. Turan, «Realization of Horizontally Staggered Light Guide Solar Concentrator», *Progress In Photovoltaics (submitted)*
2. Ö. Selimoğlu and R. Turan, *«Development of HOR-CON Solar Concentrator Module», 9th International Conference on Concentrator Photovoltaic Systems (CPV9),* Miyazaki, 2013 (accepted)
3. Ö. Selimoğlu ve R. Turan, «Exploration of the horizontally staggered light guides for high concentration CPV applications,» *Optics Express, vol:*20, no. 17, pp. 19137-19147, 2012.
4. Ö. Selimoğlu and R.Turan, «Horizontally Staggered Light-guides for High Concentration CPV Applications», oral presentation, *SOLARTR-2 Solar Electricity Conference and Exhibition*, Antalya, 2012
5. Ö. Selimoğlu and R. Turan, « A Waveguide For Concentrated Solar Collectors And A Solar Collector Thereof », WO 2012169980, Ankara, 2011 (patent pending)

6. O. Yilmaz, F. Turk, and O. Selimoglu , «Radiometric calibration and SNR calculation of a SWIR imaging telescope» AIP Conf. Proc. 1476, pp. 365-369, Antalya, 2012

7. O. Yilmaz, and O. Selimoglu , «MTF measurement of a SWIR imaging telescope using star test images» AIP Conf. Proc. 1476, pp. 131-135, Antalya, 2012

8. O. Selimoglu, O. Yilmaz, O. Şengül, and B. Akarca, «Mechanical FMC techniques for removing image blur in digital aerial cameras*», ISPRS Istanbul Workshop 2010 on Modeling of optical airborne and spaceborne Sensors, WG I/4, Oct. 11-13, IAPRS Vol. XXXVIII, part 1/W4,* Istanbul,2010

9. O. Yilmaz, O. Selimoglu, B. Ucar and O.Sengul, «Design steps to temperature and pressure insensitive optical systems for digital aerial imaging », *ISPRS Istanbul Workshop 2010 on Modeling of optical airborne and spaceborne Sensors, WG I/4, Oct. 11-13, IAPRS Vol. XXXVIII, part 1/W4,* Istanbul,2010

APPENDIX-A

OPTICAL GRADE PMMA

Data sheet of optical grade PMMA (PLEXIGLAS® Optical POQ66) from Evonik Corporation is given here.

PLEXIGLAS®

Product Information

PLEXIGLAS® Optical POQ66

Product Profile:

PLEXIGLAS® Optical POQ66 is an amorphous thermoplastic molding compound based on polymethylmethacrylate (PMMA).

In addition to the familiar properties of PLEXIGLAS® molding compounds, such as

- excellent light transmission and brilliance,
- very good weather resistance,
- high mechanical strength, surface hardness and mar resistance,

PLEXIGLAS® Optical POQ66 is distinguished by its

- guaranteed purity and clarity,
- high luminous efficiency in medium to long light paths,
- absolute colorlessness even in thick layers.

Application:

PLEXIGLAS® Optical POQ66 is suitable for manufacturing extruded sheets to meet stringent optical requirements.

Examples:

Small to medium-sized injection-molded or injection compression-molded lightguide panels for display applications, lightguides.

Processing:

PLEXIGLAS® Optical POQ66 can be processed on extruders with conventional three-section screws for engineering themoplastics.

For manufacturing extruded lightguide panels, it is advisable to maintain processing temperatures at the lower end of the scale.

Physical Form / Packaging:

PLEXIGLAS® Optical POQ66 is supplied as pellets of uniform size in big-bags; other packaging on request.

Properties:

	Parameter	Unit	Standard	PLEXIGLAS® Optical POQ66
Mechanical Properties				
Tensile Modulus	1 mm/min	MPa	ISO 527	3200
Stress @ Break	5 mm/min	MPa	ISO 527	69
Strain @ Break	5 mm/min	%	ISO 527	4
Charpy Impact Strength	23°C	kJ/m²	ISO 179/1eU	20
Thermal Properties				
Vicat Softening Temperature	B / 50	°C	ISO 306	104
Glass Transition Temperature		°C	IEC 10006	108
Coeff. of Linear Therm. Expansion	0 - 50°C	E-5 /°K	ISO 11359	8
Fire Rating			DIN 4102	B2
Rheological Properties				
Melt Volume Rate, MVR	230°C / 3.8kg	cm³/10min	ISO 1133	2.9
Optical Properties	d=3 mm			
Luminous transmittance	D65	%	ISO 13468-2	92
Refractive Index			ISO 489	1.49
Other Properties				
Density		g/cm³	ISO 1183	1.19
Recommended Processing Conditions				
Predrying Temperature		°C		max. 94
Predrying Time in Desiccant-Type Drier		h		2 - 3
Melt Temperature		°C		220 - 260
Die Temperature (Extrusion)		°C		220 - 260

All listed technical data are typical values intended for your guidance. They are given without obligation and do not constitute a materials specification.

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Evonik. Power to create.

APPENDIX B

ZEMAX OPTICAL DESIGN SOFTWARE

This is a short introduction of ZEMAX-12 software which is used for optical simulations throughout this thesis. The text given here is a summary of ZEMAX-12 user manual.[51]

What does Zemax do?

Zemax is a software which can model, analyze, and assist in the design of optical systems. ZEMAX has capability to sequential and non-sequential ray tracing and predicts the behavior of optical systems.

The interface to Zemax has been designed to be easy to use, and with a little practice it can allow very rapid interactive design. Most Zemax features are accessed by selecting options from either dialog boxes or pull-down menus.

Sequential ray tracing

Sequential ray tracing means rays are traced from surface to surface in a predefined sequence. Zemax numbers surfaces sequentially, starting with zero for the object surface. The first surface after the object surface is 1, then 2, then 3, and so on, until the image surface is reached. Tracing rays sequentially means a ray will start at surface 0, then be traced to surface 1, then to surface 2, etc. No ray will trace from surface 5 to 3; even if the physical locations of these surfaces would make this the correct path. Each ray "hits" each surface once and only once in this predetermined sequence. The sequential model is simple, numerically fast, and extremely useful and complete for many important cases.

Non-sequential ray tracing

There are times when a non-sequential trace is required. Non-sequential means the rays trace in the actual physical order they hit various objects or surfaces, and not necessarily in the order the objects are listed in the software user interface. Note rays in a non-sequential trace may hit the same object repeatedly, and entirely miss other objects. Generally, the order in which objects are hit by rays depends upon the object geometry and the angle and position of the input ray. Objects which require or at least benefit from non-sequential ray tracing include prisms, light pipes, lens arrays, reflectors, and Fresnel lenses. Certain types of analysis, such as stray or scattered light effects, are only practical in a completely non-sequential environment. Traditionally, lens design programs that supported surfaces (rather than 3D objects) for sequential ray tracing would implement non-sequential ray tracing using the same surface model; the rays would simply intersect surfaces in a possibly out of sequence order. The disadvantage of using surfaces in a more general non-sequential approach is that surfaces do not adequately describe most optical components. For example, lenses not only have a front and back surface, they also have edges and perhaps flattened outer faces for mounting. Light may intercept, and then refract or reflect from these additional surfaces normally ignored by sequential surface ray tracing codes. Complex prisms, such as a dove or roof prism, contain many faces, and the rays may intersect these faces in a complex order depending upon the input angle and position of the ray. To support these types of components in a very general and accurate way requires the use of full 3D solid object models instead of just 2D surfaces. Zemax calls this type of ray tracing non-sequential components, or NSC, which is different from non-sequential surfaces or NSS. NSC ray tracing in Zemax supports all of the following features:

- Definition and placement of multiple sources, objects and detectors.
- Real radiometric and photometric units; including watts, lumens, lux, phot, footcandles, and others.
- Automatic determination of ray-object intersection order.
- Automatic detection of reflection, refraction, and total internal reflection (TIR).
- Support for a very wide range of 3D objects, including diffractive optics.
- Polarization ray tracing and arbitrary thin film coatings.
- Statistical models for scattering, including Lambertian, Gaussian, and ABg.
- Automatic ray splitting for efficient analysis.

Lens Data Editor

The Lens Data Editor is the primary spreadsheet where the majority of the lens data will be entered. This data includes the radius of curvature, thickness, and glass for each surface in the system. Single lenses are defined by two surfaces (a front and a back), and the object and image also each require one surface. This fundamental data can be entered directly on the spreadsheet. When the Lens Data Editor is displayed, data can be entered on the spreadsheet by typing in the required values at the highlighted bar.

Ray tracing

Generally, when a ray strikes a surface, part of the energy will be reflected, part will be transmitted, and depending upon the surface properties, part may be absorbed. Because accurate reflection and transmission computation requires polarization information, ray splitting is only allowed when performing polarization ray tracing.

Once a ray splits, each of the "child" rays will in general strike another object, and the rays may split again and again. After many ray-object intersections, the total number of rays can become extremely large, so controls must be placed on the ray tracing to ensure that the computation will eventually end.

Optimization

The Local Optimization (or simply, "Optimization") feature provided by Zemax is quite powerful, and is capable of improving lens designs given a reasonable starting point and a set of variable parameters. Variables can be curvatures, thicknesses, glasses, conics, parameter data, extra data, and any of the numeric multi-configuration data. Zemax uses either an actively damped least squares or an orthogonal descent algorithm. The algorithms are capable of optimizing a merit function composed of weighted target values; these target values are called "operands". Zemax has several different default merit functions and these merit functions can be changed easily using the Merit Function Editor.

Optimization requires three steps:

1) A reasonable system which can be traced,

2) Specification of the variables,

3) A merit function.

A reasonable system is a rather loose concept which means that poorly conceived designs are not likely to be transformed into exceptional designs by the optimization algorithm. You must specify all variables before using optimization algorithms.

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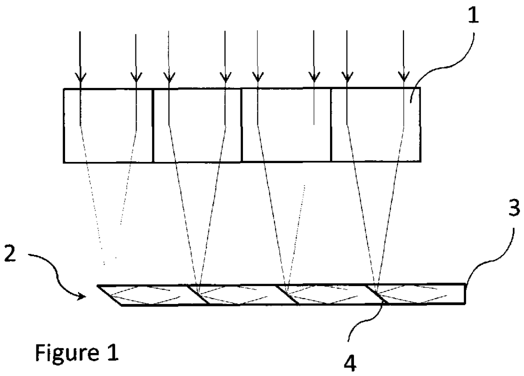


Figure 1

(57) **Abstract**: The present invention relates to a waveguide for solar collectors and a solar collector employing such a waveguide to be used for concentrated solar power generation. In scope of this invention, a waveguide having an array of directing surfaces is developed, such that the waveguide and the array of directing surfaces lie on a plane nonparallel to the direction of incident light. Moreover, a solar collector having an array of concentrator cells and a waveguide lying on a plane nonparallel to the direction of solar radiation from said array of concentrator cells is developed.

WO 2012/169980 A1

A WAVEGUIDE FOR CONCENTRATED SOLAR COLLECTORS AND A SOLAR COLLECTOR THEREOF

Field of the Invention

The present invention relates to a waveguide for solar energy collectors and a solar energy collector employing such a waveguide to be used for concentrated solar power generation.

Background of the Invention

Due to the scarce of energy resources and threat of climate change resulting from extensive use of carbon containing fuels, clean power generation means are being developed. Photovoltaic cells are among such means. Conventional photovoltaic power generators comprise a planar array of photovoltaic cells. Unfortunately, widespread use of conventional photovoltaic generators is hindered by their high production costs. Thus concentrated photovoltaic power generators, employing a reduced area of photovoltaic cells, are used. Incident solar radiation is concentrated through a solar collector comprising various concentration means and is directed to photovoltaic cells of an area smaller than the surface area of the concentrated solar power generator.

The document numbered US2011011441A1 discloses a concentrated solar power generator, which is seen to employ an array of lenses used to concentrate solar radiation. The concentrated solar radiation is then transferred to a photovoltaic surface by optical fibers, with each fiber connected to one lens of the array at one end and every fiber connected a distinct area of the photovoltaic cells on the other end. The invention disclosed in this document aims to construct a flexible solar collector. Since it does not have a rigid structure, such a collector is inefficient in terms of acceptance angles, thus making less use of the incident light.

Classical concentrating photovoltaic systems are using only big Fresnel lens arrays and other large lenses as an optical concentrator. Although using large lenses provide a high concentration, such lenses also have long focal lengths thus increasing collector thickness. If, instead, an array of a large number of small lenses is employed, then the complexity is increased. Further, systems incorporating only an array of lenses do not enable an efficient use of the photovoltaic cells; a lens generally produces a circular image of the sun on a photovoltaic cell which is generally rectangular. Non-imaging means are employed to effectively distribute light over the photovoltaic cells. In order to overcome such issues, collectors incorporating waveguides that collect, direct and concentrate the light from concentrating elements to photovoltaic cells have been proposed. Among these are, waveguides containing directing surfaces to direct the solar radiation emerging from an array of concentrators into the waveguide.

Generally, such waveguides have a stepped structure so that light acquired by one directing surface is not hindered by another while inside the waveguide. With respect to the direction of incoming light, the steps are constituted on top of each other thus increasing the overall thickness. Such waveguides can incorporate line focus optics, providing a low concentration. The concentration can further be increased by rotating a section of the waveguide structure around a line onto which the concentrated output of the waveguide will fall. This configuration is not very efficient considering its heat dissipation, weight of the material and ease of manufacture.

One such waveguide is described in the document numbered US7664350B2. The waveguide mentioned in this document contains directing surfaces each corresponding to a concentrator to direct the concentrated light into the waveguide. In order to avoid a directing surface from interrupting the light directed by another directing surface, the directing surfaces are to be placed in virtual slabs on top of each other with respect to the direction of light emerging from the concentrators. Due to this configuration and further to the planar distribution of the concentrators, the waveguide is a stepped structure with said steps consecutively arranged along the direction of light emerging from the concentrators, wherein each step acts as a directing surface corresponding to a concentrator. Such a configuration results in a waveguide with high thickness and weight.

Another solution is described in the document numbered WO2010056405A1. The collector described in this document employs a transmissive medium layer between the light collecting element and the waveguide. Many of similar series of layers can be sandwiched with different transmissive medium layers in between and it is revealed that the output of such series of layers can be combined using a secondary light concentrator. Such a solar collector has components with high thickness and weight values and is cumbersome for tracking applications.

In the two documents above, the incoming light is focused on a line or a curve by the primary concentrators providing a concentration only along a single dimension, i.e. a two dimensional light distribution is reduced to a one dimensional light distribution. Thus the collectors described above provide low concentrations.

Waveguides with high thickness and weight require the solar collector to have stronger frame members thus increasing costs. Also, for active solar power generator systems, tracking means are harder to operate. Moreover, such waveguides themselves are also produced for higher costs.

Objects and Brief Description of the Invention

The object of the present invention is to provide a waveguide that has a low thickness and weight compared to the solar collector it is associated with.

It is a further object of the invention to provide waveguide that provides an effective distribution of light over the photovoltaic cells.

A further object of the invention is to provide a waveguide providing further concentration of the light while moving through the waveguide.

Another object of the invention is to provide a solar collector having an increased acceptance angle.

Another object of the present invention is to provide a waveguide for a solar collector enabling dissipation of the heat generated due to the concentrated solar radiation.

It is also an object of the invention to provide a solar collector employing a waveguide according to the objects aforementioned.

In order to achieve the objects of this invention, a waveguide having an end surface (3) onto which the guided radiation is to be directed, and an array of directing surfaces on the borders of said waveguide is developed, such that the waveguide and the array of directing surfaces lie on a plane.

Moreover, a solar collector having an array of concentrator cells and a waveguide lying in a plane is also developed.

In an embodiment of the invention, in order to provide a waveguide providing further concentration of the light while moving through the waveguide, extra concentration surfaces are employed.

In another embodiment of the invention, a solar collector having an increased acceptance angle is provided by employing enlarged directing surfaces while the concentrator cell sizes are kept constant.

Description of the Drawings

The figures attached, depicting some aspects of the present invention, are as listed.

Figure 1 is a schematic side view of a solar collector according to the invention, partially depicting exemplary light paths.

Figure 2 is a top view of the waveguide of figure 1, partially depicting exemplary light paths.

Figure 3 depicts a waveguide according to invention.

Figures 4 to 10 depict various concentration cells that can be used with the present invention together with a waveguide according to the invention, partially depicting exemplary light paths.

Figures 11 and 12 depict possible concentrator cell arrays according to the present invention.

Figures 13 and 14 depict possible directing surfaces which act through reflection.

Figures 15 to 20 depict waveguides having extra concentration surfaces.

Figures 21 and 22 depict possible waveguides comprising more than one stepped structure.

Figures 23 to 27 depict solar collector configurations according to the present invention.

Figures 28 and 29 are side and top views respectively of a possible configuration of two waveguides.

The references seen in the figures listed above correspond to the following.

1. Concentrator cell
2. Waveguide
3. End surface
4. Directing surface

5. Extra concentration surface
    5a. Side cut
6a. Reflecting coating
6b. Reflecting piece

Detailed Description of the Invention

The solar collector according to the present invention, essentially comprises,

- a concentrator consisting of an array of concentrator cells (1), for concentrating the incident solar radiation;
- at least one waveguide (2), having at least one end surface (3), which is the output surface of the waveguide (2) and onto which light to electricity converters such as photovoltaic cells are to be attached;
- an array of directing surfaces (4) on the borders of said waveguide (2), such that each directing surface (4) corresponds to a concentrator cell (1) and directs the incident light i.e., the concentrated solar radiation, into the waveguide (2) with an angle providing total internal reflection (TIR);
- optionally, at least one extra concentration means at the end regions of the waveguide (2), to further concentrate the solar radiation

wherein, the waveguide (2) and the array of directing surfaces (4) lie on a plane nonparallel to the direction of incident light. The thickness of the waveguide (2) is constant along its length thus minimizing the weight and cost of the waveguide (2), excluding the extra concentration means at the end region. The waveguide (2) according to this invention is generally a rigid component. Figure 1 schematically depicts such a solar collector and figures 2 and 3 are top and perspective views of the waveguide (2) used in figure 1. Since the directing surfaces (4) are on borders of the waveguide (2), the optical paths emerging from a directing surface (4) are not interrupted by another directing surface (4).

Solar radiation incident to the solar collector is first concentrated through the array of concentrator cells (1), then to be directed into the waveguide (2) by the directing surfaces (4). Solar radiation is then transmitted to the photovoltaic cells attached onto the end surface (3) by TIR through the waveguide (2). For TIR to take place, the waveguide (2) has a refractive index greater than that of its surroundings.

The directing surfaces (4) can be planar or curved. The planar directing surfaces (4) or the planes tangential to the curved directing surfaces (4) are inclined with respect to the plane of the waveguide (2) such that there is an angle Θ, between the plane of the waveguide (2) and the directing surfaces (4) or said tangential planes, facing the surface of the waveguide (2) nearest the concentrator cells (1). In an embodiment of the invention, the angle Θ is obtuse and the directing surfaces (3) reflect the incoming radiation into the waveguide (2). Preferably, the angle Θ is 135°. In another embodiment, the angle Θ is acute and the directing surface refracts the incoming radiation into the waveguide (2).

The waveguide (2) according to the invention is a non-imaging component due to its structure. Therefore the output of the waveguide (2) is mostly homogeneous in illumination and wavelength distribution, increasing the efficiency of the light to electricity converters. Further, the output surface of the waveguide (2) is the end surface (3) being in a shape and size to match the light to electricity converters to be attached. A preferred end surface (3) shape is rectangular since photovoltaic cells are generally cut in rectangles from a wafer.

The array of concentrator cells (1) is arranged such that the focal point of each concentrator cell (1) lies on the vertices of a virtual grid, said grid being a parallelogramic grid lying on a plane. Thus the array of directing surfaces (4) is arranged such that the centroid of each directing surface (4) substantially coincides with the vertices of said grid. Since light is focused on an array of points, such an array of concentrator cells (1) provides a higher concentration than other concentrators that focus light on a line or a curve, i.e. a two dimensional light distribution is reduced substantially to a point. Further, such a high initial concentration allows flexibility in waveguide (2) design, enabling directing surfaces (4) that provide a higher tracking tolerance.

Generally, a single waveguide (2) comprises an array of directing surfaces (4) along a single line of the virtual grid, thus forming a stepped structure. Such a structure allows many waveguides (2) to be arranged in a regular pattern. A possible waveguide (2) according to the invention comprises an array of directing surfaces (4) arranged in groups having more than one stepped structure along more than one line of the virtual grid. Possible examples of such a waveguide are depicted in figures 21 and 22.

Concentrator cells (1) can be chosen among different optical units according to particular designs. Possible such units include various simple or compound lenses, Fresnel lenses, parabolic mirrors, compound parabolic concentrators, diffractive concentrators, Cassegrain devices, crossed cylinders etc. Some concentrator cells (1) are seen in figures 4 to 10.

For concentrator cells (1) of lens type, an array of lenses can either be kept above the waveguides (2) by some frame or the lens may extend along the optical path to the waveguide (2) thus being carried by said waveguide (2). Such an extended lens type concentrator cell is depicted in figure 9. When said extended lens type concentrator cells (1) are employed, in order to guarantee TIR inside the waveguide (2), either the lens material has a refractive index lower than that of the waveguide (2) or a layer of low refractive index than that of the waveguide (2) is applied between the collector cells (1) and the waveguides (2). The regions between the outer lens surfaces and the waveguide (2) not containing the optical paths do not contribute to solar power generation and thus can be left empty to reduce the weight of the solar collector as can be seen in figure 10. Moreover, this configuration provides collection of some of the diffuse radiation and increase tracking tolerances. The array of concentration cells (1) can be of various polygonal patterns such as rectangular, squared, hexagonal etc. with a squared and a hexagonal example depicted in figures 11 and 12. Various other examples can be seen in figures 23 to 27. The concentrator cells (1) in figure 27 form a squared pattern in which the projection of the focal points onto the surface does not coincide with the centroids.

If a directing surface (4) acting through reflection is coated from outside with a reflecting coating (6a) as depicted in figure 13, than the angle Θ of the directing surface (4) can be freely adjusted while providing the conditions of TIR inside the waveguide (2). For incident light perpendicular to the plane of the waveguide (2) and circularly symmetric concentrator cells (2), the highest concentration provided by the waveguide (2) is obtained when the angle Θ is chosen to be 135°. On the other hand, when the angle Θ is chosen to be larger than 135° higher acceptance angles can be achieved. However, TIR from the directing surface (4) for most incoming light is obtained when the angle Θ is chosen to be smaller than 135°, for example 125° for a waveguide of a material with a refractive index of 1,5. With a reflecting coating (6a) on the directing surface (4), reflection from the directing surface (4) occurs at wide range of angles, thus allowing an optimization of concentration and acceptance angle according to a particular application. Alternatively, a highly reflective reflecting piece (6b) can be attached on the outside of each of said directing surfaces (4) preferably with an air gap in between as seen in figure 14. The air gap will provide the opportunity of TIR at the directing surface (3) for some of the light rays while the rays that cannot satisfy the TIR condition at the directing surface will be reflected from the reflective piece (6b) attached.

In an embodiment of the invention, in order to obtain further concentration of solar radiation in the waveguide, the waveguides (2) further comprise at least one extra concentration surface (5). An extra concentration surface (5) is formed on portions of a waveguide (2) ending at the end surface (3). Said portion of the waveguide (2) is in the shape of a known non-imaging optical concentrator with an input aperture width and height equal to the maximum width and thickness of the waveguide (2) and the output aperture is the end surface (3) having a width and/or thickness smaller than said input aperture. Figure 15 is a side view of a possible waveguide having an extra concentration surface (5). One possible way to obtain such an extra concentration surface (5) is to produce a waveguide (2) in a shape with some portions from at least one edge removed, leaving behind said extra concentration surface (5). A specific example of such an extra concentration surface (5) is a side cut (5a) formed by extracting a region on a side. Other possible waveguides (2) having extra concentration surfaces (5) are depicted in figures 16 to 21; these figures depict top views of waveguides (2). Among these possible waveguides (2), the one depicted in figure 16, 17 and 18 comprise a side cut (5a) formed by extracting a region on a side such that said surface (5) is formed of a curve, a straight line and two curves respectively. Generally, said surface (5a) may be formed of at least one region comprising at least one curve or straight line or a combination of several curves and lines. In figures 19 and 20, the regions of the waveguide (2) near the end surface (3) comprise two extra concentration surfaces (5) with one on each side. Figure 21 depicts a waveguide (2) comprising more than one stepped structure having side cuts (5a) on each stepped structure.

Figure 23 is a top view of a portion of a solar collector according to the invention with an array of square lens concentrators (1) arranged on a planar square grid. Another solar collector according to the invention is with an array of hexagonal lens concentrators (1) is seen from the top in figure 24.

In another embodiment of the invention, at least two waveguides (2) are placed on top of each other with the directing surfaces (4) not blocking the light directed to each other from the concentrator cells (1). The array of concentrator cells (1) to be employed with this embodiment can be composed of groups of concentrator cells (1) each equidistant from the corresponding directing surfaces (4) and thus the corresponding waveguides (2) or of groups of concentrator cells (1) each with different focal lengths according to the corresponding directing surfaces (4) and thus the corresponding waveguides (2).

Since the waveguide (2) developed with the present invention has a planar structure, all regions of the waveguide (2) are in the proximity of a heat conducting planar sheet placed below the waveguide (2) and thus the waveguide (2) provides a very low thermal resistance easily dissipating the heat released during operation. The cooling of the waveguide can be performed either by passive or active cooling systems. In systems employing water or oil as a heat carrying medium, the excess heat can be transferred to be used in another application.

The waveguide (2) according to the invention can be produced by molding, cutting or other means leaving a smooth surface and from optically transparent materials. Preferably, materials are chosen to produce a rigid waveguide (2).

Various embodiments and applications employing the principles of the present invention can be implemented. Therefore the scope of the invention is not limited to the examples above but determined by the following claims.

CLAIMS

1. A solar collector comprising
   - a concentrator consisting of an array of concentrator cells (1), for concentrating the incident solar radiation;
   - at least one waveguide (2) having at least one end surface (3) , which is the output surface of the waveguide (2) and onto which light to electricity converters are to be attached;
   - an array of directing surfaces (4) on the borders of said waveguide (2), such that each directing surface (4) corresponds to a concentrator cell (1) and directs the incident light i.e., the concentrated solar radiation into the waveguide (2) with an angle providing total internal reflection;
   - optionally, at least one extra concentration means at the end regions of the waveguide (2), to further concentrate the solar radiation

   characterized in that; the waveguide (2) and the array of directing surfaces (4) lie on a plane nonparallel to the direction of incident light and the thickness of the waveguide (2) is constant along its length excluding the extra concentration means at the end region.

2. A solar collector according to claim 1, characterized in that; the array of concentrator cells (1) is arranged such that the focal point of each concentrator cell (1) lies on the vertices of a virtual grid, said grid being a parallelogramic grid lying on a plane and the array of directing surfaces (4) is arranged such that the centroid of each directing surface (4) substantially coincides with the vertices of said virtual grid.

3. A solar collector according to claim 1 or 2, wherein; the end surfaces (3) are in a shape and size to match the light to electricity converters to be attached.

4. A solar collector according to any of the preceding claims, wherein; the concentrator cells (1) are simple lenses, compound lenses, Fresnel lenses, parabolic mirrors, compound parabolic concentrators, diffractive concentrators, Cassegrain devices or crossed cylinders.

5. A solar collector according to any of the preceding claims, wherein; the directing surfaces (4) are planar.

6. A solar collector according to claim 5, wherein; the angle between the plane of the waveguide (2) and the directing surfaces (4), facing the surface of the waveguide (2) nearest the concentrator cells (1) is acute.

7. A solar collector according to claim 5, wherein; the angle between the plane of the waveguide (2) and the directing surfaces (4), facing the surface of the waveguide (2) nearest the concentrator cells (1) is obtuse.

8. A solar collector according to any of claims 1 to 4, wherein; the directing surfaces (4) are curved.

9. A solar collector according to claim 8, wherein; the angle between the plane of the waveguide (2) and the planes tangential to the curved directing surfaces (4), facing the surface of the waveguide (2) nearest the concentrator cells (1) is acute.

10. A solar collector according to claim 8, wherein; the angle between the plane of the waveguide (2) and the planes tangential to the curved directing surfaces (4), facing the surface of the waveguide (2) nearest the concentrator cells (1) is obtuse.

11. A solar collector according to claim 7 or 10, wherein; the directing surfaces (4) are coated with a reflecting coating (6a).

12. A solar collector according to claim 7 or 10, wherein; a reflecting piece (6b) is attached on the outside of each directing surface (4).

13. A solar collector according to claim 12, wherein; there is an air gap between each highly reflective piece (6b) and the relevant directing surface (4).

14. A solar collector according to any of the preceding claims, wherein; the waveguides (2) further comprise at least one extra concentration surface (5).

15. A solar collector according to claim 14, wherein; an extra concentration surface (5) is formed on portions of a waveguide (2) ending at the end surface (3) and is in the shape of a non-imaging optical concentrator.

16. A solar collector according to claim 15, wherein; the waveguides (2) are produced in a shape with portions from at least one edge removed, leaving behind said extra concentration surface (5).

17. A solar collector according to claim 16, wherein; said extra concentration surface (5) is a side cut (5a) formed by extracting a region on a side, comprising at least one curve or straight line or a combination of both.

18. A waveguide (2) comprising,
    - at least one end surface (3), and
    - an array of directing surfaces (4) on the borders of said waveguide (2) directing the incident light into the waveguide (2) with an angle providing total internal reflection,
    - optionally, at least one extra concentration means at the end regions of the waveguide (2), to further concentrate the solar radiation

    characterized in that; the waveguide (2) and the array of directing surfaces (4) lie on a plane nonparallel to the direction of incident light and the thickness of the waveguide (2) is constant along its length excluding the extra concentration means at the end region.
19. A waveguide to claim 18, wherein; the waveguides (2) further comprise at least one extra concentration surface (5).
20. A waveguide to claim 19, wherein; an extra concentration surface (5) is formed on portions of a waveguide (2) ending at the end surface (3) and is in the shape of a non-imaging optical concentrator.
21. A waveguide according to claim 20, produced in a shape with portions from at least one edge removed, leaving behind said extra concentration surface (5).
22. A waveguide according to claim 20, wherein; said extra concentration surface (5) is a side cut (5a) formed by extracting a region on a side, comprising at least one curve or straight line or a combination of both.

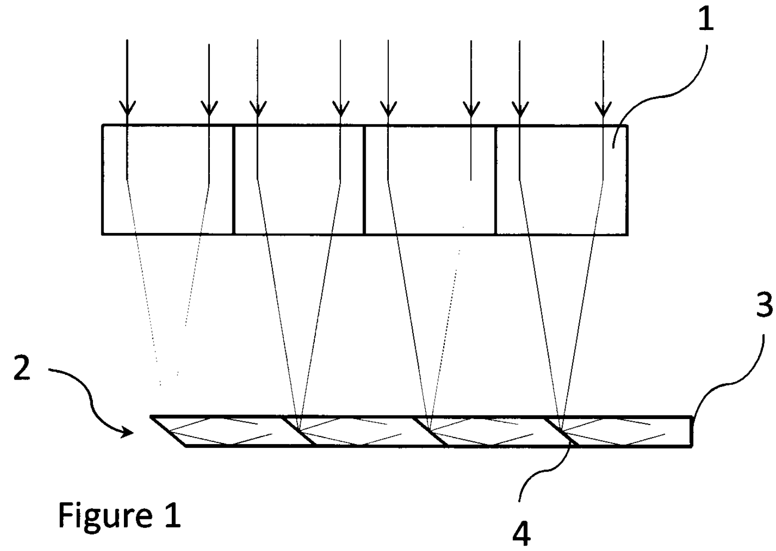


Figure 1

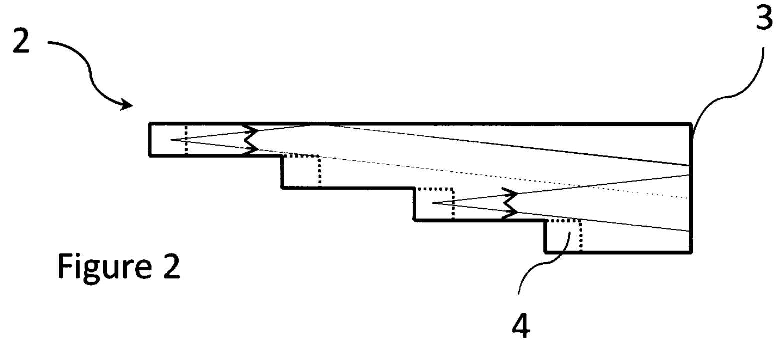


Figure 2

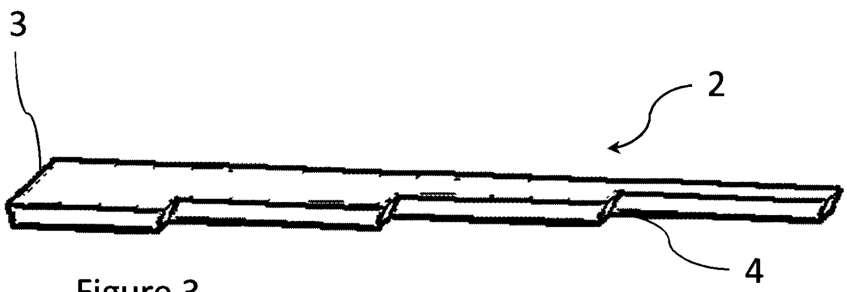


Figure 3

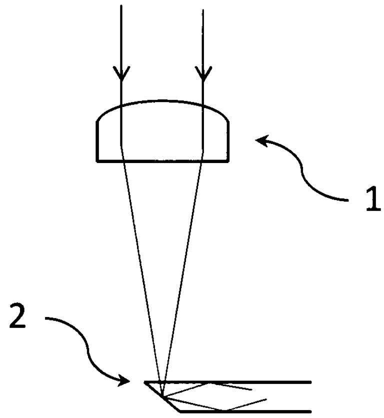
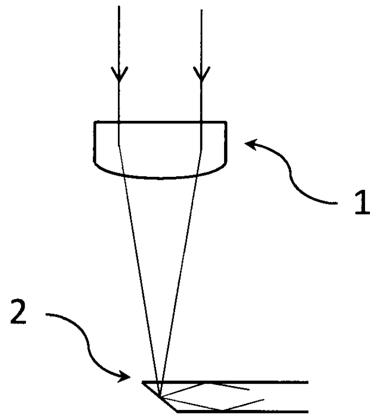


Figure 4



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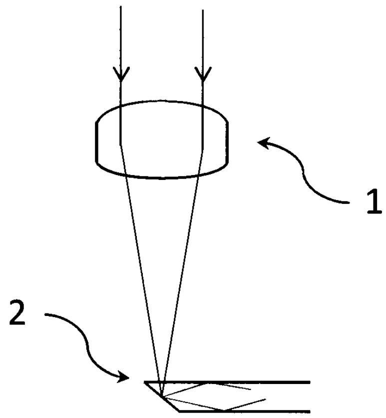

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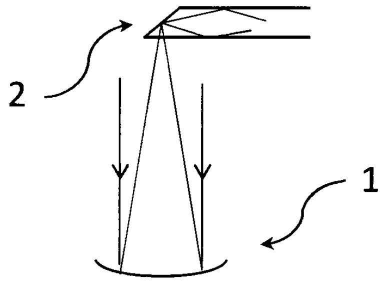

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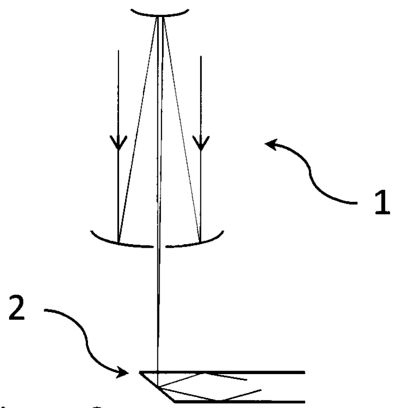

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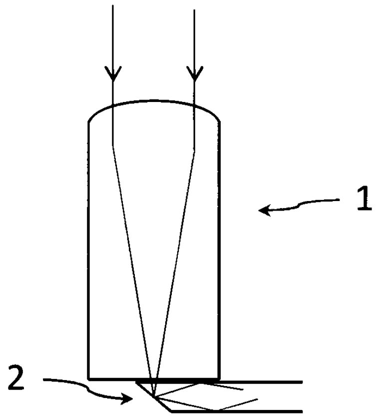

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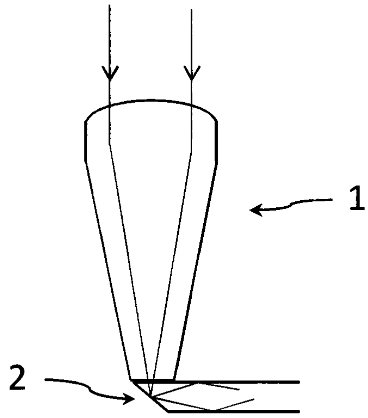

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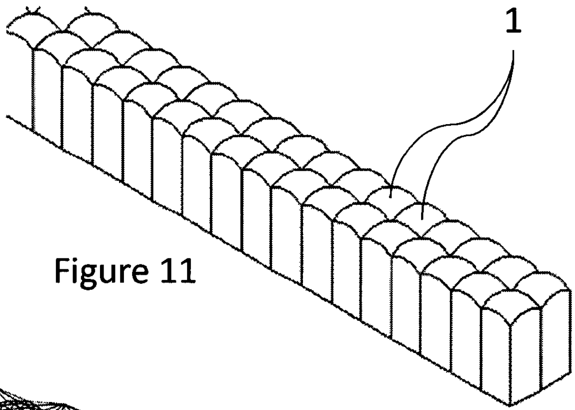

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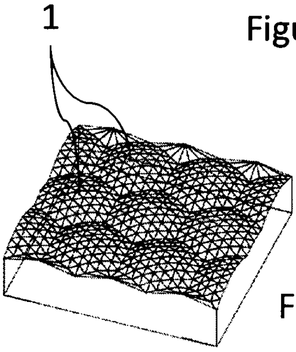

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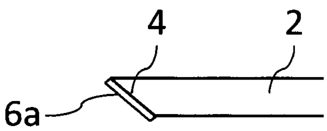

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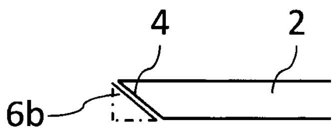

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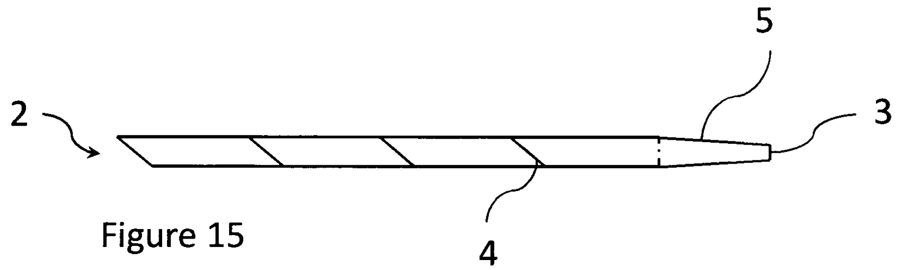

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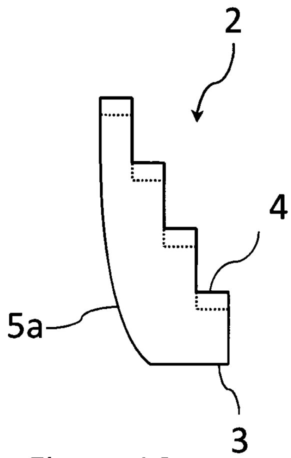

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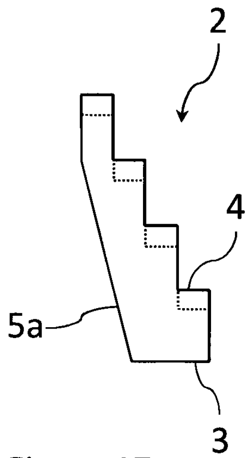

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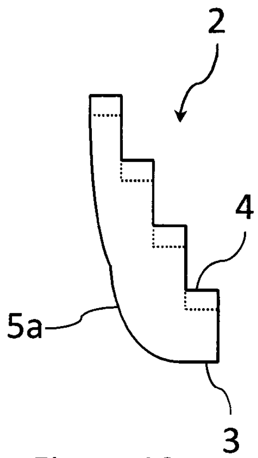

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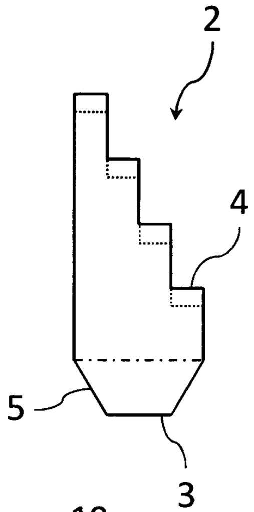

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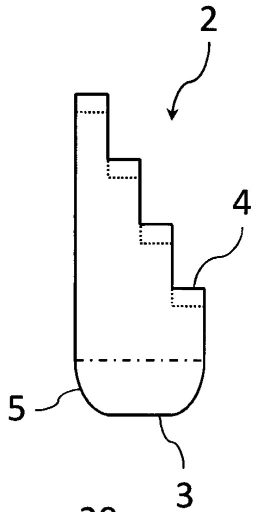

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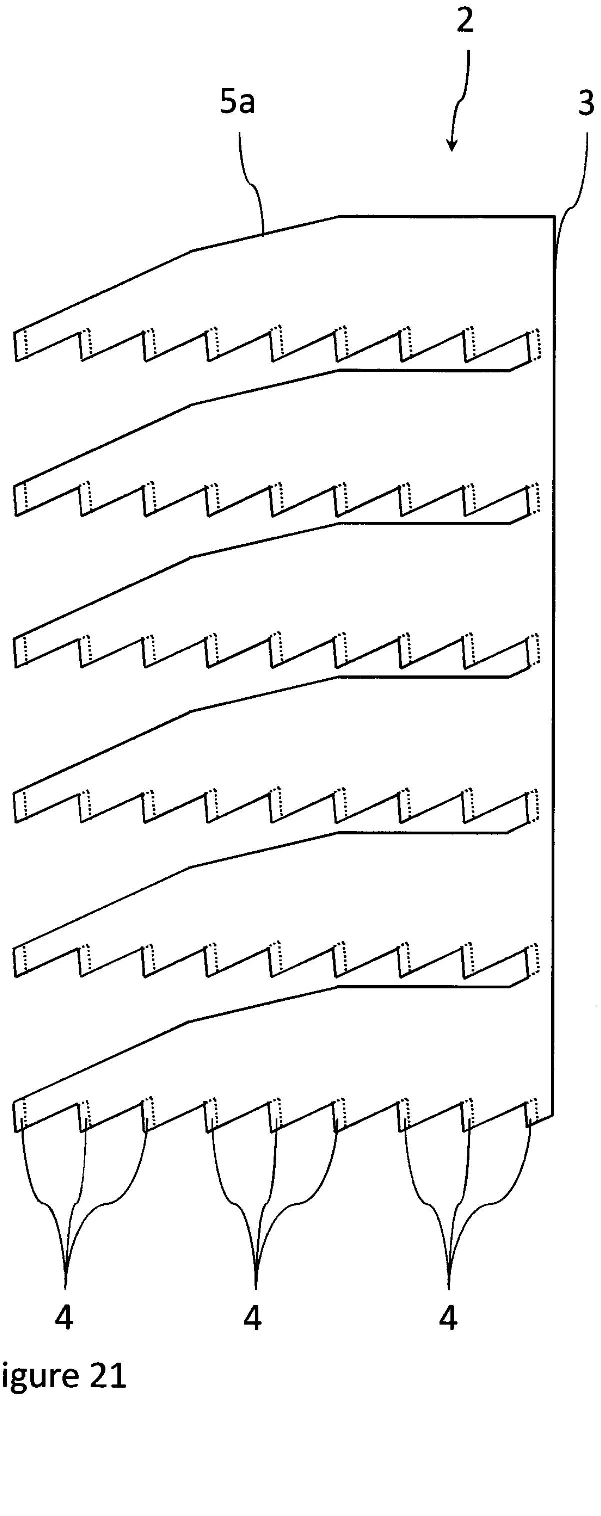

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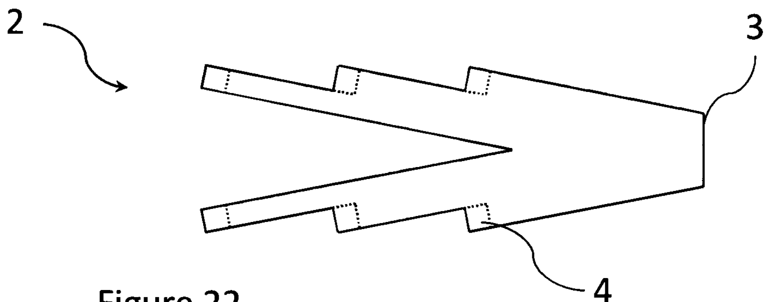

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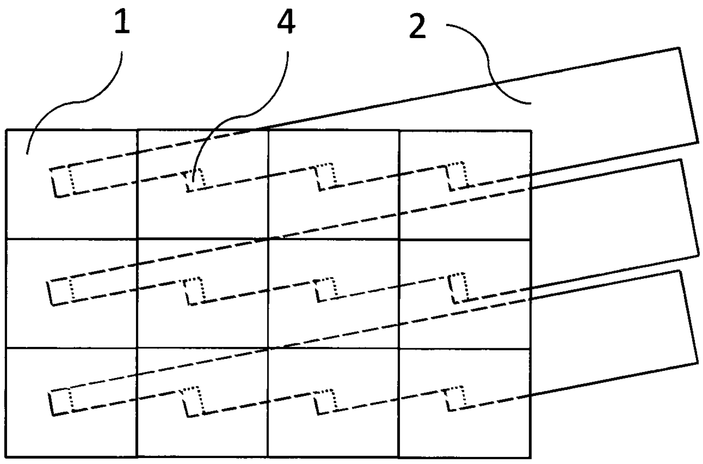

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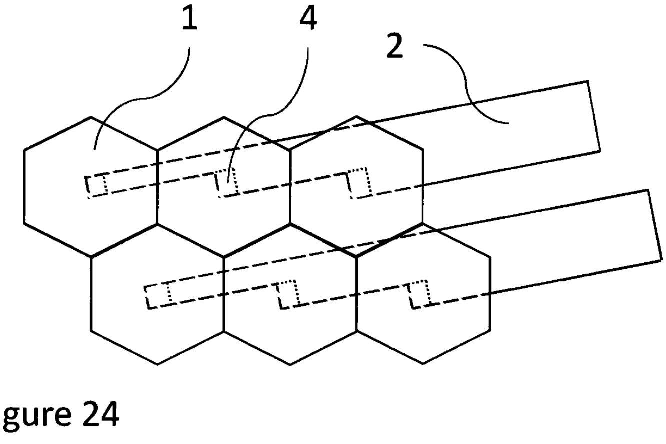

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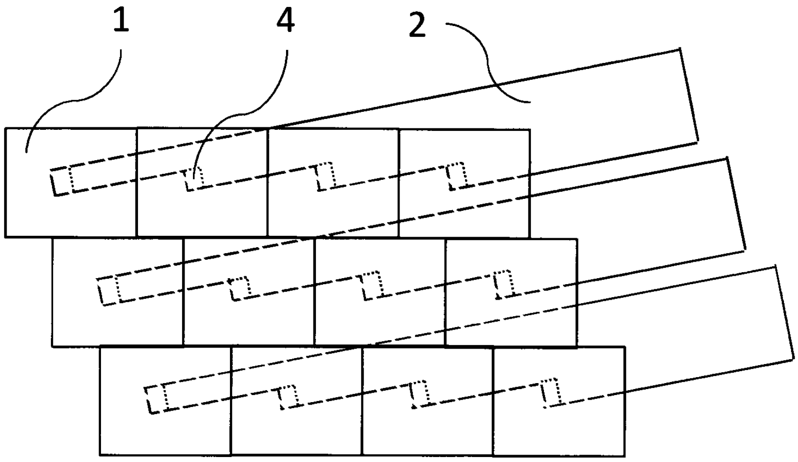

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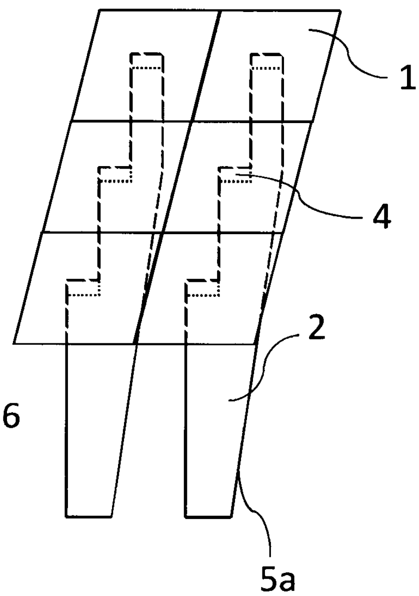

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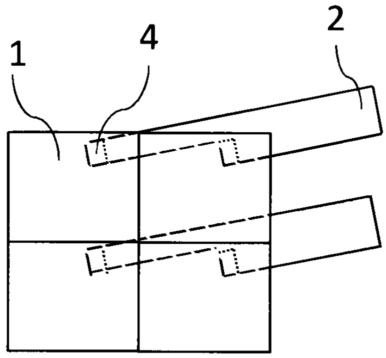

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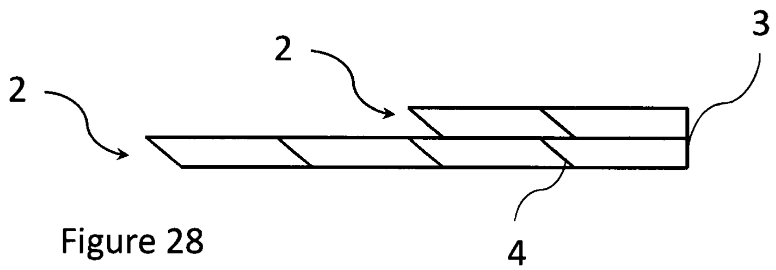

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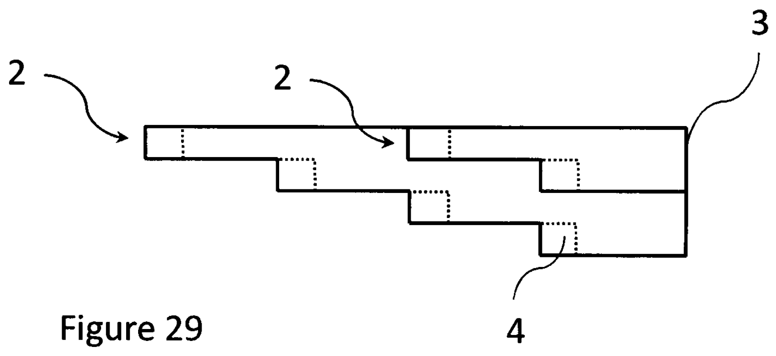

Figure 29