

# MASTER'S THESIS

# Daylighting by Optical Fiber

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# Preface

With the work presented in this report we want to cast some light on fiber optic daylighting. Indeed it is for most of us an unknown lighting technology. At least it was for us before we started this study. Hopefully this report will give the reader some knowledge about existing fiber optic daylighting systems, prerequisites for the technology and also some ideas on how new systems of this kind could be designed.

We would like to thank our supervisor and examiner, Professor Bo Nordell, for valuable ideas and support, to mention just a few things.

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# Abstract

Even on a grey day with an overcast sky there is normally an excess of light outdoors in comparison with what is required at most work places indoors. This excess of light can be harvested, concentrated and distributed indoors by fiber optics to replace most of the electrical lighting that is used today.

A system suggested in this report, 1-axial turning troughs, is predicted to have an efficiency of between 33 and 16 % in utilising the collected light. It tracks the sun merely for its altitude and not in the east-west direction. In doing so it could have an operation period of five hours each day with its peak efficiency at noon, if the system is south oriented.

This system is dependent on unblocked sunlight and would have to be combined with an alternative light source to provide continuous lighting. Provided clear weather a collector area of less than 5 m<sup>2</sup> is predicted to be sufficient for an office of 100 m<sup>2</sup> located in Copenhagen. With this location the system could deliver at least 500 lux of illumination five hours a day between the vernal and autumnal equinoxes, when the sun is visible. This level of illumination meets the recommendations for several situations.

The system would also include the possibility to produce hot water by utilising the infrared portion of the sunrays.

At least three fiber optic daylighting systems exist already. It is the Japanese Himawari, the German SOLUX and the American Hybrid Lighting. They are all 2-axial tracking systems that depend on sunlight. The first two utilise Fresnel lenses to concentrate the light and the third uses a reflecting parabola.

There also exist a wide variety of other daylighting systems that are more or less actively light collecting and that utilises either sunlight or diffuse light from the sky.

There are several benefits of using daylight for lighting purposes, energy savings being one of them. Not only is electric lighting replaced, but also unwanted heating produced by this lighting is reduced. Correctly designed a daylighting system can both filter away unwanted heat in the light and supply heat to the building depending on the season.

Other benefits of daylighting include health advantages and psychological benefits that have been shown in studies. Some concrete examples are less absenteeism at work places and better performance by students in daylighted schools.

To design a fiber optic daylighting system several aspects have to be considered. The collected light has to be concentrated to pass through the aperture made up by the fiber end. The fiber will only accept and transmit light within its acceptance angle, which can range from less than 20° and up to over 80°. This makes it desirable to utilise a high power light source supplying light with uniform direction. The sun is such a light source, the sunrays incident on the earth are close to parallel. However, the availability of sunlight is unpredictable in most climates; the sun can disappear behind clouds for a second or for days.

These conditions should be the main consideration for the designer of fiber optic daylighting systems. It should also be kept in mind that all optical elements in the system will cause light losses. This includes the optical fiber that will cause a loss ranging from more than 15 % and down to 5 % per metre, depending on the material.



# Sammanfattning

Även en grå och mulen dag finns det ett överskott av ljus utomhus, jämfört med behovet för de flesta arbetsplatser inomhus. Detta ljusöverskott är möjligt utvinna, koncentrera och leda inomhus med fiberoptik, som en ersättning för merparten av den elektriska belysning som används idag.

Ett system som föreslås i denna rapport, 1-axligt roterande rännor, beräknas ha en effektivitet mellan 33 och 16 % för det insamlade ljuset. Systemet följer endast solhöjden och inte solens rörelse från öst till väst. Genom detta får det en användningsperiod på fem timmar dagligen, med högst effektivitet mitt på dagen för en sydorierad installation.

Systemet är beroende av direkt solljus och måste därför användas i kombination med en alternativ ljuskälla för att kunna leverera konstant belysning. Förutsatt klart väder beräknas en ljusfångarearea på mindre än 5 m<sup>2</sup> vara tillräcklig för att förse en kontorsyta på 100 m<sup>2</sup> i Köpenhamn med ljus. Med dessa förutsättningar skulle systemet kunna leverera en belysningsstyrka på minst 500 lux, fem timmar om dagen mellan vår- och höstdagjämning, när solen är synlig. Denna belysningsstyrka uppfyller rekommendationerna för ett flertal situationer.

Det är också möjligt att producera varmvatten med systemet genom att utnyttja den infraröda delen av solens strålar.

Det finns åtminstone tre fiberoptiska dagsljussystem redan idag. De är det japanska Himawari, tyska SOLUX och amerikanska Hybrid Lighting. Dessa är 2-axligt solföljande system, beroende av direkt solljus. De två första använder fresnellinser för att koncentrera ljuset och det sistnämnda använder en reflekterande parabol.

Det finns också ett brett spektrum av andra dagsljussystem som är i olika grad aktiva och som utnyttjar antingen solljus eller diffust ljus från himlen.

Det finns flera fördelar med att använda dagsljus för belysningsändamål, en av dem är energibesparingar. Det är inte bara elektrisk belysning som ersätts, utan även oönskad uppvärmning från denna minskas. Ett väl konstruerat dagsljussystem kan både avskilja oönskad värme i ljuset och förse byggnaden med värme beroende på säsong.

Enligt ett flertal undersökningar ger dagsljusbelysning också fördelar psykologiskt och för hälsan. Några konkreta exempel är mindre frånvaro på arbetsplatser och bättre prestationer för elever i dagsljusbelysta skolor.

För att konstruera ett fiberoptiskt dagsljussystem måste flera aspekter tas i hänsyn. Det insamlade ljuset måste koncentreras för att kunna passera bländaröppningen som fiberändan utgör. Fibern accepterar och leder endast ljus som faller in inom dess acceptansvinkel, som kan variera beroende på material från mindre än 20° upp till över 80°. Att ljuset måste koncentreras gör det önskvärt att använda en kraftig ljuskälla som ger ett riktat ljus; solen. Men tillgängligheten för den här ljuskällan är oförutsägbar i de flesta klimat, den kan försvinna för en sekund eller flera dagar bakom moln.

Dessa förutsättningar bör ges störst hänsyn av konstruktören av fiberoptiska dagsljussystem. Det bör också hållas i minnet att alla optiska element ger ljusförluster. Detta innefattar också den optiska fibern som ger förluster mellan mer än 15 och ner till 5 % per meter, beroende på material.



# Zusammenfassung

Im Vergleich mit den empfohlenen Beleuchtungsstärken in Büros ist selbst an einem grauen bewölkten Tag draußen in der Natur ein Lichtüberschuss vorhanden. Dieser Lichtüberschuss kann gesammelt, konzentriert und über Faseroptik in Räume transportiert und dort verteilt werden. Dieses Licht kann einen Großteil des heutzutage benutzen elektrischen Lichtes ersetzen.

Ein vorgeschlagenes System, ist in diesem Report ein ein-axial linear parabolisches System. Die geschätzte Leistung liegt etwa zwischen 16 und 33 Prozent Ausnutzung des gesammelten Lichts. Das System folgt der Sonne lediglich in der Höhe und nicht in Ost-West Richtung. Dadurch hat es eine Betriebszeit von täglich fünf Stunden die maximale Leistung erreicht es um 12 Uhr Mittags, wenn die Kollektoren in südlicher Richtung ausgerichtet sind. Dieses System hängt davon ab, dass das Sonnenlicht ungehindert einstrahlen kann und muss mit einer alternativen Lichtquelle versehen werden, um eine konstante Beleuchtung zu ermöglichen. In Kopenhagen ist unter der Voraussetzung von gutem Wetter, eine Kollektorfläche von fünf Quadratmetern erforderlich, um ein Büro von 100 Quadrat Metern zu beleuchten. In der Betriebszeit kann das System im Zeitraum von Frühjahrsanfang bis Herbstanfang, unter diesen Bedingungen mindestens eine Beleuchtungsstärke von 500 lux bringen.

Vorrausgesetzt das die Sonne sichtbar ist und nicht hinter Wolken verdeckt ist. Diese Beleuchtungsstärken erfordern unterschiedliche Lösungen für die einzelnen Situationen. Das System kann auch erweitert werden, um auch Beispielsweise heißes Wasser zu produzieren, in dem man die Infrarotstrahlung der Sonne ausnutzt.

Mindestens drei Systeme dieser Art existieren bereits. Zum einen das japanische Himawari, das deutsche SOLUX und das amerikanische Hybrid Lighting System. Diese Systeme basieren auf einem sonnenabhängigen zweiaxialem Tracking-System. Zwei von diesen Systemen benutzen Fresnellinsen und eines einen Parabolspiegel, um das Licht zu konzentrieren.

Des Weiteren existiert eine ganze Bandbreite von anderen Tageslichtsystemen, die mehr oder minder aktive Systeme sind und sowohl das Sonnenlicht als auch das diffuse Licht ausnützen.

Es gibt verschiedene Vorteile, Tageslicht für Beleuchtung anzuwenden. Bedeutend ist in diesem Zusammenhang die Energieeinsparung durch das Ersetzen des elektrischen Lichtes. Zusätzlich wird die Wärmeproduktion durch herkömmliche elektrische Beleuchtung reduziert. Mit Hilfe von gut durchdachten Tageslichtsystemen kann zum einem die ungewünschte Wärme aus dem Licht herausgefiltert werden und diese saisonbedingt dem Gebäude anderweitig zugeführt werden.

Ein weiterer Vorteil von Tageslicht sind gesundheitliche und psychologische Aspekte wie Studien zeigten. Konkrete Beispiele sind der Rückgang an Krankmeldungen am Arbeitsplatz und bessere Leistungen von Schülern an tageslichtbeleuchteten Schulen.

Um ein Tageslichtsystem mit Faseroptik zu planen sind einige Aspekte zu beachten. Das gesammelte Licht muss gebündelt werden, um es in die Öffnung der Faseroptikenden einzuspeisen. Das Licht kann nur in einen gewissen Winkel in die Faseroptik eingeleitet werden. Weiterhin wird eine starke Lichtquelle benötigt, welche

paralleles Licht spendet, wie die Sonne. Allerdings ist die Verfügbarkeit der Sonne nicht sehr beständig. Wolken können sie für Sekunden aber auch Tage verdecken.

Diese Umstände müssen beachtet werden, wenn man ein Tageslichtsystem entwickelt. Es sollte des Weiteren bedacht werden, dass alle optischen Elemente Lichtverluste mit sich bringen. Das betrifft auch die Faseroptik die einen Lichtverlust von 5 Prozent bis über 15 Prozent pro Meter in Abhängigkeit des Materials beinhalten kann.

# Contents

Preface .....	i
Abstract.....	iii
Sammanfattning .....	v
Zusammenfassung .....	vii
Contents .....	ix
Introduction.....	11
Background .....	11
Objectives.....	11
Method.....	12
Why daylighting?.....	15
What is light? .....	15
History of lighting.....	15
Energy saving .....	16
Value of daylight .....	17
Benefits of central lightning .....	19
Overview of existing and planned systems for daylighting .....	21
Active systems with optical fibers .....	21
Himawari.....	21
Hybrid lighting .....	22
SOLUX.....	25
Central lighting systems .....	27
Active systems with heliostats .....	28
Mosque, Kuala Lumpur.....	28
Underground train station, Berlin.....	29
Heliobus, Switzerland .....	30
ARTHELIO, Semperlux and the Berlin University of Technology (BUT).....	31
Passive systems .....	32
Windows.....	32
Toplighting .....	34
Key concepts for daylighting.....	37
Light.....	37
Rayleigh scattering.....	37
Refraction and reflection.....	37
Collecting the light.....	38
Concentration of the light .....	38
Transmission of the light .....	38
Use of light.....	39
Distribution.....	39
Mixing daylight with artificial light sources .....	40
Conditions for daylighting.....	43
Availability of sunshine .....	43
Amount of light gained out of sunlight and daylight.....	44
Luminous efficacy.....	44
Received solar radiation .....	45

Key concepts for fiber optic daylighting systems .....	47
Transmission via optical fiber.....	47
Construction .....	47
Composition .....	47
Fiber factors.....	48
Light losses in a fiber .....	48
Problem with using optical fiber for daylighting systems .....	51
Light collector .....	51
Concentration .....	52
Lenses (converging lenses) .....	54
Fresnel Lenses .....	55
Reflecting surfaces .....	55
Separation.....	57
Controlling and mixing .....	59
Light distribution.....	60
Cooling .....	60
Some suggestions for new designs of fiber optic daylighting systems .....	61
A few ideas .....	61
Array of 2-axis turning troughs.....	61
Array of fixed south facing 1-axis turning troughs.....	64
Central receiver with heliostat array .....	69
Array of small parabolas .....	74
Discussion.....	75
The central ideas for daylighting with fiber optics .....	75
The varying weather decides the daylighting design.....	75
Lighting control and illumination thermostats.....	76
Alternative light sources .....	76
Future work.....	77
References.....	79
Appendix A: Lighting dimensions and units.....	87
Appendix B: Calculation of clear sky solar beam radiation.....	89
Appendix C: Rough calculation of blocking losses for a Fresnel mirror.....	93
Appendix D: Lighting performance for 1-axis turning troughs .....	99

# Introduction

## Background

The use of electric lighting in our homes and at our workplaces stands for a significant portion of the society's electric energy consumption. At the same time as the electricity is flowing through our lamps inside our houses, an overflow of light is flowing down from the sky and hits the exterior of the same houses. At almost any day the daylight is superior in both illumination level and quality compared to the artificial light we are using for our everyday tasks. So why not utilise the daylight instead?

In fact we are doing that. Daylight and sunlight is let in to our buildings through windows designed both for view and for lighting purposes. Until electrical lighting became efficient and cheap enough in the mid 20<sup>th</sup> century the major changes in architecture aimed at letting more light in. This was the objective of the Roman and the Gothic groin vault as well as the 19<sup>th</sup> century Crystal Palace [Lechner, 1987].

In order to fully replace electrical lighting with daylight during daytime one must take one step further than windows and other architectural solutions. The question is how to get the light into the buildings, when windows and skylights cannot do the job. There are some existing technical systems with e.g. sun tracking mirrors – heliostats – and “light tunnels” to distribute the light. The most valiant daylighting system ever suggested should be Znamya – a Russian attempt to light up the night with satellite based solar reflectors. Russian scientists hoped that this would be a relatively cheap way of illuminating Arctic cities in the permanent night of winter. In 1993 and 1999 practical experiments were carried out with Russian satellites reflecting sunlight onto the earth [Whitehouse, 1999]. This was of course a grand project, but on a more down to earth level, a really leap forward for daylighting would be if light could be piped and distributed in something similar to electric wires.

The flexibility of wires conducting daylight is achievable if the light can be put into optical fibers. Their best-known use today is for communication, but fibers can also be used for electrical illumination, harnessing solar power [Liang, 1998] and distributing sunlight for illumination purposes. If optical fibers would come out as a viable option for daylighting systems, they could provide almost the same flexibility and opportunities for lighting solutions as electrical lighting. Already today some systems with fibers that pipe sunlight exist. The shape of their luminaires is varying, but some concepts are similar to ordinary luminaires for electrical lighting.

The major design challenge for fiber optical daylighting is at the other end of the fiber. How can sun- or daylight be harvested and put into the fibers in the most efficient way? It is a matter of designing a light collector system that is efficient, reliable and cost effective, and which fits into the architecture of buildings.

This paper mainly considers the light collector issue, but it is also an overview of possibilities and problems with the fiber optic daylighting concept.

## Objectives

The main goal for this master's thesis project was to:

Design a central lighting system based on fiber optics with daylight as main light source. The system should include the possibility to be operated 24 hours a day. Viable

applications for this kind of system should be suggested. If possible a demonstration model should be built.

This goal was set before the authors discovered that several systems or concepts of this kind already existed. Then, it was a natural step to alter the aim of the project and include an overview of work that already had been done in the area. The scope was later decided to include:

#### *Design*

Design a central lightning system with fiber optics as the medium to transfer the light. Other mediums could be considered and mentioned.

The main light source should be daylight. Other light sources will also be investigated in order to use in combination with daylight and as an auxiliary light source.

Functional solutions should be developed for all essential parts of the system. The focus was on finding operational and reasonably viable design solutions for each part of the system rather than optimising different parts.

#### *Economy*

A cost comparison between conventional systems and suggested systems should be made. This includes a survey of costs for different parts, maintenance and life expectancy.

#### *Niches*

Feasible niches for daylight central lightning and similar systems should be investigated and presented.

#### *Existing systems*

A survey of existing central lightning systems and systems using daylight should be made both to present as a comparison and to use as a base when developing design solutions.

#### *Advantages and environmental effects*

Economical and other consequences of suggested systems should be investigated.

### **Method**

A lot of time was spent on free thinking about the subject and searching of literature regarding the subject in a wide perspective.

During the first time of brainstorming and development of design concepts several different ideas were suggested, considered and most of them were also scrapped or put aside. For example a lot of effort was put into passive solar collectors. This concept, which would be an attractive solution, was later skipped since it seemed too difficult to develop such a solution for a fiber optic system.

Some ideas survived this phase and those have been developed to the design concepts, which are presented in this report.

The literature study included both specific information about already existing systems and also more generic information about light, lighting, daylighting and materials, parts and technologies that could be useful in a fiber optic daylighting system. The literature also gave limited cost information regarding some materials and parts that might be included in a system.

Some calculations of efficiency and performance have been carried out for the design concepts suggested at the end of the report. These are merely rough estimates intended to give an idea of how much light a system could deliver, how large the collectors would have to be, etcetera.

Some time were also spent on rough calculations of available sunlight in Northern Europe.



# Why daylighting?

## What is light?

Light is purely a human sensation in similar fashion to sound, taste, smell and warmth. Something is necessary to stimulate the senses, and in this case it is electromagnetic radiation falling on the retina of the eye. Light can therefore be considered as a combination of radiation and our response to it.

The brightness of light as we humans experience it depends on the surrounding. If the eye is kept in a low light situation for some time the eye grows more sensitive and a given quantity of light will seem brighter than normally [Gordon, 1957].

For this reason there are standardised mathematical descriptions of visual sensitivity.

These interrelated units describe the flow of the light, its intensity in space, illuminance at the point, and the luminance of a surface. These units are both physical and psychological, since they depend on both the physical properties of electromagnetic radiation and our perception.

*Luminous flux* describes the total flow of a light from a light source. The output of a lamp is given in *lumen (lm)*. The *luminous efficacy* gives us the relation between a lamp's light output and its electrical input. The intensity of the light, from a source, in a certain direction is defined as *luminous intensity* with the unit *candela (cd)*. The amount of light falling on a surface is the *illuminance* measured in *lux (lx)* [Tregenza and Loe, 1998]. The light units and dimensions are further described in appendix A.

## History of lighting

In the early history of the humans, the sun was the only light source. Around 400 000 B.C. the human discovered the fire and learnt how to control it. The flaming torch and the campfire constituted the first use of artificial lighting.

The first lamps were quite primitive and made of naturally occurring materials, such as rocks, shells, horns and stones. These lamps were filled with grease and had a fiber wick. They typically used animal or vegetable fats as fuel.

The natural oil lamp was followed by basic designed lamps and pottery lamps. These were invented in the early Greek time. In the beginning they were handmade and later they were manufactured. Pottery lamps provided a cheap and practical mean of illumination, easy to produce, easy to use, but rather messy to handle. The oil would often ooze from the wick hole and run down the side of the lamp.

The invention of the candles dates back to about 400 A.D., perhaps somewhat earlier. Candles were rarely used in the home until about the 14<sup>th</sup> Century; however they were an important symbol of the Christian religion. The best candles were made of bee wax and were chiefly used in church rituals because the bee was regarded as a symbol of purity.

William Murdock, a Scotsman, is generally regarded as the father of gas lighting. In 1792 he heated coal to produce gas and used it to light his home and office in Cornwall, England.

Thomas Edison invented the first practical electric lamp in 1879. Edison's original lamp used a carbon filament placed in vacuum. Today's light bulbs contain a tungsten wire and argon gas.

Edison's original lamp converted less than 1 % of the electricity into light. Today's household bulbs convert 6 to 7 % into light, the rest being wasted as heat. Compact fluorescent lamps today can be 50 times more efficient than Edison's original lamp and last for years.

Today there is an increasing amount of lamp types available for home, work place and exterior lighting. In addition small businesses, such as retail stores and restaurants are finding that well designed lighting can have a significant effect on the customer's view of their products and their establishments [Williams, 1999].

## **Energy saving**

What motivates this resurgent interest in daylighting? The answer might be quite complex, but the potential for energy conservation is the most dominant factor. Using renewable natural light in a space reduces the need for electrical light, which is usually generated at the expense of a non-renewable resource. Another factor is energy cost saving, which is closely associated with energy conservation, but is distinctly different. When sufficient daylight is available, which depends on the location and climate, a good daylighting design allows artificial lighting to be lowered or turned off. That can reduce the energy cost for lighting.

Daylighting may also reduce heating and cooling costs for a building. It is possible to construct daylighting systems so that it produces less heat than artificial light. Of course sunlight can also provide supplementary building heat. [Hopkinson et al, 1966]

Nicklas and Bailey [1997] showed that the most obvious conclusion is that daylighting, even excluding all of the productivity and health benefits, makes sense as a financial investment. The energy cost of a daylighted school was reduced between 22 and 64 % compared to a normal school. So even the higher investment for building a daylighted school will have less than three years payback, and in the long term the cost saving benefits for such a school will be considerable. For example a daylighted school in North Carolina save about 40,000 USD per year compared to a typical school [Heschong Mahone Groupe, 1999].

Commercial, industries and public facilities such as school, libraries and hospitals can have a significantly reduction of artificial lightning, when using daylight.

In commercial and public buildings 40 to 50 % of the energy consumption accounts for artificial light, and 10 to 20 % of energy consumption in industry. Daylighting in combination with energy efficient lighting reduces the energy consumption considerably. The lighting power density can be reduced by using daylight, in some office buildings from 23.7 W/m<sup>2</sup> to 9.5 W/m<sup>2</sup>, without any reduction in the measured light levels [US Department of Energy, 2002].

A study in Hong Kong showed that natural light alone could provide an average indoor illuminance, for about 50 % of a typical working day [Lam and Li, 1998].

Such energy savings depends on factors like climate, location, energy load, and design of the building. But when sufficient daylight is available, a good daylighting design may allow artificial lighting to be lowered or turned off. That would reduce the energy use especially in commercial and institutional buildings that are mainly used

during the day. The fact that commercial and institutional buildings use a lot of energy for artificial lighting and that they are mainly used during the day, make this kind of buildings suitable for daylighting.

Using daylight may also reduce energy use for heating and cooling. Daylight produces less heat per unit of illumination than many artificial lights, so the cooling demand is reduced when artificial light is replaced by daylighting. The opposite way is also possible; sunlight can provide supplementary building heat as a part of passive solar heating system.

To minimize energy use, innovative designs have to be invented to optimise the balance between heating, cooling and lighting needs. Design components such as light sensors, and optimising mechanical and electrical systems not only reduces cooling and lighting cost, it also reduce the cost of maintenance as less lighting fixtures will be needed.

## **Value of daylight**

Daylighting has become increasingly important in buildings, in part because it is recognised as related to improved morale and productivity of the people, which are working or living, in such buildings. No electrical lamp can match the colour variation of daylight. The human eye adapts easily to daylight and especially windows give the occupants a sense of contact with the outdoors [US Department of Energy, 2002].

The information that our brain receives from the illuminated environment is an essential element in shaping our moods, reactions and physiological well being [Sze-Hui, 1999]. So, physiological and psychological benefits are good reasons for using natural light. Daylight generally increases occupant satisfaction by providing a healthier and more pleasant environment. It seems like humans function better, emotionally and physically under natural light, it seems like our bodies were designed for natural light.

By receiving the full spectrum light the human body get beneficial effects like producing more vitamin D, get a better calcium absorption, metabolism, and hormone secretion. The body's ability to assimilate calcium is essential for formation and maintenance of bones and teeth and it depends on the presence of vitamin D. A healthy person receives enough of this vitamin through a daily exposure of the hand and face to 15 minutes of sunlight. Of course we get some vitamin D from the food, but up to 90 % of the vitamin D in our body is built up by the reaction that occurs when our skin get exposed to ultraviolet light, which is present in e.g. sunlight. Children with softening bones or old people with brittle bones have problems with vitamin D insufficiencies, which can be prevented or even cured by exposure to small quantities of ultraviolet radiation [Neer et al, 1971]. Recent Swedish studies have shown that people in the northern part of the country more often get hip fractures than people in the southern part. This is thought to be caused by the lack of exposure to sunlight, and thereby lack of vitamin D [William-Olsson, 2002].

A study on daylighting in schools shows that students get more productive in daylighting schools, than in traditionally illuminated schools. Students with optimal daylighting in their classrooms progressed 20 % faster on math tests and 26 % faster on reading tests in one year, compared to students in the least daylighted classrooms

[Plympton et al, 2000]. Students tend to be more attentive and display lower levels of hyperactivity [Thayer, 2000].

An analysis by Nicklas and Bailey shows that students exposed a full spectrum of light were healthier and attended school 3.2 to 3.8 days more per year, than students at comparative non-daylighted school. The full spectrum lighting induced more positive moods; and because of the additional vitamin D received by the students in full spectrum light, students had nine times less dental decay, than students in a non-daylighted school [Nicklas and Bailey, 1997].

Libraries with superior light resulted in significantly lower noise levels. Daylighting bring the effect that heating, ventilation and air condition systems can be downsized, which also reduced the noise levels in offices, classrooms and library, thus enhancing the environment for working and studying [Plympton et al, 2000].

Another primary difference between natural and artificial light is the inherent variability of daylight and its unpredictability. Levels fluctuate as clouds move through the sky, successively obscuring and revealing the sun. Some studies have showed that this variability of the daylight has a relaxing effect on the eyes [Sze-Hui, 1999].

Daylight has a better “light quality” than electric light. Light quality is a holistic term which includes a number of attributes of the environment that are generally considered to be positive, like better distribution of light, better colour radiation, absence of flicker.

Daylight is a very diffuse source of light, and tends to illuminate surfaces more evenly in all directions. Electric lighting for offices or schools is mostly designed so the light is directed downwards towards the desktops. For that reason the horizontal surfaces are more brightly illuminated than vertical surfaces. The stronger horizontal component of daylight improves visibility. Therefore daylight has a *better distribution of light*.

Colours look more natural in daylight than under electrical light, as most electric light sources are stronger in some areas of the light spectrum and weaker in others. Daylight on the other hand has a continuous spectrum and therefore provides *better colour rendition*. Colours tend to look much more vivid in daylight.

Daylight does not flicker; fluorescent lamps can have a noticeable flicker. People blame this flicker for a multitude of problems, like headaches, eye strain and attention deficit problems. Fluorescent lights that run on electronic ballast, have considerably reduced flicker problems, but only daylight guarantee a total *absence of flicker*.

Another aspect of “lighting quality” from daylight is sparkle or highlights on three-dimensional objects. Artists like to have a daylighted studio partly for the way shadows and highlights make objects more attractive and easier to understand three dimensionally, and a lot of the artists see a certain richness of their design in the variability of the light [Plympton et al, 2000].

All the benefits of daylight will not be present when sunlight is piped, as the ultraviolet and infrared rays probably will have to be eliminated before the sunlight can be piped. During cloudy days we have to add artificial light, which remove the guarantee of total absence of flicker. But even if we do not get all the benefits of the daylight if it is piped, it would be an improvement if we just get some benefits.

## Benefits of central lightning

Today fiber optical lighting systems are used as central lighting systems.

Fiber optic lighting systems have the advantage to traditional light, that the light source is separated from the light output, and that there is no electricity transported into the fiber. No heat or current, no infrared and no ultraviolet radiation are led through the fiber, only light.

This is for the most general used fibers in fiber optic lighting systems, manufactured by e.g. Roblon, Philips or Schott, but there are fibers, which are able to transmit wavelengths from 400 to 2400 nm. This means that in such fibers a big part of the infrared radiation (700 to 14000 nm) is also transmitted [Liang et al, 1998].

One advantage of the fiber optic lighting system is that it is possible to use in contact with water, as there is no electricity transported, like for swimming pools or water fountains.

Electrical lighting is a problem in spaces that need to be explosion proof. Whenever electricity is present, the risk of explosion through sparks cannot be eliminated totally. As the fiber do not carry any electricity or heat, it is beneficial to use fiber light guides in such surroundings. It will improve the safety on for example oil platforms.

Usually the light fittings for a fiber optic lighting system do not have to be exchanged. According to Roblon these corrosion and acid resistant fittings are maintenance free. So problems associated with the replacing of lamps at inaccessible locations do not arise when fiber optics are used. The light source can be located in an easily accessible place from where it can power a great number of points of light but there is only one lamp to replace. The maintenance will become considerably easier and cheaper. That makes fiber optic lighting systems a good option for light signal systems or traffic guidance systems on railway tracks, roads or runways, etcetera.

If cold light is wanted, i.e. light with no ultraviolet or infrared, fiber optic lighting systems can be the solution. This makes such systems perfect for lighting objects and materials, which are sensitive to heat, ultraviolet or infrared rays, such as works of art, paper, perfume, leather goods or fresh food. This special quality also makes such systems feasible for exhibitions where cold light is wanted, like in museums or shops.

One other advantage of using fiber optic lighting systems is that we can light several fittings with one light source. As an example, a traditional Christmas tree with up to 575 lighting points requires just a 75 W generator, which equals 0.13 W per light point [Roblon].

The disadvantages of the light source generator is that you cannot switch it on and off like traditional lamps, as the most types of discharge lamps need several minutes to warm up fully, and cool down after using. For this reason fiber optic lighting systems may not be viable for private homes [Littlefair, 1990].



# Overview of existing and planned systems for daylighting

There are several possible ways of bringing daylight into use as lighting in buildings. The most basic solution would be a simple window. The most sophisticated solutions thought of today are a variety of systems with moving solar collectors. These follow the sun's path and collect direct sunlight, which is transmitted to luminaires by optical fibers. The different concepts can be divided into two areas, active and passive solutions. Obviously there is a running scale between the two extremes. Though in this report the existence of automatic and moving parts is considered to be the divider.

Typically systems with moving parts are designed to collect direct sunlight instead of diffuse light from the sky. Hence they have sun collectors rather than light collectors.

Passive systems can make use of direct sunlight, but are also dependent on other daylight. This means diffuse light from all of the sky, which is sunlight scattered by the atmosphere and by clouds.

## Active systems with optical fibers

To further extend the view of the active systems using optical fibers some facts about fiber optic lighting systems with an electrical light source, i.e. central lighting systems, are presented at the end of this section.

### Himawari

This is a daylighting system based on concentrating Fresnel lenses and glass optical fibers. It was developed in Japan in the late 70ies by professor Kei Mori and it was named after the Japanese word for sunflower. The first version, "Mono-lens HIMAWARI", first saw daylight in 1979.



*Figure 1: One of the largest Himawari collectors [Laforet Eng. Co., 2001].*

### *Light collection*

Himawari is a sun tracking system with a sun collector made up of several hexagonal Fresnel lenses, attached in a honeycomb pattern. A sun sensor, an internal clock and a microprocessor carry out the sun tracking.

In fine weather the sun's exact position is determined by the sun sensor, which is mounted in the centre of the sun collector. When the sun is behind clouds the collector relies on the clock and the microprocessor to calculate how it should be directed. This makes it possible for the collector to always have the correct direction when the sun comes out from behind clouds.

At sunset the system positions itself for sunrise and shuts down until next morning.

### *Light transmission*

Each Fresnel lens focuses the sunlight onto the end of a glass fiber with a diameter of 1 mm. Six fibers are connected into one fiber optic cable. Thus the smallest available version of the Himawari system has six lenses in the sun collector. All the larger ones have a number of lenses dividable by six.

The fact that lenses concentrate the light is utilized to filter out some of the infrared and ultraviolet parts of the sunlight. This is possible because of the chromatic aberration that causes light with different wavelengths to focalise at different distance from the lens. The fiber ends are placed in the focus for the visible wavelengths where the infrared and ultraviolet light rays are less dense.

### *Performance*

If the sun collector is receiving 98 000 lux of sun light, each fiber can transmit a luminous flux of 1630 lm over a distance of 15 m. The light disperses with an emission angle of 58° from the fiber end. If it is placed at a height of 2 m it will illuminate the floor below with 420 lux in average within a circle of the diameter 2.2 m.

### *Luminaires*

At the Himawari web page some ordinary down lights and a spotlight fitted at the end of an optical fiber are shown.

### *Economy and different models*

The prices for the collectors are ranging from slightly more than 4000 USD for the smallest to over 140 000 USD for the biggest model. This is the 198-lenses XD-160S/198AS, which provides 198 optical fibers with light. The price in Japanese Yens was 19 500 000 in 2001. There are two 12-lenses models, the cheapest of them being XD-50S/12AS. In 2001 the price was 560 000 JPY.

The models in between of the extremes are two 36-lenses and one 90-lenses version.

The glass optical fiber costs approximately 140 USD per meter and the light appliances ranges from just over 35 USD to near 280 USD.

### *Applications*

According to the Himawari web page this system can be used for a wide variety of applications: common room illumination, visual effects, aquariums, and etcetera. One interesting application is to use it for photobioreactors, tanks for cultivating photosynthetic cells in laboratories. These can be of cylindrical shape with tubular light radiators inside, which spreads the light delivered by the Himawari system [Ogbonna, 1999].

### *References*

[Laforet Eng. Co., 2001; Furuune, 2002] where not otherwise is stated.

## **Hybrid lighting**

This is a US partnership research project. It aims to provide annual energy savings of over 30 billion kWh and economic benefits exceeding five billion USD by the year 2020. The concept is a parabolic sun collector providing both sunlight, transmitted with optical fibers, and electricity, generated by photovoltaic cells.

The partnership consists of several universities, laboratories and companies. Among them are 3M, Sandia National Laboratories and Oak Ridge National Laboratory, which is providing information about the research via their web page.

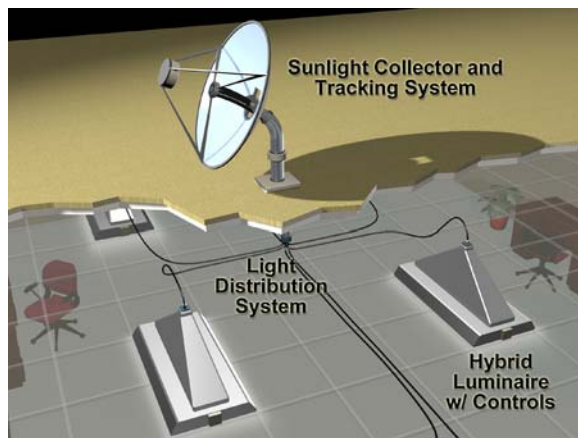
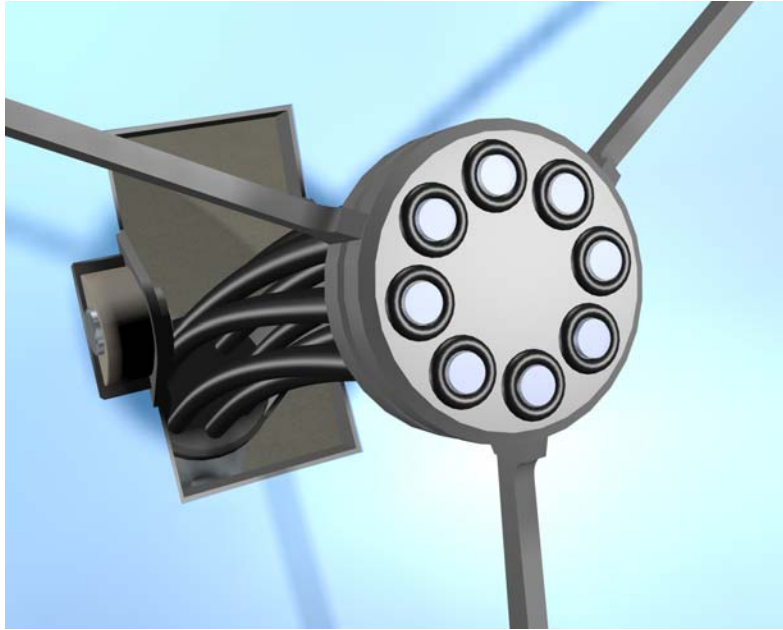


Figure 2: An overview of the Hybrid Lighting system with collector, light guides and luminaires [Laymance, 2002].

#### *Light collection and electricity generation*

Similar to the Himawari system the Hybrid Lighting sun collector is a 2-axis sun-tracking collector. It is designed as a parabolic mirror (the primary mirror) that reflects direct non-diffuse sun light onto a secondary optical element (SOE), placed in focus of the parabola. The SOE is a spectrally selective cold mirror, which separates the visible portion of the solar spectra from the near infrared spectra (wavelengths between 700 and 1100 nm). It reflects the visible portion of the sunlight onto a number of large-core optical fibers placed in the centre of the dish. The infrared rays are transmitted through the cold mirror and are utilized by a photovoltaic cell to generate electricity. This solar cell is especially sensitive to the near infrared wavelengths.



*Figure 3: A close-up of the eight fiber ends placed in the centre of the collector dish [Laymance, 2002].*

#### *Light transmission*

The SOE is divided into eight sections that reflect the light onto eight fiber ends placed in a circle, 54 mm in diameter, in the centre of the dish. The fibers are large-core plastic fibers with a diameter of 18 mm. The number of fibers used and their size is dictated by the size of the primary mirror.

#### *Luminaires*

The system is called “hybrid lighting” since it requires an alternative light source in cloudy weather or when the sun is below the horizon. The alternative light source is planned to be some kind of electrical lamp mounted together with dispersers for the sunlight in hybrid luminaires.

This dual system will have a control system that ensures that the illumination remains constant even if the sun is temporarily hidden behind clouds. The control system employs ballast dimmers that adjust the electrical light according to how much natural light is available. In this way electrical energy is saved. It will also be possible to dim both the natural and electrical light based on preference and to switch it on and off.

In order to provide a good mix of light from the two sources it is important that they both have the same characteristics such as light colour and spatial intensity distribution, according to the Hybrid Lighting-partnership. It is also important that the control system responds quickly to intensity fluctuations in the natural light, due to changing cloud coverage for example, so that constant illumination can be ensured.

Two different light dispersing techniques that allow fiber optic end-emitted light to mimic the light from a standard cylindrical fluorescent light tube have been investigated. They were both based on common commercial fluorescent fixtures, which were modified to incorporate the sunlight dispersing devices.

One technique is to employ cylindrical diffusing rods placed adjacent to the ordinary light tubes in the luminaires. Light is emitted from the end of this rod, with the

diameter 2.54 centimetres. The half of the rod that faces the floor is clear and transmits light, while the upper half is diffuse and scatters light downwards.

The opposite end of the rod to the fiber end contains a concave mirror that further improves the light scattering. A drawback with this concept is that optical efficiency was low for the rod, only 50 %, and the inclusion of the rods also decreased the efficiency of the electric lighting for the fixture from 64 to 53 %.

The other, more promising, technique investigated, is based on dispersing elements in the luminaire's acrylic lens diffuser. The light dispersing elements are 15 centimetres in diameter with micro-optic structures to disperse light coming from the fiber-end mounted above pointing downwards. The optical efficiency of this design has been estimated to 90 %. The overall optical efficiency for the luminaires was lowered by the dispersing elements from 76 to 73 %.

### *Performance*

Based on performance values for the different components the total performance has been estimated to approximately 50 % for a single-storey application and 30 – 35 % for second-storey. This means that half of the light or more will be lost due to losses in the primary mirror, SOE, fiber entrance, transmission and luminaires. Aging of components and build-up of dirt was included in this evaluation.

These estimated values means that a collector of 2 m<sup>2</sup> receiving 100 000 lux of sunshine could deliver 100 000 or 60 000 lm respectively for a first-storey or a second-storey application. If this light were distributed evenly over 90 m<sup>2</sup> of floor space it would give an illumination of more than 1000 or 650 lux respectively.

The estimated replacement of electricity is close to 100 % in peak periods. This is possible in spite of losses occurring in for example collection and transmission of the sunlight. The main reason is the much higher luminous efficacy for filtered sun light than for electricity driven lighting. Electric light gives typically 63 lm/W, while the filtered sunlight gives approximately 200 lm/W. The visible portion of sunlight per 1000 W incoming solar flux is 490 W and the near-infrared radiation is 360 W.

### *Economy*

The overall installation cost for a single-storey application of this system has been estimated to 3000 USD in commercial quantities. This is valid for a system with one collector of 2 m<sup>2</sup> providing around 12 luminaires and about 90 m<sup>2</sup> of floor space with light.

### *Future*

A project to install a first generation version of this system is scheduled to start 2003 in Sacramento, California. During the first year the Sacramento Municipal Utility District and Oak Ridge National Laboratories (ORNL), that have been awarded the contract by the California Energy Commission, will select a suitable office building. The second year the system will be installed and operated by ORNL.

### *References*

[ORNL, 2001; Muhs, 2000a; Earl and Muhs, 2001; Muhs, 2000b; Muhs, 2002].

## **SOLUX**

This is a Fresnel lens-based daylighting system developed by the German company Bomin Solar Research (BSR). The collected sunlight is transmitted by liquid light

guides. A first demonstration system with three collectors has been installed at the German museum of technology in Berlin among with other daylighting systems. Roman Jakobiak, architect at IBUS (Institut für bau-, umwelt-, und solarforschung), have worked with the daylighting at the museum and was kind enough to show the authors of this report the SOLUX-system. At that occasion it was, however, taken out of work due to problems with liquid leaking from the light guides and for installation of new software.



*Figure 4: A SOLUX-collector without the protecting acrylic dome [Colsman-Freyberger, 2002].*

### *Collector*

The collector is a sun tracking 2-axis turning unit. The plastic Fresnel lens is 1 m in diameter and concentrates the sunlight 10 000 times. A filter that the light passes through before it enters the liquid light guide extracts heat. According to Jakobiak there have been ideas about designing concepts for using the extracted heat. However, this is not included in the units installed at the roof of the museum in Berlin.

The sun tracking is carried out by a dual system, which is self-learning according to Jakobiak [Jakobiak, 2001]. It is made up of a solar direction sensor and a microprocessor calculating the position of the sun.

When mounted at a roof a clear acrylic dome to protect it covers the whole collector. This is an extra source of light losses. However, the protection also makes it possible to employ a less robust design and thus a less expensive design.

### *Light transmission*

The concentrated and filtered sun light from the collector is fed to a liquid light guide. This is a flexible pipe, 2 centimetres in diameter, filled with an optical clear liquid made up of several components. The demonstration system installed at the German museum of technology in Berlin has had some leakage problems. The reason is that a wax component froze due to low outdoor temperatures. It is possible to solve this by replacing this component, according to Roman Jakobiak.

### *Luminaires*

The light from the liquid light guides is released into diffusing tubes that spread the light in the room. Because of the transmission through the liquid the light is somewhat greenish. The tubes at the installation in the Berlin museum, about 5 – 7 meters in length and approximately 20 centimetres in diameter, hang from the ceiling. Natural light from the collectors enters one end and at the other end an electric lamp is used when the sunlight is not sufficient.

### *Performance*

The light loss in the liquid light pipes is about 10 – 15 % per 10 m, according to Dr. Claus Colmsan-Freyberger at BSR. (Authors' comment: very low losses compared with fiber optics.)

### *Economy*

The price for this system in mass-production has not yet been determined. However, Colmsan-Freyberger made a very rough guess estimating that the price for one collector (Fresnel lens 1 m in diameter) with a 10 m light pipe would be about 2000 USD.

### *Future*

The Solux technology is being implemented by another company than BSR, within the Bomin group.

### *References*

Visit at the German museum of technology in Berlin, November 2001. [Jakobiak, 2001; Colmsan-Freyberger, 2002].

## **Central lighting systems**

These are not daylighting systems, but rather electrical lighting systems with a central light source. They are manufactured by for example Roblon (Denmark), Philips (Netherlands) and Schott (Germany). Since all of these systems utilise optical fibers they are known as “fiber optic lighting systems”.

### *Function*

Light from a central lamp, or projector, is transmitted by optical fibers to light fixtures located where the light is required. The fibers can be made of either glass or plastic. The light sources use high efficacy lamps, e.g. metal halogen, with power ranging from 40 W up to at least 150 W [Flux, 2001].

The fixture, or luminaire, can either be some kind of optics mounted at the fiber end for an end-emitting fiber or it can be the fiber itself if it is a side-emitting fiber. The latter one can be used for effects similar to neon lights.

### *Applications*

To the best of the authors' knowledge fiber optic lighting systems are not used in any general illumination applications. Instead it is used for effect lighting, guiding, spotlights and other special applications. Some examples are illumination of swimming pools, building exteriors, guidance light at walking paths, signs and illumination in showcases. The last application can be especially viable if the subject that is displayed is sensitive to heat.

## **Active systems with heliostats**

A heliostat is a device that consists of a mirror continuously reflecting the sunlight to one specific point. This can be used to divert sunlight into windows, sunpipes or other kinds of light or sun collectors.

There have been several projects with large heliostat arrays reflecting the light onto a receiver in order to harness the solar energy. One example of such a system was the experimental facility Solar Two, a so called power tower, that generated 10 MW of electrical power until it was shutdown in 1999 [US Department of energy, 2000].

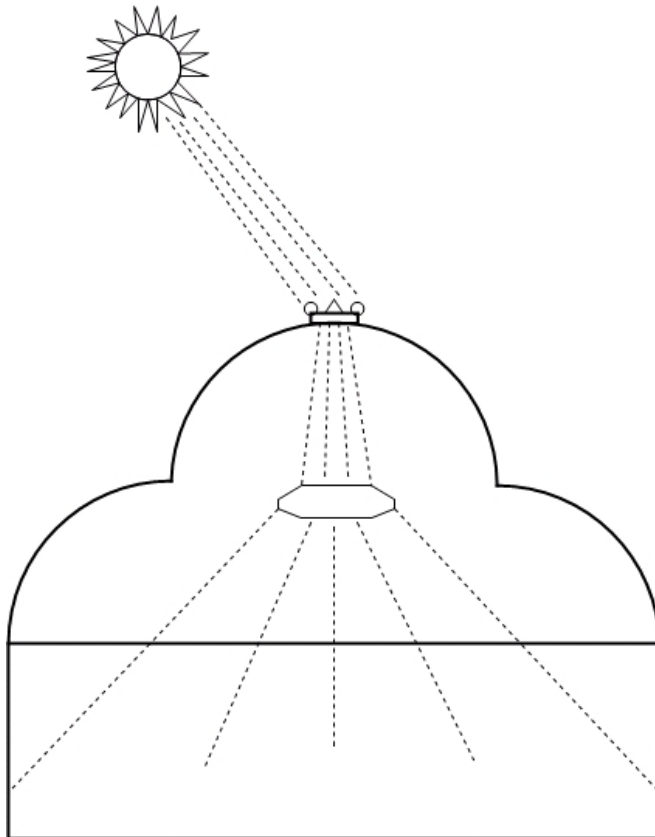
### **Mosque, Kuala Lumpur**

The mosque Masjid Wilayah in Kuala Lumpur, Malaysia, has been equipped with a daylighting system employing twelve heliostats to illuminate the prayer hall of 3 600 m<sup>2</sup>.

The roof of the mosque is made up of one central major dome and three smaller domes adjacent to the first one. The heliostats (1 m in diameter) are placed on the top of the central dome. They are reflecting sunlight on a mirror-pyramid. This focuses the light and beams it down onto a chandelier in the prayer hall. The chandelier spreads the light so it covers the floor.

During nighttime the heliostats are placed horizontally to allow projectors on their backside to focus artificial light onto the mirror-pyramid.

The heliostats for this daylighting system have been delivered by Bomin Solar [Bomin Solar, 2001].



*Figure 5: Cut view of the mosque showing the heliostats, the pyramid and the chandelier that spreads the light [after Bomin Solar, 2001].*

### **Underground train station, Berlin**

As a part of the modern architecture at Potsdamer Platz lightpipes connect the underground station with the outside. In an open place, surrounded with elaborate skyscrapers, stands three tall lightpipes with heliostats on top of them. This allows daylight to stream down through the pipes to the underground.

It is a large station and this system does not mean so much for the illumination as for the architectural connection between the outside and the underground. During nighttime artificial light illuminate the light pipes, which allows the observer to make a connection to the underground.



*Figure 6: One of the lightpipes at Potsdamer Platz during installation [Signer, 2002].*

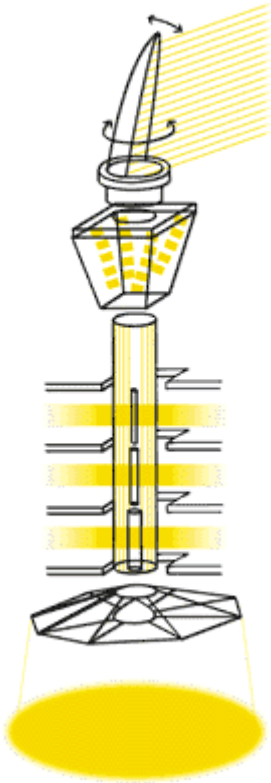
These light pipes are designed as two pipes, a glass pipe enclosing a steel pipe. The latter one has inner walls covered by a highly reflective foil and it transports the daylight, diverted underground by the heliostats.

The outside of the steel pipe as well as the inside of the glass pipe is covered with a special highly reflective, transparent foil. Artificial light is added right where the pipe cuts the ceiling. During the night this light illuminates the pipe both above and below ground, giving it a special distinct look.

This project was carried out by the Swiss company Heliobus that also has designed several other daylighting systems [Heliobus, 2001; study visit, 2001].

### **Heliobus, Switzerland**

A more general heliostat based daylighting system that can be installed in different buildings comes from the same company. It is called Heliobus and it employs a spoon shaped heliostat mounted on the roof on top of a light pipe.



*Figure 7: A schematic cut view of the Heliobus system showing heliostat, transition element, light guide and extractors in the light guide [Heliobus, 2001].*

The light guiding system below the heliostat is made up of a transition element, a vertical light guide and extractors inside the light guide.

The transition element is located where the system cuts through the roof and links the light collector to the light guide. It also includes an artificial light source.

The vertical light guide is coated with light-guiding foil and transports the light into the building.

The extractors are installed in the centre of the light guide where light extraction is desired. It is a diffusing rod, which alters the path of the light beam so that it can leave the light guide [Heliobus, 2001].

### **ARTHELIO, Semperlux and the Berlin University of Technology (BUT)**

ARTHELIO, which stands for “artificial and heliostatic light”, is a European research project. Within this project a daylighting system have been built in the hallway of the lighting company Semperlux in south Berlin.

Also a demonstration installation for the combined utilisation of daylight and artificial light have been put up at the roof of the institute of electronics and lighting technology of BUT.

Both systems use a large rectangular heliostat with a dual-axis tracking system to reflect sunlight onto Fresnel lenses. The difference is that the system at the university uses a secondary concentrating mirror, which has several segments, and a smaller heliostat (4 m<sup>2</sup>). The segments of the secondary mirror can be moved independently to give the optimal concentration. The concentrated light is beamed onto a Fresnel lens with an optical diameter of 0.9 m. This lens concentrates the light into the hollow light pipe. The system installed at the university is an experimental setup that can illuminate

a small room at the top floor. The illuminating device is a large-diameter horizontal light pipe hanging from the ceiling. The heliostat is placed on the roof area, a terrace, adjacent to the illuminated room.

The Semperlux system is mainly based on the same idea. The system has a bigger heliostat area (6 m<sup>2</sup>), and no secondary mirror. The reflected sunlight goes directly onto four Fresnel lenses with a focal length of 1.2 m. Directly behind the focal point four parabolic mirrors, diverting the light downwards into the light pipe. The Fresnel lenses and the parabolic mirrors are built in a small house on the roof, which protects the lenses and the mirrors from dirt. The problem with the parabolic mirrors is the high heat gain from the concentrated light, which destroys the surface of the mirrors.

The system has two parallel vertical light pipes that supply a whole staircase of three floors with light. One of the light pipes is directly beneath the transition unit. The other is supplied with light from the first by a horizontal light pipe on the top floor. This connecting pipe has a sulphur lamp at one end and on top of each vertical pipe is a mixing unit. These units mix the light so that the light from both the sun and the artificial source is evenly distributed to the vertical pipes.

Both the system at the university and at Semperlux uses the same kind of hollow light guides. It consists of a transparent plastic tube with a diameter of 30 cm. The inside is covered with an optical lighting film from 3M. The patented transparent film has a smooth surface on one side and longitudinal micro prisms on the other. Light with low incident angle hitting the film will undergo total internal reflection.

The Semperlux system has 12 m long hollow light guides. To get the light spread out evenly over this tube; small white reflecting cylinders are used. These hang in a particular order at the centre of the light guide; the diameter of the cylinder gets proportional bigger from the top to the bottom. With help of this cylinder the total internal reflection in the pipe is interrupted by changing the angle of the light hitting the pipe's walls. This allows the light to be evenly distributed along the light pipe. This design of the light pipe with reflecting cylinders can be compared with the extractors of the Heliobus system reviewed above [study visit, 2001; Kaase, 2000; Müller, 2000]

## **Passive systems**

These are often more architectural than the active systems. This makes them a part of the building itself rather than something installed in the building. Therefore they often have to be planned from the very beginning when the house is designed. There are however some exceptions.

According to some, the history of daylighting and the history of architecture were one until the second half of the 20<sup>th</sup> century [Lechner, 1987a]. This was when fluorescent lighting and cheap electricity started to be commonly available. Until then the major structural changes in building design had reflected the goal of increasing the amount of daylight entering the building. Below are some examples of passive techniques that can be used to provide building interiors with daylighting.

### **Windows**

This is of course the main strategy to let daylight into buildings. Windows are a daylighting system in themselves, but they can also be part of a whole structure of the building that can be adapted for daylighting. Light courts are a typical example of this.

The illumination from an ordinary window is high just inside the window, but it drops rapidly further in. Other drawbacks are that the view of the sky can cause glare and direct sunlight can create both excessive brightness and in the summertime unwanted heating.

To make the most of windows they should be placed high on the walls to allow light to penetrate deep into the room. They should also be widely distributed and preferably be placed on more than one wall in a room. This makes the daylight more evenly distributed and makes the contrasts lower since there are more light sources.

Windows should be placed next to interior walls, which then act as low-brightness reflectors that spread the daylight. This also reduces glare from the window, which lowers the contrast. [Lechner, 1987b].

#### *Using the ceiling as reflector*

To distribute the daylight deeper into the building it can be reflected onto the ceiling. This should be of bright colours, preferably white, and act as a diffuse reflector. For the bottom floor light-coloured walkways or similar can be used to reflect light through the window onto the ceiling. For buildings with more than one storey reflecting parts can be included in the structure. Those can be wide window sills or light shelves placed above eye level. Other ways to reflect light onto the ceiling are to use Venetian blinds or light-directing glass blocks. The blinds also have the benefit that they are possible to adjust for different lighting situations. The normal task for blinds is to protect from unwanted light and glare. This can be done also when they are employed for daylighting, as can light shelves and glass blocks [Lechner, 1987a, c].



*Figure 8: Reflective Venetian blinds at a building at Luleå University of Technology.*

#### *Different kinds of glazing*

Normally clear glazing is used in windows. This is good both for transmitting daylight and for providing a view of the outside. There are also a variety of other sorts of

glazing: diffusing, tinted, heat absorbing, reflective and selectively reflective. However, none of them is an obvious better choice for daylighting than clear glazing.

Diffusing, or translucent, glazing can become a source of glare when direct sunlight falls on it, but does not allow for a view. However, large areas of low-transmitting translucent glazing can be used for lighting without glare problems. This can for example be achieved by translucent roof areas.

Selectively reflective glazing reflects more of the short-wave infrared than of the visible light. This could be used if unwanted heat gain from the sun otherwise would be a problem [Lechner, 1987c].

## **Toplighting**

There are several ways of letting daylight in through the roof. A classic concept is the saw tooth clerestories of old factories. This and a few other examples are reviewed below. They present ways of achieving high and uniform levels of illumination. But there are also drawbacks, most methods are only possible to use on the top floor and as overhead light sources they can give glare problems through veiling reflections. The latter issue can be dealt with by placing the toplighting sources correctly or by diffusion through reflection or the use of baffles for example [Lechner, 1987c].

### *Skylights*

These are openings in the roof that let daylight in. They are horizontal or just slightly sloped and because of this they view a large part of the sky dome. This allows them to transmit a high level of illumination. Direct sunbeams are undesirable and this calls for some kind of diffuser. For skylights diffusion can be achieved by for example translucent glazing, baffles or by placing the skylight next to a back wall that acts as reflector. Also other kind of reflectors can be used to bounce the incoming light in the e.g. ceiling.

Horizontal skylights collect more light and heat in the summer than in winter. If they are sloped towards the south (for the northern hemisphere), they will provide light more uniformly throughout the year. As the slope increases, the skylights eventually become clerestories or monitors.

Skylights can also be combined with heliostats to make them an active system. The heliostats than track the sun to always provide the skylight opening with high levels of illumination [Lechner, 1987d].

### *Clerestories*

Monitors, clerestories and saw tooth clerestories all use vertical or steeply sloped glazed openings on the roof. They can be either north or south facing. On the northern hemisphere south facing openings will provide a high, but varying, level of illumination. Except for at very northern latitudes direct sunbeams are easy to shade. North facing openings will provide a low, but near to constant, level of illumination. east- or west facing openings are avoided because it is difficult to shade the low sun. South facing clerestories are often a good solution that will provide good lighting all year and also sun heating in the winter.

Light can be reflected both on a high-reflective roof and on a bright interior wall or ceiling to increase both the amount of light entering the building and the utilisation of it. Also other kinds of inner reflectors, or daylight fixtures, can be used to improve the function of this toplighting system [Lechner, 1987d].

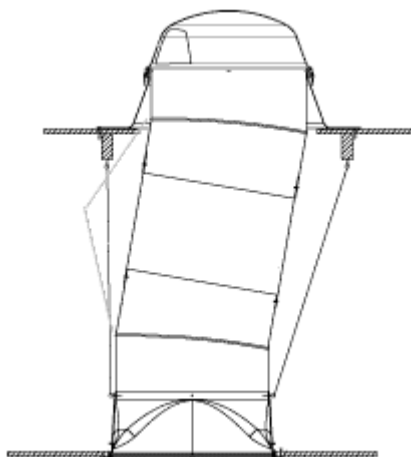


*Figure 9: Toplighting at the library building of Luleå University of Technology. There are two rows of clerestories below a 45° monitor furthest away on the sloped roof. The light from the monitor falls onto the back wall of the library, which acts as a diffuse reflector.*

### *Sunpipes*

This is a less architectural system, it is more technical and on the limit of being an active system. Actually some of these systems are active and have heliostats included, an example of such a system is the Heliobus mentioned above in the section about active systems.

The Solatube system is an example of a passive sunpipe [Solatube, 2001]. The light collector for this system is simply a transparent dome with a reflector inside, which is placed on the roof. The collected light is transmitted through the roof by a tube with a highly reflective inside. Where the tube cuts through the ceiling the light is released into the room in question through an acrylic diffuser.



*Figure 10: A cut view of the Solatube system, 530 mm diameter version [Solatube, 2001].*

According to Solatube the largest version of their system should be able to deliver as much as 8200 lm on a sunny day. The largest model has a tube diameter of 530 mm

and the tube length in this example is 2 m. The company's smallest model has a diameter of 250 mm.

# Key concepts for daylighting

## Light

Sunlight is a mixture of electromagnetic waves with different wavelengths.

Each wavelength in the light produces a different colour sensation in our eyes, from red to green to violet. If we see a picture with beautiful colours, we should know that the colours do not belong to the picture itself. The colours are present in the sunlight, with a mixture of different wavelengths. When the light hits the picture, the different parts of the picture reflect certain wavelengths more strongly than other giving each species its colourful pattern.

Visible light has approximately a wavelength from 360 – 760 nm; which is a small part of the electromagnetic spectrum [Robbins, 1986].

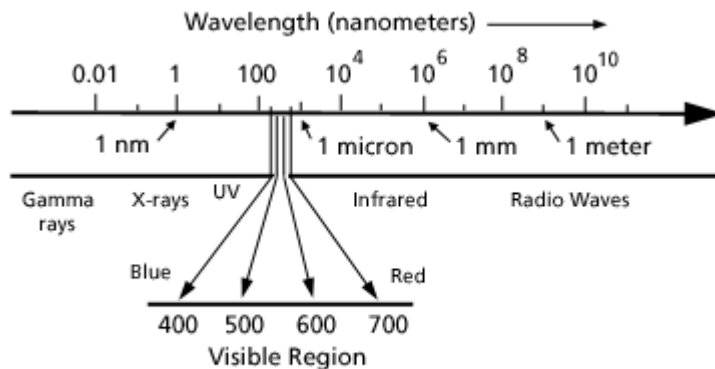


Figure 11: The Electromagnetic spectrum [Acept W<sup>3</sup>-Group, 1999].

## Rayleigh scattering

The blue colour of the sky is caused by the scattering of sunlight of the molecules of the atmosphere. This Rayleigh scattering is more effective at short wavelengths (the blue end of the visible spectrum). Therefore the light scattered down to Earth at a large angle with respect to the direction of the sun's light is predominantly in the blue end of the spectrum [Cutnell, 1995].

## Refraction and reflection

When light strikes the interface between two transparent materials with different optical properties, such as air and water, the light generally divides into parts. Part of the light is reflected, with the angle of reflection equal to the angle of incidence; the remainder of the light is transmitted across the interface. If the incident ray does not strike the interface at a normal incidence, the transmitted ray has a different direction than the incident ray. The ray that enters the second material is said to be refracted. This phenomenon is utilised to design lenses [Cutnell, 1995].

## **Collecting the light**

To collect daylight in an efficient way it is necessary to understand that daylight comes in two forms, diffuse and direct. The direct light from the sun is available when the sun is visible and this is a high-power light source with close to parallel light. In clear days it stands for about 85 % of the available daylight [Muhs, 2000b]. The diffuse light is sunlight scattered by the atmosphere, i.e. by the air molecules, dust, moisture, etcetera [Duffie and Beckman, 1991]. It is the blue light from the sky and it is the white light from an overcast sky.

The sun is a high-density light source, but using it for daylighting means that one has to take into account its movement. This calls for an active collecting system; some kind of tracking sunlight collector, for example a heliostat [Robbins, 1986]. All kind of tracking and moving collecting systems are referred to as active systems in this report. Non-moving systems such as ordinary windows or skylights are called passive systems.

## **Concentration of the light**

Different collecting strategies can be adopted to meet the two forms of light. Direct sunlight has nearly a uniform direction and is therefore possible to concentrate. Diffuse light has multiple directions – it is coming from the whole sky. In fact the skylight can be characterized as the integration of an infinite number of point light sources [Lechner, 1987a; Robbins, 1986]. Therefore it is not possible to concentrate; at least there are limits for how much [Littlefair, 1990]. Also we have found no technique where diffuse light can be concentrated and in addition to this be given a uniform parallel direction.

Concentrating sunlight is viable if you want to pipe it in narrow conduits to the space where illumination is desired. In other words, this is what makes it possible to design daylighting systems that distribute light in the same fashion as electricity or water in a building [Littlefair, 1990].

The concentration can be done by several different techniques using optical aberration and reflection. The most common techniques are Fresnel lenses and reflecting parabolas [Laforet Engineering Co. Ltd., 2001; Oak Ridge National Laboratory, 2001; Colman-Freyberger, 2002]. Other possible techniques for light concentration include heliostat arrays and wedge shaped light traps, where the latter is intended for photovoltaic cells as presented by Maruyama [Duffie and Beckman, 1991; Maruyama, 1999].

## **Transmission of the light**

Once collected the daylight should be transmitted to where it is needed, concentrated or not. However, transmission to remote spaces or rooms is typically intended for concentrated light. It takes up less cross-sectional area and is because of that less space demanding when transmitted. Non-concentrated light is generally used closely to where it is collected, e.g. windows, skylights, atriums, etcetera.

Concentrated light can be transmitted in several ways:

- Simply an empty shaft through which a collimated light beam can travel. Lenses can be included to keep the beam concentrated [Littlefair, 1990].
- Metal tubes with a highly reflective interior. In this case light not parallel with the tube undergoes multiple reflections and fast attenuates [Littlefair, 1990; TIR Lighting Solutions].
- Hollow light guides. Made of translucent plastic these can have either circular or rectangular cross section. The inside has a prismatic structure that ensures total internal reflection for certain angles and emits light for other angles [Littlefair, 1990; TIR Lighting Solutions].
- Optical fibers. These use the principle of internal reflection as they transmit light along thin cables, which are nearly as flexible as electric cables. They could be made of both glass and plastic, for different advantages. Generally the diameters are very small; up to 1 mm [Schott, 2002]
- Solid core optical fibers. Similar to common optical fibers. But where those are most often developed for communication purposes, these are designed for illumination purposes. They have diameters around 10 mm and have a core of either plastic or a gel for the best light transmission [Poly Optics Australia, 2000; Lumenyte, 2002].
- Liquid light guides. Similar to the solid core optical fibers, but with a liquid core. Used in the Solux-system. Remarkably low light losses according to Bomin Solar, the company that designed the Solux system [Colsman-Freyberger, 2002; Jakobiak, 2001].

Common for all of these transmission techniques is that light will be lost in the transmission. This is due to end reflections, absorptions, etcetera. Though when choosing a light guiding technique the economy, space demand, durability, and capacity also have to be considered.

## Use of light

Light from daylighting systems can be used for several different purposes. It can also be delivered to the illuminated space with a variety of methods, depending on the purpose and the transmission technique.

### Distribution

The transmission method is important for in which way the light can be spread in the room. Concentrated light admits other possibilities than non-concentrated light:

- End-emitting optical fibers. Possibly combined with optical fittings to give the desired distribution of light [Roblon a]. Also Fresnel lenses are possible to combine with end-emitting fibers [Earl and Muhs, 2001].
- Side-emitting optical fibers. Similar to common optical fibers, but these are emitting light along their length [Lumenyte, 2002; Roblon a].
- Hollow light guides. Mentioned above as a light transmission technique. It is also a method for emitting light. A diffusing rod, extractor, can be used inside the light guide to give the light a direction that allows transmission through the light guide wall [Müller et al, 2000; Heliobus, 2001].

- Lenses, prisms and similar optical devices. Such systems can for example be used to spread concentrated light provided by heliostats. Can provide both concentrated light beams and widely spread general illumination. One example is the mosque Masjid Wilayah in Kuala Lumpur, Malaysia [Bomin Solar, 2001].

If it is a matter of non-concentrated light the distribution method most often is directly given by the collecting method. For example several techniques involving windows, skylights, clerestories and similar solves the distribution issue by directing the light onto a highly reflective diffuse surface, e.g. a white wall or the ceiling [Robbins, 1986].

What kind of distribution that is chosen also depends on the purpose of the daylighting illumination. Task illumination at work places or spotlighting demands a concentrated and collimated light beam. General lighting of a whole room on the other hand could be provided with diffuse and not so concentrated light.

Another important aspect of daylighting is glare from bright windows. If a high amount of light falls on the windows this can create glare for the inhabitants of the building. This could be avoided by increasing the illumination level indoors. However, this means that the interior illumination becomes higher than required just to level with the outdoor levels. One way of dealing with this could be to redirect the light creating the glare so it is utilised for illumination rather than creating a need for illumination [Energy Efficiency and Renewable Energy Clearinghouse, 1996]. Methods for this, for example light shelves, are mentioned in the chapter “Overview of existing and planned systems for daylighting”.

### **Mixing daylight with artificial light sources**

As mentioned above, daylighting is most probably to be used in combination with other light sources, i.e. electrical lighting. The main reasons for this are the unpredictability of daylight availability and difficulties in distributing daylight evenly and deep into buildings [Energy Efficiency and Renewable Energy Clearinghouse, 1996]. Thus a supplementary light source is needed.

Combining electrical light with daylighting can be done in several ways. There is a choice of where to put the electrical light source and also how to control it.

If daylight is being piped by some kind of light guide there are mainly two concepts of where to put the backup light source. Either, using a central lamp, it can be placed so that the light guide pipes the light or else lamps could be placed in the illuminated rooms. The first concept means that light loss along the light guide has to be considered. The latter one means that either a double set of luminaires have to be used or that electrical and daylight fittings have to be somehow integrated in the same luminaires. Either way, means of providing the same light distribution for electrical and natural light has to be considered.

Controlling the lighting can involve different degrees of automatization. The control consists of two parts: first measuring the present illumination and second adjusting the light output so that the desired illumination level is maintained.

Most often this is done by our own visual judgement and manually switching on or off available lamps in the room. In some cases there are also dimming devices to make

it possible to adjust the light output from a lamp. This is called a manual control system.

According to Robbins automatic control systems can be of mainly three different types: on/off, multistep and continuous dimming. For all of these the room in question can be divided in different control zones depending on available daylight. For example the area next to south facing windows can be one zone and the area furthest away from any window can be another.

On/off control systems simply switch on the electrical light when the available daylight not is sufficient to reach the required illuminance level. This means that the total illuminance level can become very high if the available daylight is just below the limit and the electrical light is switched on.

Multistep systems make use of daylight even when this is not enough to provide all of the required light. Electrical light is turned on in steps depending on the daylight level. The steps depend on the number of lamps in each luminaire and the manner in which these are wired or ballasted.

Both on/off and multistep systems will give sudden changes in illuminance when electrical lighting is turned on or off. According to Robbins a change in illuminance of 50 lux and below is usually unnoticeable. Bigger changes are noticeable and if they are over 200 lux they can be very annoying [Robbins, 1986].

Continuous dimming control systems can either include off controls or not. Simple dimming controls can vary the electrical light output in response to the available daylight. More advanced dimming controls also include the possibility to turn off the electrical light [Robbins, 1986].

For all of these systems the available light needs to be measured. This can be done with photo sensors. These are electronic control devices made up of a photocell connected to a circuit that sends out a control signal in response to the detected illuminance. They are often placed on the ceiling. Different manufacturers suggest different concepts for how to place them and where to aim them. One concept is to place the sensor directly above a work surface that should receive a representative amount of light [National Lighting Product Information Program, 1998].



# Conditions for daylighting

## Availability of sunshine

All daylighting systems are dependent on the climate, weather and latitude of the location. Especially systems utilising only sunlight, i.e. all the active systems in this report, are depending on good weather with clear skies. Since they will provide almost no lighting at all when the sun is behind clouds, they have to be combined with some kind of backup lighting, most likely electrical in form of discharge lamps.

Unfortunately most discharge lamps need some time to warm up. A system using these will not work on a partly cloudy day, when the lamps have to be switched on and off repeatedly [Littlefair, 1990].

Sweden, UK, Germany and most other countries in northern Europe have a climate with a lot of cloudy or partly cloudy days, which makes a daylighting system dependent on clear skies less viable. According to Littlefair sunlight is available for 35 % of all days in UK, but much of this is on partly cloudy days [Littlefair, 1990]. In Hamburg, Germany, the sun shines in average 36 % of the possible time; when it is above the horizon [Duffie and Beckman, 1991].

In Sweden the sun shines between approximately 1500 and 2100 hours per year. The maximum possible amount of sunshine hours ranges between 4473 hours on the 56° latitude in the far south and 4557 hours on the 68° latitude in the northernmost Sweden [Peterson and Wettermark, 1985]. The share of sunshine varies between about 35 and 47 % out of the maximum possible in Sweden. The highest amount of sunshine is received on the island of Gotland in the Baltic Sea and in the counties of Värmland and Norrbotten. The Stockholm area gets between 1800 and 1900 hours of sunshine per year, about 40 % of the maximum possible [Peterson and Wettermark, 1985].

Statistics from SMHI (Swedish Meteorological and Hydrological Institute) agree in most parts with this distribution, though it indicates that the amount of sunshine hours is in general lower. According to SMHI the hours ranges from 1100 to 1900 per year [SMHI, 2002]. These figures would make the percentages range between 24 and 40 %, with Stockholm at 39 %.

It is however not only a question of how often the sun shines. It is also interesting to know when and for how long and uninterrupted periods it will provide non-diffused light. From a fiberoptic daylighting point of view it would be best if the sun shone without interruption between 08.00 and 17.00 on weekdays. Weather with clouds and overcasts should come after office hours and on weekends. Fortunately (if you like to spend your spare time outdoors) this is not the case and daylighting systems have to be adapted to the weather's unpredictability. Statistics for Sweden show that in average 1 to 10 days each month are clear. For most months and locations it varies between 2 and 5. The highest values are for spring and early summer and for a few cities, e.g. Gävle and Karlstad.

According to Duffie and Beckman there are several other cities in the world with other climate characteristics and much higher sunshine expectancy. This is natural and well known. For example Albuquerque in New Mexico, USA, has an average sunshine ratio of 78 % out of what is possible. This puts this desert city in a top spot in this

ranking. Another city with a lot of sunshine is Poona in India with an average of 81 % of maximum possible in the dry season, but only an average of 37 % during the monsoon [Duffie and Beckman, 1991]. This shows that there can be locations that have very varying conditions during the year for a daylighting system dependent on direct sunlight. Locations far north and south are also examples of this with dark winters and light summers.

Among the cities listed by Duffie and Beckman is also Nice in southern France with an average sunshine share of 61 % out of what is possible [Duffie and Beckman, 1991]. Even though more data would be desirable, it is clear from common knowledge and the figures presented above for Sweden, Germany and UK that clear weather and sunshine is not the normal situation in northern Europe. And even if it sometimes is sunny, the sunny periods are most often mixed up by a partly clouded sky [Littlefair, 1990]. The same goes for several other parts of the world.

## **Amount of light gained out of sunlight and daylight**

If the sky is clear and the sun is visible it is still a question of how much light is received from it. This depends on the power of the received solar radiation and on the amount of visible light in this radiation.

### **Luminous efficacy**

The amount of visible light received from the sun can be calculated using the luminous efficacy of the sunlight. According to Robbins the luminous efficacy is defined as “the quotient of the total luminous flux emitted by the total lamp power input expressed in lm per W” [Robbins, 1986]. There are several other slightly varying definitions mentioned by both Robbins and other authors. Hopkinson et al states that the luminous efficiency of radiation is “the quotient of luminous flux by the corresponding radiant flux”, while the luminous efficiency of a source is “the quotient of the total luminous flux emitted by the total power consumed” [Hopkinson et al, 1966]. Littlefair on the other hand indicates that luminous efficacy would simply be the “light-to-heat ratio” [Littlefair, 1990].

In this report it is assumed that luminous efficacy follows Hopkinson’s definition for radiation when daylight or sunlight is considered and the definition for sources when electric light sources are considered. The latter is equal to Robbins’s definition.

According to Robbins the luminous efficacy for sunlight is 92 lm/W. For a clear sky it is in average 125 lm/W, or 111 lm/W in average if both the sky and the sun are taken in account. The luminous efficacy for an overcast sky is 110 lm/W [Robbins, 1986].

Hopkinson et al explains that the luminous efficiency of sunlight varies with the solar altitude. It is almost constant at 117 lm/W for solar altitudes greater than 25°. For a solar altitude of 7.5° it is 90 lm/W. A mean value of 100 lm/W is suggested. The sky is said to have a luminous efficiency of 150 lm/W in clear weather and 125 lm/W in average [Hopkinson et al, 1966].

For comparison it can be said that an ordinary light bulb, incandescent lamp, has a luminous efficacy of 14 – 20 lm/W, a candle 0.1 lm/W and an ordinary light pipe, fluorescent lamp, 50 – 80 lm/W. Among the most efficient are high-intensity discharge (HID) lamps, e.g. metal-halide, mercury vapour and sodium pressure, with luminous efficacies up to 140 lm/W [Robbins, 1986].

## Received solar radiation

The data in the above section provides a tool for calculating how much visible light there is in a certain amount of sunlight. Now it remains to decide how much solar radiation that reaches the surface of the earth. This depends on the location on the earth, time of the year and day, climate, weather, pollutions in the atmosphere, etcetera.

The solar constant,  $H_{sc}$ , tells us how much power there is in the solar radiation just outside the earth's atmosphere, when the earth is at its mean distance from the sun. Different investigations have given slightly different values, but in this report we use  $H_{sc} = 1367 \text{ W/m}^2$  that is the value adopted by the World Radiation Center [Duffie and Beckman, 1991].

This value can be used to calculate the power (W) of solar radiation on a tracking solar collector at any location on the earth, as shown in appendix B.

Using these formulas it can be shown that on a clear day, a tracking solar collector placed in the cities Luleå, Stockholm, Copenhagen and Munich would receive solar radiation as shown in table 9. The solar radiation has been calculated for the winter solstice, vernal equinox and summer solstice.

*Table 1: Incident solar beam radiation (clear sky) on a tracking solar collector at noon for four European cities at different times of the year. Luminous efficacy is assumed to be 100 lm/W.*

City	Date [DD/MM]	Local time [HH:MM]	Latitude [°]	Received solar rad. [W/m <sup>2</sup> ]	Received light [lm/m <sup>2</sup> ]
Luleå	21/12	12:00	65,3	168	16800
Luleå	21/03	12:00	65,3	549	54900
Luleå	21/06	12:00	65,3	804	80400
Stockholm	21/12	12:00	59,2	211	21100
Stockholm	21/03	12:00	59,2	624	62400
Stockholm	21/06	12:00	59,2	831	83100
Copenhagen	21/12	12:00	55,4	294	29400
Copenhagen	21/03	12:00	55,4	661	66100
Copenhagen	21/06	12:00	55,4	845	84500
Munich	21/12	12:00	48	454	45400
Munich	21/03	12:00	48	716	71600
Munich	21/06	12:00	48	866	86600

Since 1 lm/m<sup>2</sup> equals 1 lux, and 500 lux is a common requirement for office spaces, it is clear that even in the northern Luleå there is an excess of light from the sun at noon of the year's darkest day.

The 16800 lm that can be collected per m<sup>2</sup> collector could be spread over an office area of more than 30 m<sup>2</sup> that would receive an illumination of 500 lux. There are a few catches though. This is valid only for noon, in good weather, no objects can obstruct the beams from the sun, which is at a very low altitude, and there can be no losses from the collector to the luminaire.

The values for Sweden (Luleå and Stockholm) in table 1 agree well with the values given by Harderup who gives values for global solar radiation and diffuse solar

radiation [Harderup, 1995]. In Harderup's data the receiving area is horizontal, which means that lower values will be obtained than for a tracking receiver. The difference is especially noticeable during the winter with low solar altitudes. Values for direct beam radiation can be obtained by subtracting the diffuse radiation from the global.

Harderup also gives the mean power of the incident solar radiation. The mean power of the global radiation in June is 246 and 236 W/m<sup>2</sup> for Bromma (close to Stockholm) and Luleå respectively [Harderup, 1995]. These are mean values both for the day and for the month, and they should also be adjusted since the receiver is horizontal and the diffuse component should be subtracted. Still it shows that the average solar radiation situation is far from the maximum radiation. This means that what decides how viable a daylighting system dependent on beam solar radiation would be, should be how often and for how long periods it is clear sunlight at the location in question.

# Key concepts for fiber optic daylighting systems

## Transmission via optical fiber

### Construction

Optical fiber is made out of transparent dielectric material, e.g. glass, which guides light. A cylindrical core is surrounded by, and in intimate contact with, a cladding of the same geometry. Surrounding the cladding is an overcoat for protection. Often another layer called buffer, which protects the fiber from damage, surrounds the overcoat.

Most optical fibers consist of two different types of optically conductive materials. The core that is about 85 % of the total fiber and carries the light has a (slightly) higher refractive index than the cladding. [Schott, 2002]

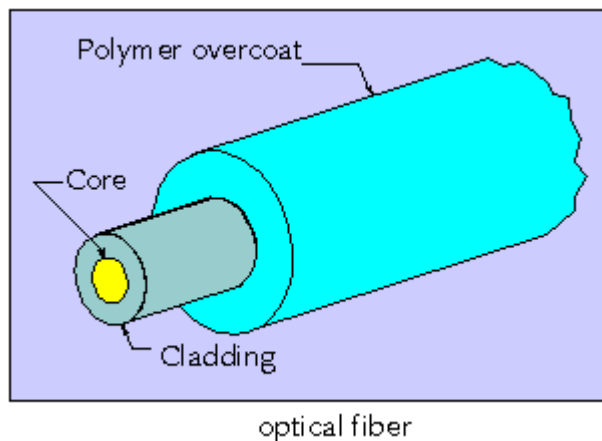


Figure 12: Construction of an optical fiber [Telecom Glossary, 1996].

### Composition

Optical fibers are commonly produced from glass, plastic or synthetic fused silica (often called silica or quartz fiber) [Fiberoptics Technology Inc., 2001]

The different kinds of fiber have different properties, giving various advantages and disadvantages. In general silica fibers are used for data communication, but glass is still the most common choice for illumination and sending applications. Plastic excels for ease of assembly in applications that do not have operating temperature above 79°C [Schott, 2002]. Solid core optical fiber is made of a combination of plastic and Teflon, and is commonly used for illumination. Poly Optics Australia uses a solid optical gel for the core (made from optical pure cast acrylic monomers, including MMA) and a cladding made of clear Teflon [Poly Optics Australia, 2000].

## Fiber factors

The optical fiber has no inherent brightness. The brightness of an optical fiber is dependent on many factors such as the amount of incoming light, colour, refraction angle, viewing angle, transmission loss, and etcetera.

One limitation to brightness is the in coupling loss from the light source to the fiber, dependent on how much visible light is delivered to a fiber within an acceptable angle.

Another limitation is the transmission loss, which is given by the light accepting and carrying capacity of the fiber itself. The transmission loss mainly depends on the refraction indexes of the materials that the fiber is made of. The physical mechanisms attenuation and dispersion also take place during the transmission.

Limitation of brightness is also dependent on the heat enduring ability of the fiber. A service temperature, which is too high, will degrade the fiber over time. Illumination design can become very complex for this reason [Advanced lighting systems, 1999].

## Light losses in a fiber

### *In coupling loss*

The sketch below shows a typical fiber. The core has a refractive index of  $N_1$  and the cladding an index of  $N_2$ . Light enters the fiber under the angle  $A$  and is transmitted through the fiber. If angle  $A$  is too large, the light will be not reflected at the interface; it will exit through the side of the fiber and not be transmitted. The angle beyond which the light cannot be carried through the fiber is called the critical angle. This can be calculated from the refraction indexes of the core and the cladding. The sine of the critical angle is the numerical aperture (N.A.). The acceptance angle of the fiber is two times the critical angle. When the acceptance angle is rotated around the axis of the fiber it forms an acceptance cone within which light will be accepted.

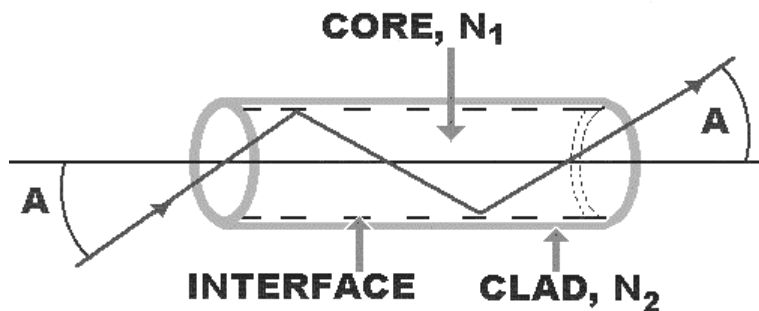


Figure 13: The critical angle ( $A$ ) of a fiber is dependent on the refractive indexes of the core ( $N_1$ ) and the cladding ( $N_2$ ) [Fiberoptics Technology Inc., 2001].

$$N.A. = \sqrt{N_1^2 - N_2^2} \quad [1]$$

Equation 1 shows the relation between the numerical aperture and the refractive indexes. The numerical aperture is an important parameter of any optical fiber; but using a low N.A.-fiber will not focus the light from a lamp. The output cone of the light will be narrow, but the acceptance cone in the other end of the fiber is equally narrow. Optical fiber tends to preserve the angle of incidence during the light

transmission and therefore angle A is shown at both the entrance and exit ends of the fiber in figure 10.

Glass fiber has a quite small acceptance angle, which is dependent on the refractive index, a material property. Compared to glass, plastic and solid core fibers have a larger acceptance angle. [Schott, 2002; Poly optics Australia, 2000]

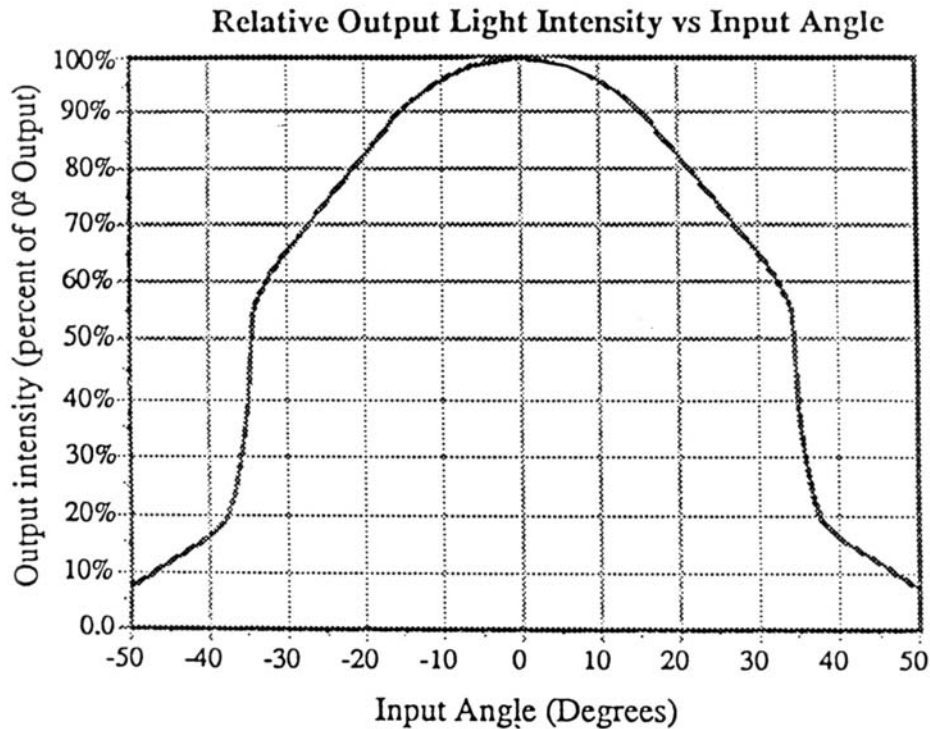


Figure 14: The relative output light intensity depending on the input angle for a fiber with an acceptance angle of  $70^\circ$ . As can be seen the optimal input angle is orthogonal with the fiber end surface [Advanced lighting systems, 1999].

#### *Transmission characteristic of a single optical fiber*

The maximum light transmission for a single fiber in general cannot be higher than 75 % because of how a fiber is constructed. Each fiber has a clad, which stands for 17 – 25 % of the whole fiber cross sectional area. This part does not carry light. The surface reflection at the ends of the fiber is approximately 4 % for glass fiber, and the attenuation in the glass fiber due to absorption and scattering is 13 – 16 % per m of light guide [Fiberoptics Technology Inc., 2001].

Because the attenuation depends on the material, plastic fibers have different numbers for absorption and scattering, but in general these are all higher than for glass fibers. This is why use of these is not recommended for longer distances than 15 m [Roblon]. Solid core optical fibers have according to Poly Optics Australia an attenuation of less than 5.3 % per m light guide; which is surprisingly low, as usually silicate fiber, and glass fiber are recommended as the fiber with the lowest attenuation.

According to Bomin Solar the attenuation is even lower for their liquid light guides, with losses between 10 and 15 % for 10 m [Colsman-Freyberger, 2002].

### *Transmission characteristics of optical fiber bundles*

The maximum transmission for a fiber bundle is lower than for a single fiber because of the space between the fibers, which are filled with epoxy. The epoxy fills 12 to 15 % of the fiber bundle area and carries no light. The maximum transmission for a fiber bundle is approximately 60 – 65 % [Fiberoptics Technology Inc., 2001].

### *Colour Shift*

For glass fibers shorter wavelengths will attenuate faster than longer wavelengths; this is due to Rayleigh scattering. Even the best glass fiber will have some colour shifting. Colour shifting represents the preferential attenuation of some wavelengths over others. Blue (short wavelength) may still appear as blue after 15.5 m, but it might begin to fade over a distance greater than 23 m, while colours with longer wavelengths will remain longer. If we transfer for example halogen light, this is a little bit blue, through a fiber, it become slightly greenish after some meters [Advanced lighting systems, 1999].

According to Roblon, plastic optical fiber and especially PMMA (Poly Methyl Methyl Acrylate), is more suited to transport shorter wavelengths. Longer wavelengths will attenuate faster than shorter wavelengths. PMMA is a light guide material with good light transmission properties, especially for white light. When using long light guides, the light turns towards the cold spectrum of the scale, green/blue [Roblon, 2001].

### *Bend Radius*

The light will travel without major losses, if the bend radius is 8 times the fiber diameter or greater. If the bend radius is less than 8 times the fiber diameter, it will result in a loss of optical properties at the bend. This is because the internal reflection will fail.

Multiple bends at a larger radius have no detrimental effects. The light will follow the fiber and propagate without losses due to the bends; the total internal reflection will be undisturbed. A very tight bend radius will cause a noticeable optical defect [Advanced lighting systems, 1999].

### *Moisture and exposure to ultraviolet light*

Fiber should never be exposed water, especially at the fiber ends. When the core absorbs water, the optical properties will change dramatically. However, the fiber end can be sealed for use in underwater applications [Roblon].

Exposure to ultraviolet rays (UV) is another problem. It is not recommended to expose fiber to ultraviolet rays; especially plastic fiber will degrade if left in direct sunlight or other UV sources. Glass fiber, if exposed to UV rays, should be enclosed in an UV stabilised material, such as an UV protected polycarbon track or a similar product with no less than 92 % UV resistance [Advanced lighting systems, 1999].

If just the fiber ends are exposed to UV-rays, a UV filter can be used, but the drawback will be a higher in coupling loss.

### *Heat Resistance*

Standard fibers from Fiberoptic Technology are designed for operation at a maximum of 177°C. Above this temperature the fiber slowly starts to soften and will fail in a relatively short time. With special manufacturing techniques, glass fibers that endure

482°C can be created. Plastic fiber optics usually has an operation temperature of 79°C [Fiberoptics Technology Inc., 2001].

Solid core fiber optics has a maximum operation temperature of 120°C [Poly Optics Australia, 2000].

### *Diameter*

According to Roblon, the light transmission capacity of the fiber is directly proportional to the diameter. The thicker the fiber, the more light it can guide [Roblon].

### **Problems with using optical fiber for daylighting systems**

The maximum light transmission for a single fiber in general cannot be higher than 75 % per metre because of how a fiber is constructed. The maximum transmission for a bundle of fibers is 60 – 65 %. The minimum loss will be 25 – 40 % per metre in general because of this [Fiberoptics Technology Inc., 2001]. However there do exist light guides with lower losses, as mentioned in the previous section about fiber characteristics.

The other basic problem for using optical fiber for lighting is the in coupling loss, which is dependent on the refraction index of the fiber material and the reflection at the ends of the fiber. This results in a loss of approximately 4 % at each end of a glass fiber [Fiberoptics Technology Inc., 2001].

Because of the different material properties, glass fibers have a better transmission in the fiber than plastic, but the acceptance angle will be very small. This means that the light has to be in coupled in a narrow angle, or major losses will occur. In coupling in a narrow angle means that the sun collector must be carefully adjusted to the sun and the fiber, which makes the system complicated.

Plastic fibers have because of the material properties a higher acceptance angle. But because of the material properties the light transmission in the fiber is subject to higher losses and subsequently the plastic fiber is ineffective for distances greater than 15 m [Roblon].

Solid core optical fiber is supposed to have a high acceptance angle and a good transmission in the fiber [Poly Optics Australia, 2000].

The main problem with using plastic fibers or solid core optical fiber for daylighting systems is the low operation temperature, which is approximately by 92.7°C for plastic fibers and 120°C for solid core fibers. For glass fiber the operation temperature is higher, about 277-400°C, but the in coupling losses will be higher than for plastic fibers or solid core fibers. [Fiberoptics Technology Inc., 2001; Poly Optics Australia, 2000]

### **Light collector**

Tracker systems exist as 1-axis or 2-axis tracker systems. The single axis tracker system follows the path of the sun during the day across the horizon, from east to west. The two axis tracking system follows the path of the sun during the day as well, and it also adjust their horizontal angle throughout the year in response to the position of the sun in the sky as it change from season to season. All two axial systems returns at night fall to the sunrise position; ready to immediately start tracking when the sun rises.

The one-axial system is not the best for a sunlight collecting system. Such a system needs a quite precise angle between the sun and the collector, to achieve the maximum efficiency for the light concentration into the fiber. Higher accuracy can be obtained with a two-axial system. The two-axial system just exists as an active solar tracking system, which means that an engine is needed to move the collecting dishes. The moving of the dishes can be controlled in different ways. One possibility is that a computer, programmed with the astronomical sun coordinates over the year for that specific location, controls the system.

The most common systems are electro-mechanical with controllers that use sensors for following the sun. The accuracy for such systems is dependent on position, quantity and accuracy of the sensors.

There are also combined systems, so the system uses the programmed astronomical data from the computer and combine them with the data from a sensor. Often those systems, which have a high accuracy, have a combination of a digital angle sensor and astronomical tracking system. [Arboiro et al, 1997].

The problem with sensor controlled systems is the climate aspect. In very cloudy weather the system may not track at all. The computer controlled system is more expensive, but giving the advantage that it also track the sun on a very cloudy day, so even very defuse light can be collected [Arboiro et al, 1997].

The self aligning system is able to observe the true sun position, looking for the maximum output of the system, and relating the observed sun position with the calculated position. At start up, the system scans around the calculated position looking for the maximum current output. This maximum current output position is compared with the calculated position, and over a least square algorithm the right parameter gets calculated. The most common problem for this system is the accuracy of the clock used as the time reference in computing the sun coordination. The drifts will have to be corrected for, to make the system efficient [Arboiro et al, 1997].

For all these different tracking systems, the accuracy is dependent on how smoothly the system can turn. That is, in how small steps it can rotate.

## **Concentration**

### *Parabolas*

The most common techniques to concentrate light are Fresnel lenses and reflecting parabolas. Parabolas have because of the shape, special reflective properties. They reflect the incoming light to one point from every point of the parabolic dish surface. From the physics it is known that if a ray hit a plane mirror, the angle of the reflection is equal to the angle of incidence. The same physical law is valid if the surface is curved.

A single ray that hit any point of a parabola is reflected as if would have hit the tangent plane of the parabola in the same point. The angle of incidence considering the tangent is equal to the angle of reflection.

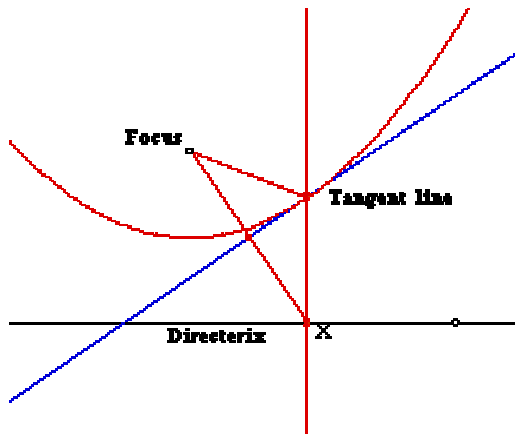


Figure 15: Tangent on a parabola [Giddings, 1996].

The sun can be assumed to be far away enough so that the sunrays hit the parabolic dish vertically.

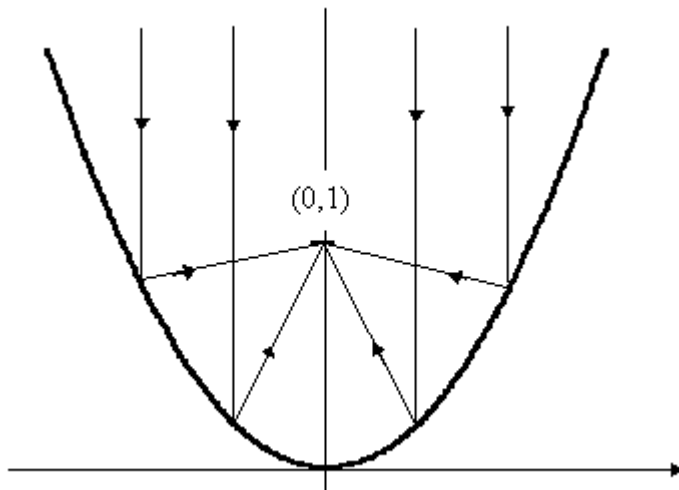


Figure 16: Rays hitting the parabolic dish vertically [Mathematic dep. Texas University, 2000].

The parabola is defined as the locus of a point that moves so that it is always at the same distance from a fixed point (the focus) and a fixed line (the directrix).

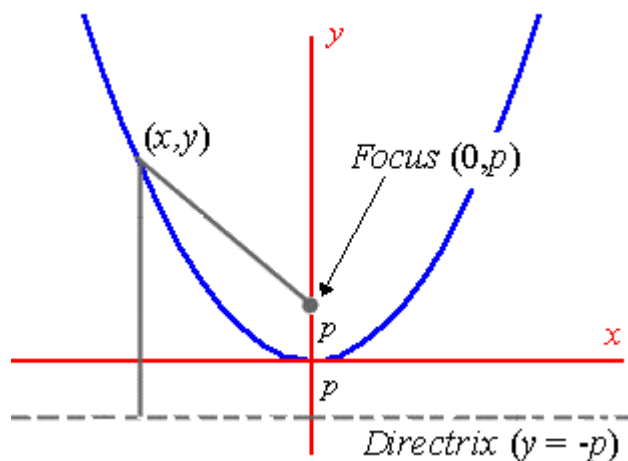


Figure 17: How a parabola is constructed with the focus and the directrix [Bourne, 2002].

The geometry of the dish gives the location of the focal point; it is independent of the radiation wavelength.

The standard form of the equation of the parabola with vertex at (0, 0) with the focus lying  $p$  units from the vertex (see Figure above) is given by:

$$x^2 = 4py, \text{ or } y = x^2/4p. \quad [2]$$

Parabolas that are used for collecting light are usually made out of fiberglass with an embedded reflective foil.

References: [Beckmann, 2000; Weston Harley, 2001; Sellers James A., 2001; Mathematic dep. Texas University, 2000].

### Lenses (converging lenses)

A lens is made of a transparent material that refracts light. The lens that is used for collecting light is a converging lens. Because of the shape, converging lenses refract the light in such way that the light will be focused in one point. Converging lenses exists in different shapes, but in general a lens that is thicker at the centre than at the edges will function as a converging lens. This type of lenses is also known as convex lenses.

The horizontal axis of a lens drawn trough the optical centre is called the principal axis. If light travels parallel to this axis trough the lens, the light will be focused behind the lens in one point, the principal focus. The distance between the principal focus point and the centre of the lens is the focal length.

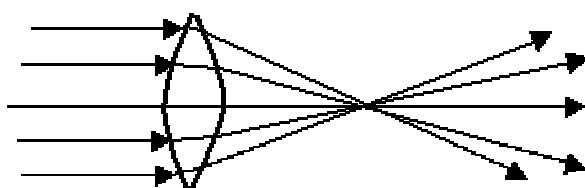
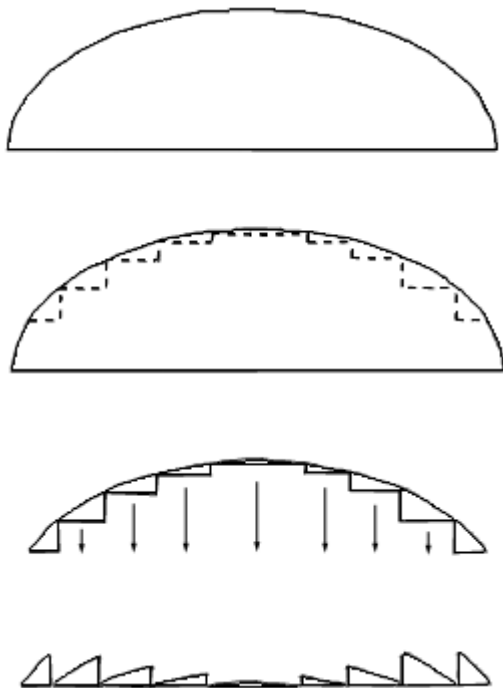


Figure 18: Converging lens with the principal focus [Colwell, 2002].

References: [Henderson Tom, 2001; Cutnell, Johanson, 1995; Saskatchewan Education, 2000; Colwell, 2002]

### **Fresnel Lenses**

The Fresnel lens was developed during the 19<sup>th</sup> century by the French physicist Augustin Fresnel (1788-1827). In that time France was looking for a way to build new lighthouses. The conventional lenses were both bulky and expensive. So in 1748 Georges de Buffon realized that you only need the surface of the lens to bend the light. He cut the inside of the lens away and left rings with edges on the outside. Fresnel adapted this idea and developed the Fresnel lens. His lenses were basically used for the lighthouses in that time. Fresnel lenses have a much lower image quality than a normal lens; but because the lens is thin, very little light is lost by absorption. That makes Fresnel lenses very efficient for light gathering applications. The big advantage is that this lens is flat and light compare to a normal lens. You can see Fresnel lenses often on the back window of vans or busses, so that the driver can have a wider view of the area behind the vehicle. They are also used in overhead projectors.



*Figure 19: A schematic cut away diagram showing how a Fresnel lens is constructed [Dep. of Physics and Astronomy, Arizona, 1999].*

References: [Nave Carl R., 2000; Dep. of Physics and Astronomy, Arizona, 1999].

### **Reflecting surfaces**

All objects around us reflect light. The reason why we can see the objects around us is that the light is diffusely reflected from them. When the surface of the objects is not smooth, diffuse reflection will occur. The reflected rays from a non-smooth surface leave the surface in multiple directions. If the surface of an object is smooth, such as glass or a mirror, the reflected rays will follow the law of reflection (angle of incidence is equal to the angle of reflection) [NASA, 2001].

If we would have a perfect mirror, the entire incident light would be reflected according to the laws of classical optics. That mean we would not have any losses trough transmission of the light or conversion of the light energy into another energy form. But as mirrors and reflecting surfaces are made out of atoms, we do not have a perfectly flat, perfectly reflecting surface. Thus, perfect reflection will not occur [NASA, 2001].

To choose the right reflecting surfaces for a collecting system a few requirements have to be considered.

First we have to consider that the choice of the material depend one which wavelength we want to have a high reflection for. Different reflecting materials have better reflecting properties for different wavelengths. For example there are materials that have good properties for x-rays and other that have better properties for UV-rays. As we want to reflect the sunlight, we need a material that has a high reflectance in the wavelength range of the solar spectrum, especially in the wavelength from the visible light (360 – 760 nm). Good reflecting materials for solar radiation are silver, aluminium and stainless steel [Nostell et al, 1998].

The reflectance can be measured in hemispherical reflectance and specular reflectance. Specular reflectance means that the light will be reflected in a narrow beam, while the hemispherical reflectance is more diffuse. For our purpose the specular reflectance is the interesting one, as we want to collect the light in one point.

Another aspect is the long-term stability. The material will be exposed to the environment: weather, dirt, pollution, and etcetera. The most reflecting materials need for this reason a protective coating. If good reflecting materials as silver or aluminium are unprotected and exposed to the outdoor conditions they will deteriorate quickly and after only two years exposure an unprotected surface is not longer acceptable [Nostell et al, 1998]. Therefore the material has to be covered with a transparent layer, e.g. lacquers or plastic, or anodising the surface. The drawback of the necessary protective coating is the decrease of the reflectance properties. Even for the coating we have to make a careful choice, it exists coatings like PVF<sub>2</sub> (Polyvinylidene fluoride) that shows good long-term stability properties, but the optical properties are not as good as for other covers. Other materials that can be used are polyvinyl florid and polymethyl methacrylate (PMMA) [Nostell et al., 1998].

Another possibility is to choose a material that is stable, but with lower optical properties, like stainless steel.

Yet another aspect is the price of the material. Considering the prices for some interesting materials it is clear that anodised aluminium have a quite low price with 50-100 SEK/m<sup>2</sup>; PVF<sub>2</sub> lacquered anodised aluminium would cost about 70-120 SEK/m<sup>2</sup>; more expensive would be vacuum evaporated aluminium foil from 3M with 100-200 SEK/m<sup>2</sup>; and the most expensive one would be stainless steel with 200 SEK/m<sup>2</sup> [Nostell et al, 1998].

All these aspects should be weighed together. A long term study by Nostell et al shows that the vacuum evaporated aluminium foil from 3M has an excellent long-term stability, and because of that it keep the quit high optical properties over years; the solar specular reflectance decrease from 85 to 81 % over 6 years. The drawback is the price.

The anodised aluminium has a quite low price, but no acceptable long term stability. The solar specular reflectance for the anodised aluminium decrease from 80 to 33 % over 7 years.

The PVF<sub>2</sub>-coated anodised aluminium shows an acceptable long-term stability and the specular component decrease during 4 years from 75 to 64 %. The cost for the PVF<sub>2</sub>-coated anodised aluminium is a bit lower than for the 3M foil.

Stainless steel does not have the optical properties as aluminium, the specular component decreased during 4 years from 51 to 42 %. But the mechanically durability make it interesting for reflectors and collectors, but the cost is too high.

The solution according to this long term study would be to use the 3M foil if a long-term stable surface of high specular reflectivity is required [Nostell et al, 1998].

## Separation

### *Selective surfaces*

If daylight is to be transmitted over fiber optics no heat is wanted. Cold mirrors are used in certain applications where the heat and the light components of the spectrum need to be separated. The cold mirror is a selective surface that reflects the visible component, while the heat portion is transmitted.

There are as well hot mirrors, designed to transmit the visible spectrum and to reflect the infrared. The basic idea about selective surfaces is that this surface reflects a certain range of wavelength and transmits a different range of wavelength. Most cold mirrors have an average transmission from 85 – 97 % from 750 nm to 2500 nm, and an average reflectance from 95 – 97 % for the wavelengths from 450 nm to 700 nm, under a certain incident angle.

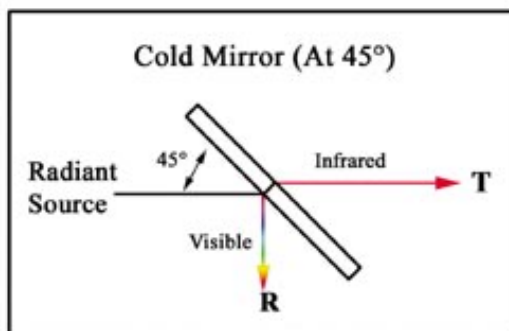


Figure 20: Cold mirror reflecting the visible light and transmitting the infrared [Kupo, 2000, 2000].

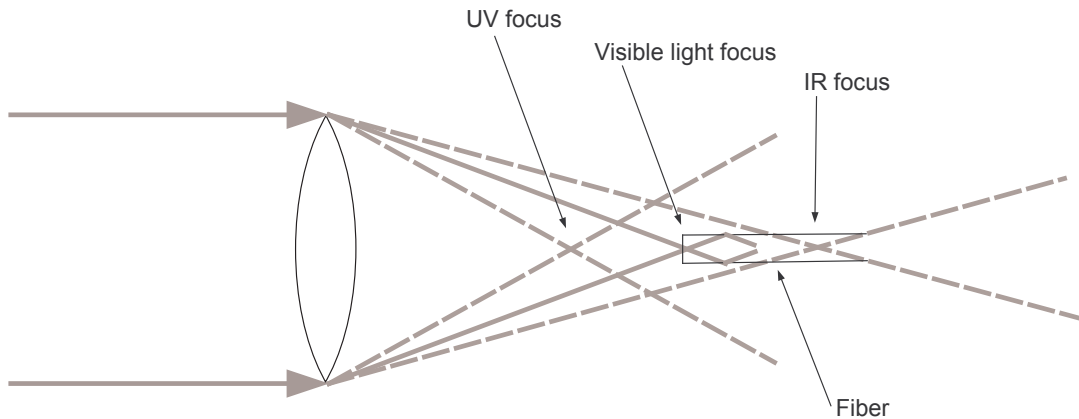
The selective surfaces can be coated so that they can be exposed to a harsh environment. The operating temperature for a selective surface is depending on the material. Borofloat glass for example can have an operating temperature of up to 450°C. Some other glass materials can have an operating temperature range from -150°C up to 300°C.

The Hybrid Lighting system use a cold mirror as a secondary mirror in the sunlight collecting system to filter most of the unwanted heat out.

References: [Edmund Industrial Optics, 2001; Optical Components, inc., 2001; Optical Coatings Japan, 2000; Denton Vacuum, 2001; Kupo, 2000, 2000].

### *Lenses*

For separation of different wavelengths the converging lens can be used. If sunlight passes through a convex lens, the focal point for the sunlight will not be exactly at one point. Different wavelengths have slightly different focal points behind the convex lens. The different focal length, give the possibility to eliminate a part of the sunlight which is unwanted. The Himawari system is using this fact for cutting out most of the ultra-violet and infrared radiation.



*Figure 21: The different focal point for different wavelength [after Laforet Engineering Co. Ltd., 2001].*

Reference: [Laforet Engineering Co. Ltd., 2001].

### *Filter*

Filter would be another possibility to separate a part of the collected sunlight. There are all kinds of filters for different wavelengths. For a daylighting system the visible part of the sunlight is the desired part, whereas infrared rays and ultraviolet rays are the unwanted rays for a daylighting system. As it is not recommended to expose fiber optics, especially plastic fiber optics to the ultraviolet rays, elimination of these rays is needed. Infrared rays give the problem of unwanted heat, as fiber optics is not very resistant to heat. For this reasons it is good to eliminate infrared and ultraviolet rays.

The IR filters are used as heat absorbing filters since they let the visible spectral range pass, while the infrared rays from 780 nm are blocked. An IR-filter block around 85 % of the infrared radiation and transmits 85 % or more of the visible light [Optical Coatings Japan, 2000].

UV filters block around 98 % of the ultraviolet rays (rays below 360 nm) and transmit about 88 % of the visible light [Kupo, 2000, 2000].

There exist as well UV/ IR filters. This multi coated interference filter blocks 98 % of the unwanted UV radiation and 85 % of the IR radiation. The transmission of the visible light is up to 90 % [Rodenstock, 2002].

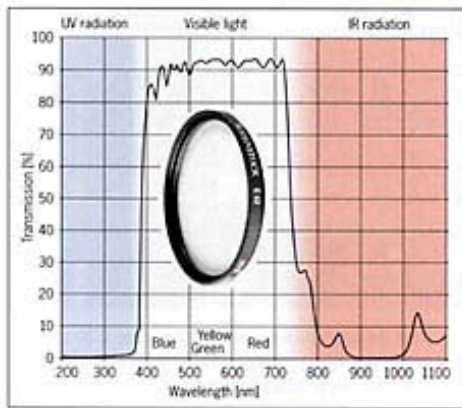


Figure 22: the transmission of a UV/IR-filter [Rodenstock, 2002].

### Controlling and mixing

For controlling and mixing daylight with artificial light, light sensors and dimmers are needed. Photosensors are most commonly used in daylighting applications to dim electric lighting when the total illuminance exceeds a specific level. Other photosensors just switch on and off the light.

A photosensor is made of a photocell and a circuit that converts the electrical current into a control signal suitable for dimming electronic ballasts. The photocell has a light responding silicon chip that converts incident radiant energy into electrical current.

A lot of photosensors include a filter to make the responses of the photocell approximate the response of the human eye.

Most photosensors work by modulating current through the input control wires of dimming ballasts. When a photosensor detects a low illuminance, the current in the control wires is limited, so the control voltage will rise to a maximum, and there will be a full light output from the controlled lamps.

The opposite will happen if the photosensor detects high illuminance, the current in the control wires will increase, causing the voltage to drop, and the lamps will be dimmed as much as the dimming ballast allows.

Photosensor control systems can be either existing in an open-loop system or in a closed-loop system. In an open-loop system, the photosensor is located on the outside of a building, for detecting the illuminance from the daylight. In a closed-loop system the photosensor detects both the electrical light in the room as well as the daylight in the space. Closed-loop systems are more common to use, as it is more precise because the actual lighting in the room is measured. To have an efficient closed loop system it is important to place the photosensor right. Most manufactures suggest placing the photosensor in the ceiling near the luminaires it controls and directly above a work surface that receives a representative amount of daylight. Some manufactures suggest that it is better to aim the photosensor towards a wall to avoid the effect of changing reflectance on the work surface and sensing direct sunlight. The California Energy Commission (CEC1993) recommends that a photosensor should be located away from the window at a distance equivalent to approximately two thirds the depth of the area controlled by the photosensor.

Reference: [National lighting product information program, 1998].

## **Light distribution**

There are a few possibilities existing for the distribution of the collected sun light. For fiber optic systems a number of different fixtures exist. There are a lot of different shapes with or without optics as well as crystal fittings or even self-designed fittings [Roblon].

Another possibility would be to distribute collected daylight with the help of light pipes, like the ones that are used in the ARTHELIO system in Berlin. They are using a plastic tube with a special 3M lighting film and white cylinders, extractors, inside the tube to spread out the light evenly [Kaase et al, 2000].

As fiber optic lighting systems usually just are controlled over the light generator, dimming and on-off switching will be not possible at all. The brightness of this lightning system will be dependent on the amount of incoming daylight. To switch a fiber optic lighting system off, the generator has to be switch off. To switch off the daylighting system the whole light collector has to be “turned off”. The other possibility would be to find a solution to cover the fiber ends when no light is wanted.

## **Cooling**

Cooling will be needed, as heat will be generated when sunlight is collected and the fibers just can work up to a certain temperature.

The Hybrid Lighting system uses some kind of cooling equipment that is based on proprietary technique. No further information has therefore been available to the authors.

The German SOLUX system has a cooling system, but also in this case further information is missing.

The Himawari system is supposed to work without a cooling system, because of two factors. One factor is that the fact that the light is concentrated by a lens, which is utilized to filter the infrared parts of the sunlight. The second factor is that this system is operated with glass fibers, which can have a quite high operation temperature.

There are probably some different ways to cool the system. It might be possible to use a liquid cooling system, and to use this heat for other applications. A ventilation system would be another possibility.

# Some suggestions for new designs of fiber optic daylighting systems

So far existing knowledge and technologies have been reviewed. Now the question remains, how can these technologies be combined and utilised in new ways to design viable, attractive and functional lighting systems? The main focus is on how optical fibers or similar light guides could be used, because they provide flexibility for piping the light.

## A few ideas

When we first started out with this thesis we started from scratch. We had little knowledge about daylighting in general and how to utilise optical fibers for daylighting in specific. Regardless of this we have sometimes found that our ideas have wandered the path of already existing concepts.

Some of our design ideas were not found elsewhere and some of them are quite similar to existing concepts that we have presented in this report. Our most feasible ideas are presented below with their advantages, drawbacks and possibilities for development.

### Array of 2-axis turning troughs

This is a system with a primary parabolic reflector and a secondary selective reflector focusing the visible light onto fiber ends. So far it is similar to the US Hybrid Lighting concept. Though the turning through system is based on troughs, linear parabolic, instead of an actual parabola.

This type of concentrating collector, though not 2-axis turning, is also common for thermal solar collectors. Except for trough it can also be called linear parabolic collector, cylindrical parabolic collector and parabolic trough [Sukhatme, 1996].

The drawbacks of this concept are mainly efficiency problems because of the design of both the single collector and the array of collectors.

#### *Adaptation to architecture and a winter climate*

There are two main ideas behind this design:

Firstly to obtain a solar collector with a lower profile than a parabola. This is to make it fit better into the architecture of a building. This is an important aspect since it has a major impact on how the system attracts architects and house owners.

Secondly, this low profile could make the system more suitable for Nordic conditions with snow packs on the roofs at wintertime. A low height of the system makes it more suitable to cover with a transparent shelter, e.g. non-reflective glass, protecting it from getting damaged by a snow cover. This could also make it possible to clean the solar collector area from snow.

A collector area without cover would be full of obstructions for workers trying to remove snow. These obstructions would also consist of sensitive equipment that easily could be damaged or become uncalibrated if hit by a shovel.

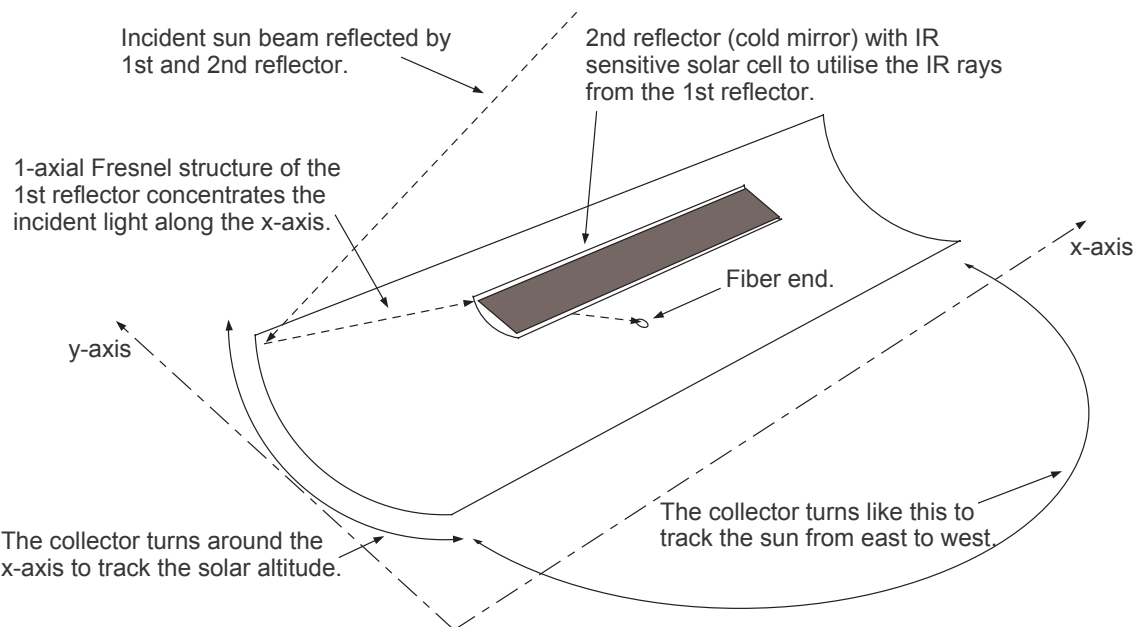
If a cover of high transmission glass or plastic were included to cover a low-profile collector, this would most probably give a higher reliability to the system. And it could

also make it possible to use the system for a longer period of the year if the snow cover is removed in the early spring. This would however introduce an extra source of light loss since some light would be lost due to reflection and transmission losses caused by the cover glass.

*Design idea for 2-axis turning troughs*

This light collecting system is meant to consist of an array of troughs mounted on a roof. The roof should have some inclination facing the south. Each of the troughs provides one light guide with light. This could be a large core fiber, a fiber bundle or something similar.

Each trough is concentrating the sunlight along two axes, vertical and horizontal. The primary mirror is parabolic in the vertical direction and by that concentrating. Horizontal it is a Fresnel mirror; it has a parabolic shape that is cut into sections in a Fresnel manner. This way it focuses the sunlight along two axes onto a secondary mirror. This reflects the light into the aperture of a fiber end, in the centre of the primary mirror.



*Figure 23: The design of a 2-axial Turning Trough.*

Since the fiber might be sensitive to infrared radiation, it would be a good idea to sort this out. This could be done in the same way as in the Hybrid Lighting-concept, with a cold mirror. To utilise the infrared radiation a photovoltaic cell sensitive to the wavelengths in question could be placed behind the secondary mirror. This might be able to power the mechanism that turns the collector.

To collect the desired amount of light an array of turning troughs is built with enough collectors. To protect the collectors the array could be covered by a low-reflective glass-cover. To calculate the number of collectors needed one have to consider the amount of light hitting each collector in the dimensioning situation. This depends primarily on the local climate, time of the year and day, and collector area. This amount must be reduced for the losses. There will be losses due to collector design,

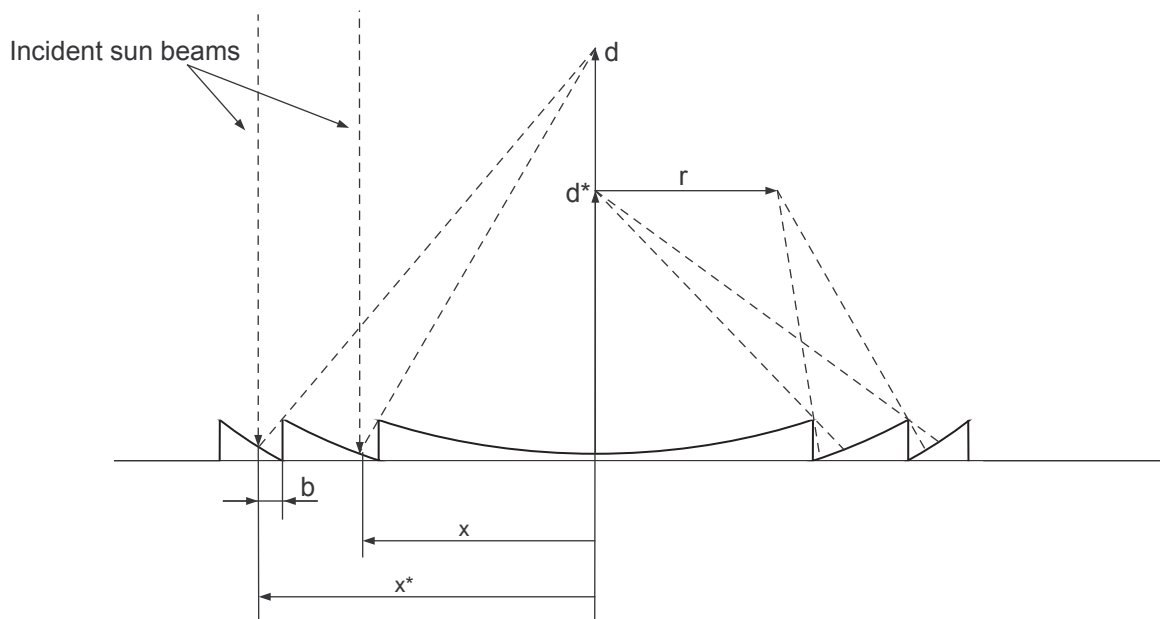
reflector materials and in the light guide. But there will also be losses depending on the design of the array.

The aspects of the array design that affects the losses are both the inclination and direction of the roof and the geometry of the array itself. The roof should be facing south and have an inclination matching the average solar altitude of the location for optimal efficiency. The array design will cause losses since the collectors can shadow each other and because the protection glass will reject a major amount of light when the sunbeams have a low incident angle.

*Drawbacks for 2-axis turning troughs*

There are a few aspects that make this concept look less viable. Most of these aspects are linked to efficiency and light losses.

There will be a light loss because of the Fresnel shaped profile along the x-axis for the primary mirror. This loss appears because the Fresnel structure for a mirror is slightly self-shading; the receiver in focus will not see all of the mirror area that faces the sun (see Figure 24).



*Figure 24: This cut view of the Fresnel shape of the primary mirror shows how some of the incident sunlight will be lost.*

Our calculations indicate that these losses could be approximately 8 % for our suggested design. The losses are dependent on the width of the reflector and the distance to the focus. The closer the focus gets to the reflector, the more area is shaded. This is the case in particular for the outermost parts of the reflector, in our case

over 23 % of the most peripheral part would be shaded from the receiver. See appendix C for calculations of losses due to the surface structure of the Fresnel mirror.

The idea of using troughs is that the required collector area could be made up by a small height and a bigger width. However this causes problems with the entrance angle for light into the fiber. The problem is that the bigger the width of the collector is, the more concentrated the light will have to be along the x-axis. This means that the entrance angle into the fiber will be quite high for light coming from the outermost parts of the primary mirror. In our calculations we have assumed that a solid core fiber with an acceptance angle of more than  $80^\circ$  is used. This is a solid angle drawing a cone within which incoming light can enter the fiber and be transmitted with total internal reflection.

If this collector design with a low height and a greater width is used, the full acceptance cone of the fiber will not be utilised.

If a glass cover is used to protect the collector array from snow, dirt, hail etcetera, this will also work as a hothouse. Even if the actual collectors would be 100 % efficient using the radiant energy of the sun, they do not cover all of the area under the cover. For example there will be space left between them so that they can move when tracking the sun. All areas not covered by the collectors are potential heat generators. All light absorbed by these surfaces will contribute to a heat build-up, which could damage the equipment (the fibers) or cause other unwanted effects. This could be dealt with in a couple of ways and the heat could also be utilised.

The unused areas could be taped with reflecting film to bounce the sunrays that otherwise would cause the heat increase. But since there are no perfect mirrors some light will not be reflected and instead cause some heat gain. This also seems like an unwise strategy since a lot of money and effort will be spent just to get rid of solar energy.

Another and probably less expensive way of avoiding heat gain would be ventilation. Especially if the collector array is placed on a roof with some inclination it could be ventilated by a natural draft driven by the heated air itself. However, this strategy would also mean that incoming solar energy is given away for free.

One way of making use of the extra area could be to cover it with some kind of thermal solar collector. Thin carpet-type collectors could be used for this. These are made of black rubber and have canals in which water can flow to absorb the heat from the sun [Nordell and Söderlund, 1998]. They should be possible to adapt to this kind of application. The produced hot water could be used for heating hot water used in the building.

### **Array of fixed south facing 1-axis turning troughs**

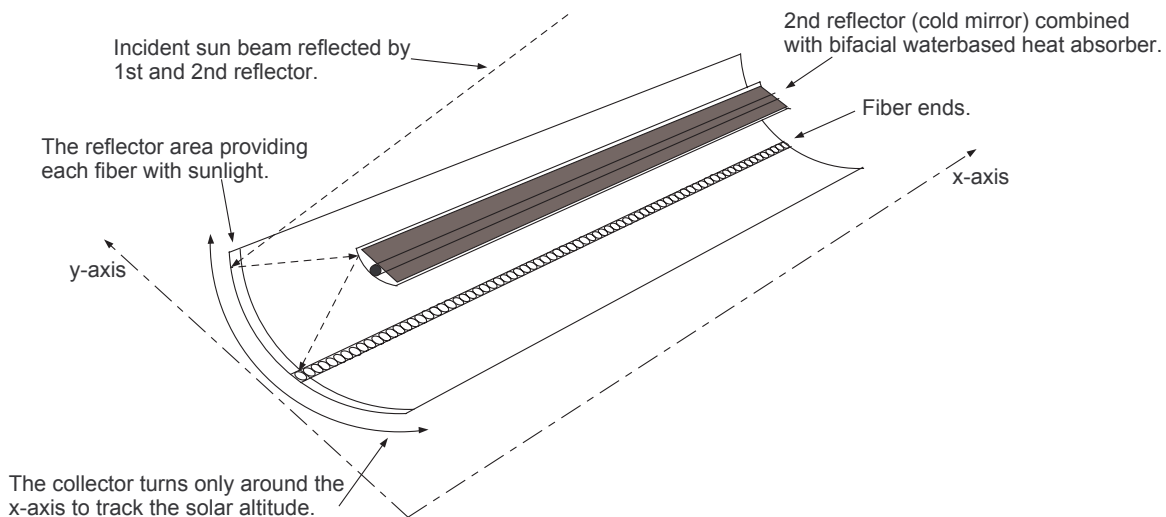
The major problem with the 2-axis turning trough strategy is all the unused space between the collectors. It is the tracking in the east-west plane that requires most of this space. So by tracking only the solar altitude, this problem would be solved. The amount of collected light per collector area should decrease because of this, but this might be outweighed by other advantages such as more collector area per roof area, less complicated and expensive system, and better possibilities to combine light collection with heat collection.

This system is heavily dependent on the orientation of the roof where it is placed. A sloped roof facing south would be the best, even though exact south is not necessarily the best. Exactly how the concentration of sunlight onto the fiber ends should be done is the most challenging problem for this concept. This should be in focus for further research on this concept. Below we present a few ideas for how this could be solved.

### *The design*

Parabolic trough collectors are placed on an inclined south-facing roof. They only follow the sun's movement depending on its altitude, not in the east-west direction. This makes it possible to pack the collectors close together. How close is dependent on the inclination of the roof, the solar altitude during the utilisation season and the risk for self-blocking of the collectors.

Unlike the 2-axis turning troughs there is no Fresnel structure along the x-axis of the collectors. The sunlight is concentrated only along the y-axis of the trough. In focus of the parabolic trough is a secondary reflector focusing the light onto a fiber at the centre of the trough (see figure 25).



*Figure 25: The design of a 1-axis Turning Trough.*

### *Getting the light into the fiber*

Since this kind of collector only is concentrating the light along the y-axis, light is projected to the centre of the trough all along its length. Therefore there must be fiber ends all along its length to collect the concentrated light.

If this design with no east-west tracking is used, the acceptance angle of the optical fiber will dictate a time window during which light can enter the fiber. When the sun follows its path over the sky during a day the hour angle changes. The hour angle is the angle between a south and the direction to the sun's east-west position. If the collector is exactly facing south, the hour angle has to be equal to or smaller than the critical angle of the optical fiber used as the light guide. The critical angle is symmetric around the meridian and creates the acceptance angle for the fiber, which is two times the critical angle.

So if a solid core optical fiber with an acceptance angle of slightly more than 80 degrees is used, e.g. Poly Optics Australia's gel fiber [Poly Optics Australia, 2000],

this means that sunbeams will be accepted for  $80^\circ$  of the sun's path. One hour equals  $15^\circ$ , which means that for somewhat more than 5 hours sunbeams will be accepted into the fibers. However, the transmittance efficiency will be lower at the end and in the beginning of this period since beams close to the acceptance angle limit are attenuated faster in the fiber.

One problem with the described system is that the light entering each fiber is only the light hitting the collector, i.e. the parabola width by the fiber diameter. This is a quite thin stripe, so unless the parabolic trough is very wide the light entering each fiber will not be concentrated enough. In the Hybrid Lighting concept approximately  $1/4 \text{ m}^2$  is providing an 18 mm large core fiber with light [Muhs, 2000]. If the cladding is neglected and 18 mm is assumed to be the core diameter the aperture area at the fiber end for the concentrated light would be  $0.00025 \text{ m}^2$ . This gives a concentration factor for the light of approximately 1000.

#### *Further concentration of the light*

For this collector design the width of the primary reflector is set to 0.35 metres. The effective width will be about 0.3 m, since the secondary reflector will block some part of the primary one. The fiber chosen is the solid core 14-mm fiber, with a core diameter of 13.2 mms, from Poly Optics Australia [Poly Optics Australia, 2000]. With these prerequisites each fiber will receive the light collected from an area of approximately  $0.004 \text{ m}^2$ . The input area for the fiber is  $0.00014 \text{ m}^2$ , so this would give a concentration factor of approximately 30. This means that the light from about 33 fibers would be needed to provide the same amount of light as a fiber from a collector with a concentration factor of 1000.

To reach such a concentration factor several fibers from the collector could be joined in a bundle. The light from this bundle could be concentrated by a Fresnel lens and put into a new fiber. This introduces at least three new sources of light loss, so the number of fibers used would have to be higher than 33. The obvious new loss source is that one extra fiber input and output is added. Also the Fresnel lens in itself will mean extra losses.

If the extra losses are assumed to be 15 % this would mean that 15 % more fibers than 33 would be needed; about 38 fibers. These fibers collect the light from half a metre length of trough collector. A bundle of 38 14-mm fibers have an approximate diameter of 0.09 m. The assumption of 15 % is based on the fact that there is a 4 % loss for every passage of the interface between air and a medium with a refractive index close to plastics'. If the fibers from the collector, the lens and the outgoing fiber were placed separately this would mean four extra passages of this type.

To keep costs for fibers down the described concentration system should be placed as close to the actual collector as possible. This is a design issue that would have to be solved in a functional way since the system will take up some space.

Another way of achieving further concentration would be to have a secondary reflector that is concentrating the light along the x-axis. But since the sun is moving from east to west this would mean that the focus point in the trough would move from west to east during the day. This could be dealt with in several ways. One idea is to have a moving fiber catching the light in the centre of the trough. This fiber could be moved so that it is always in focus and also facing the incoming radiation in the most viable way; keeping the fiber end surface orthogonal towards the rays.

Instead of moving the fiber, the secondary reflector could be flexible. One way of doing this is to have one turning secondary reflector for each fiber. These reflectors would be 0.5 m long and turn around the y-axis to face the reflected beams from the primary reflector, the trough. They would be focusing in along the x-axis and turn around the y-axis so that the fiber end is always kept in the focal point.

There are some problems with this solution; the system will be more complicated than with a fixed secondary reflector and it will also be more difficult to combine the light collection with production of hot water or electricity.

#### *Combining light collection with generation of heat or electricity*

As mentioned before there is more energy in sunlight than what can be seen as visible light. A big portion of the solar energy that hits the earth is in the infrared part of the spectrum. This is not visible and is therefore not useful for lighting, but it could be used for heating. Infrared radiation would not be transmitted by the optical fibers that we are proposing in this paper. On the contrary it could destroy them by heating them to temperatures high enough to damage them by melting.

Given that infrared rays are damaging the fibers and that this damaging energy has a potential for utilisation, it would make sense to separate the visible wavelengths from the infrared. Also the ultraviolet part of the solar radiation is damaging to the fibers and hence should be sorted out.

In the Hybrid Lighting concept the infrared part is separated from the visible light with a spectrally selective mirror; a cold mirror that reflects only visible light and transmits infrared radiation. The infrared part is used to generate electricity with a photovoltaic cell especially sensitive to these wavelengths.

The Himawari concept uses the chromatic aberration to separate the visible light. Fresnel lenses concentrate the sunlight and due to the aberration different wavelengths are focused at different distances from the lens. The fiber end is placed in focus of the visible light and this separates it from most of the ultraviolet and infrared rays.

Using a cold mirror seems to be viable for making use of both the visible light and the infrared. For the fixed south facing troughs this obviously could be done as suggested for the turning troughs and as for the Hybrid Lighting collector, placing a photovoltaic cell behind the secondary reflector that consists of a cold mirror. This would give electric energy that possible could power the operation of the collector array and more. If moving secondary reflectors are used, photovoltaic cells would be the simplest way of utilising the infrared radiation. Fixed secondary reflectors however open up the possibility of hot water production.

Long linear parabolic collectors with equally long secondary reflectors placed in focus makes it possible to combine the secondary reflectors with heat absorbing water pipes. There are plenty of examples of trough-type collectors for heating a fluid in a pipe, either for hot water production or for electricity generation [Peterson and Wettermark, 1985; Sukhatme, 1996]. One example is the MaReCo collector that is specially designed for high latitudes and heating water [Karlsson and Wilson]. In this concept the trough is not parabolic, but specially adapted and shaped for the solar altitudes on northern latitudes. The heat absorbing water pipe is bifacial and collects heat both from the reflector behind it and directly from the sun. A heat absorbing water pipe like this could be placed behind the secondary reflector in our case. It would collect direct sunlight blocked from the primary reflector by the secondary reflector

and from the primary reflector it would receive the infrared rays thanks to the cold mirror.

#### *Taking care of the ultraviolet radiation*

Although some information about cold mirrors indicates that they can transmit both ultraviolet and infrared radiation, some of the ultraviolet part might be reflected [Kupo, 2000, 2000]. If this is the case the remaining ultraviolet rays must be blocked to protect the fiber ends. This could be done with ultraviolet filters placed in the centre of the primary reflector to cover the fibers. The disadvantage of this is that the filters will also block a portion of the visible light. Kupo have UV-filters with 88 % transmission of visible light [Kupo, 2000].

#### *Concentration along the y-axis*

The light is concentrated along the y-axis by the parabolic shape of the primary reflector. The question is what shape the secondary reflector, i.e. the cold mirror, should have along the y-axis. Should it be flat, should it be concave and further concentrating or should it have yet another shape? This is totally dependent on the shape of the primary reflector and at which distance from the fiber end the secondary reflector is placed. The key is to obtain a focused light beam on the fiber with a width that matches the fiber diameter. It is also viable to have low incident angles for the light since high angles allow for greater losses at the entrance and inside the fiber.

Since a compact, low profile collector is desirable it is viable to keep the distance between the reflectors low. If the secondary reflector is placed close to the primary, the concentration factor of the latter one has to be high to keep the secondary reflector in focus. This means that the secondary reflector should be convex in order to place the focused light beam onto the fibers.

#### *Possibility to build in modules*

Fixed south facing trough collectors could easily be mounted close together. They only need space to move so that they can adjust for the solar altitude. Of course the risk that the collectors block each other should also be considered, but with a sloped roof this should be easy to avoid.

The possibility to place the collectors close together makes way for module building. It should be possible to start by put just a few collectors on the roof. A module could consist of maybe four 1 m collectors mounted side by side. These would provide four solid core fibers with light and also produce some hot water. If the owner of the building finds that it works well, the system could be upgraded by connecting more modules and place them next to the first ones.

#### *Performance for lighting*

Preliminary calculations show that the efficiency of this system would be approximately 33 % at the highest (at noon). In the beginning and the end of the utilisation period (9.30 and 14.30 each day) the efficiency would be half of that, 16 %. This is because the extra loss in the light guide for light hitting the fiber at the limit of the acceptance angle is supposed to be 50 % (see figure 11). See also appendix D.

In clear weather this would mean that for a system placed in Copenhagen a collector area of 15.1 m<sup>2</sup> would be sufficient to provide an office area of 100 m<sup>2</sup> with 500 lux illumination all year around. If the vernal and autumnal equinoxes were set as dimensioning days, it would be sufficient with a collector area of 4.9 m<sup>2</sup>.

In order to avoid that the collector troughs block each other, they need to be mounted with some spacing. If they were placed at a roof with an inclination of 45°, the required roof area for the collector areas mentioned above would be 22 and 6.9 m<sup>2</sup> respectively. The calculations are shown in appendix D.

The obtained figures can be compared with the Hybrid Lighting concept, for which 50 % efficiency has been forecasted. According to Muhs this system will collect about 100 000 lm/m<sup>2</sup> when the sun is out. Half of this will be delivered indoors so that a system with a collector of 2 m<sup>2</sup> can provide an area of slightly more than 90 m<sup>2</sup> (1000 square foot) with 100 000 lm [Muhs, 2002].

#### *Performance for heat collector*

No calculations for heat collection have been done since the main interest is the performance for lighting. According to Nordell and Söderlund concentrating solar collectors can collect between 600 and 800 kWh per year and m<sup>2</sup>. The higher the temperature of the collector, the more losses and less energy collected [Nordell and Söderlund, 1998].

According to Muhs 36 % of the available energy in sunlight exists in the infrared wavelengths [Muhs, 2000b]. Since there is a cold mirror, with 88 % transmission of IR radiation, mounted between the primary reflector and the heat absorber the energy available for heat production will be further reduced. Thus, the heat absorber might be able to deliver 32 % of 600 – 800 kWh (190 – 250) per year and m<sup>2</sup>. In this calculation the solar radiation that hits the absorber directly has not been taken into account.

#### *Benefits and drawbacks of this system*

The two obvious drawbacks with 1-axis turning troughs are that the losses are high and the limited time period under which it can be used each day.

It might be possible to achieve a higher efficiency by designing a better solution for the second concentration phase and by refining the design of the system in general.

Combining two systems facing southeast and southwest could extend the period of utilisation each day. By doing this, the total area would increase, but it should be possible to operate the system for a full working day.

The main benefits are that hot water or possibly heating could be produced, the possibility to build a more low-profile and discrete system than a parabola system and the simplicity of a 1-axis tracking system.

Since it is only tracking the solar altitude, the light losses will be limited would the tracking system be out of order for a day. With a 2-axis tracking system, the loss would be total.

It might also be possible to replace the tracking system with a small, solar cell powered, computer that keeps track of the date and knows the solar altitude for each date.

### **Central receiver with heliostat array**

This is a design inspired by solar power towers that have been tested around the world, for example Solar 1 and Solar 2 in Barstow, California [SunLab, 2000]. The idea is to have an array of heliostats – sun tracking reflectors – reflecting sun beams onto a central receiver. One heliostat could have several mirrors. For the lighting application

infrared and ultraviolet radiation should be separated from the visible at this receiver. The different fractions can be utilised as in the case with the 1-axis turning troughs.

The difference from the other proposed systems is that here one only receiver is used, which makes it possible to obtain much higher intensities. If these could be mastered that is. High intensities are demanding for the equipment; it means high temperatures and high levels of UV radiation.

This design is best suited for large applications where much light is needed. The major drawbacks are the issues of the high intensity and that each heliostat has to be individually controlled and calibrated.

### *The heliostats*

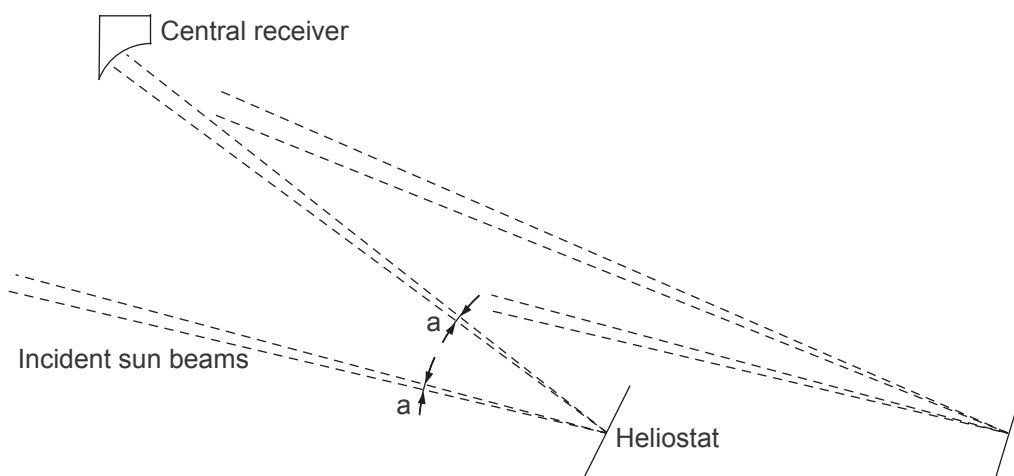
The heliostats are placed in circular arcs around a tower with the receiver in the top. For power towers the plant is built on flat ground with the heliostats forming full circles around the tower. Other solutions could be of interest for the lighting application. If a roof with an inclination towards the south is available, the heliostats could be placed in half circles around the receiver tower that would be placed at the southern edge of the roof.

If there is space available on a south facing façade the system could be turned upside down, placing the heliostats higher than the receiver. The heliostats would then be placed on the available space on the façade and focus sunlight onto a receiver placed on for example a lower roof.

The receiver should not be placed directly on the ground or otherwise easily accessible. This is because of the risk for blocking by accident and also because of the risks for humans coming in contact with high intensity radiation and high temperatures. The façade and the roof strategies, or combinations of them, could make way for utilisation of unused spaces on both existing and new buildings' exterior.

For power applications the heliostats tend to be large; the heliostats of Solar One each had an area of 39.3 m<sup>2</sup>. In lighting applications the heliostats should be smaller; an obvious reason is that it makes it easier to fit them into the design of a building. Smaller heliostats also reduce the forces affecting their fittings in strong winds. In addition to this they have benefits for the actual light collection.

Each heliostat projects an image of the sun onto the receiver.



*Figure 26: Each heliostat projects an image of the sun onto the receiver.*

The size of this image is dependent on the distance between heliostat and receiver, size and shape of the mirrors used for the heliostats. This is important because the size of the receiver has to match the size of the image projected by the heliostats. The longer the distance and the bigger the mirror, the bigger the image on the receiver will be [Sukhatme, 1996; Peterson and Wettermark, 1985]. The size of the image is given by

$$L_i = D(\theta_s + \theta_e) + W \quad [3]$$

where  $D$  is the distance between the heliostat and receiver,  $\theta_s$  is the angle subtended by the sun (approximately  $0.5^\circ$  on earth),  $\theta_e$  is the total angular error for the reflection due to factors like mirror surface imperfections and mirror orientation and  $W$  is the span of the mirrors. If the heliostat mirrors are suitably dished, the size of them will not matter, so in that case  $W$  can be ignored.

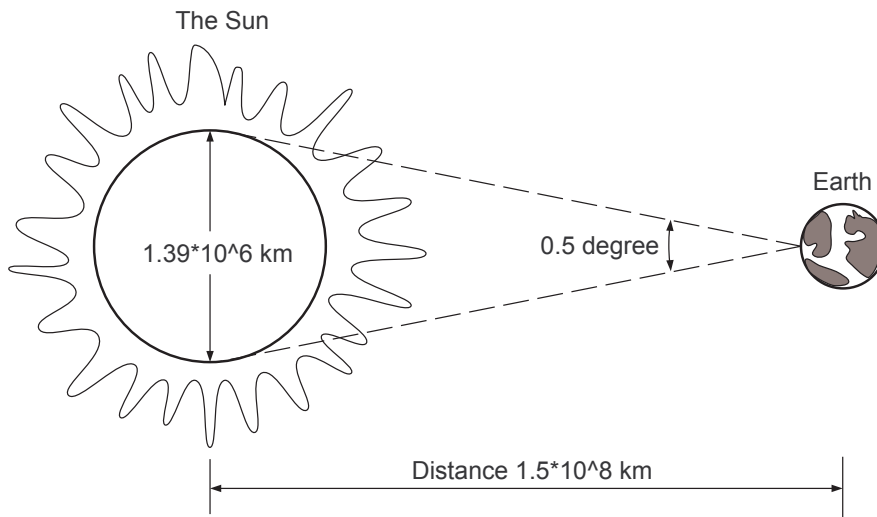


Figure 27: The angle subtended by the sun.

If the mirrors of the heliostats are dished and any angular errors are ignored they can be placed at a distance of about 115 m from the receiver before the sun image reaches a span of 1 m. It is viable to achieve a small image, since this makes it easier to design the receiver optics that will focus the light onto the fiber ends.

The heliostats could either be just one sun-tracking mirror or they could be a composition of several mirrors. Since small heliostats were beneficial for the lighting application, it is probable that they could be designed with only one mirror. To reduce the size of the image they should be dish shaped. The exact shape needed to make it possible to ignore the mirror size (when considering the size of the sun image on the receiver) is dependent on the distance to the receiver. It should be equal to the focal distance. To reduce manufacturing costs it might be a good idea to manufacture the mirrors in one shape or a couple of different shapes for some common distance ranges.

One technique that has been suggested for manufacturing light weight heliostat mirrors is to stretch a reflective membrane over a metal ring. The reflector in this case is a silvered polymer film laminated to a thin metal foil. The foil is stretched over the

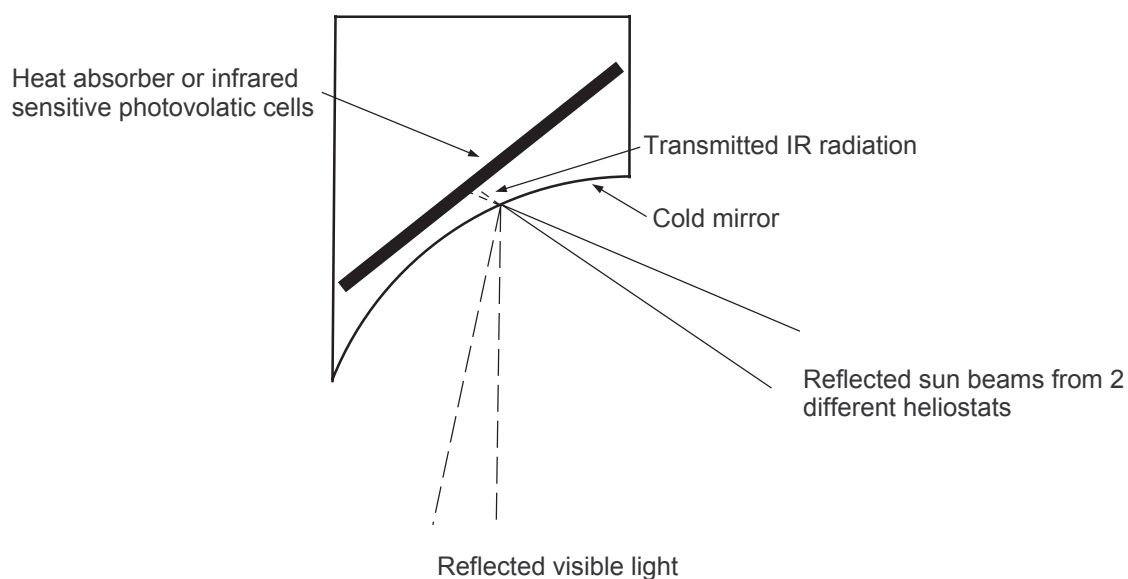
metal ring. The reflectivity of this mirror has been measured to be 0.92 [Sukhatme, 1996]. When discussing reflectivity, the effect of dirt accumulation should always be kept in mind. For the Solar One plant the average reflectivity of the heliostats were reduced from 0.903 to 0.82 by exposure to the environment.

### *The receiver*

Comparing central receiver systems for power applications and for lighting applications show that the big difference is in the receiver. Where the power receiver only has to accept and keep the incident radiant energy, the lighting receiver has to focus it into small fiber ends. This demands high accuracy and a design that can reflect the incoming light in a certain direction. The problem is the latter part since the light from the heliostats comes from multiple directions.

To separate the infrared radiation from the visible light in the receiver the concentrated sunlight from the heliostats should first fall onto a selective cold or hot mirror in the receiver. A cold mirror has the best properties for achieving high levels of visible light; its light reflection is higher than the light transmission of a hot mirror [Kupo, 2000; Abrisa].

The cold mirror should be shaped so that it focuses the reflected light onto the fiber ends in a bundle with fibers. However, a single point on the cold mirror can only have one inclination; one tangential plane. Therefore incident light beams with different directions (from different heliostats) will be reflected in different directions if they hit the same spot of the mirror.



*Figure 28: Cut view of the receiver.*

So ideally each point of the mirror should only be hit by rays from one single heliostat. Unless there is a single receiver mirror for each heliostat this is not possible, since each heliostat will project an image, with a certain size, of the sun onto the receiver mirror. In the ideal case the light from each heliostat should be concentrated onto one point of the receiver mirror.

Clearly this shows that a central receiver mirror could not concentrate all light from a heliostat array onto a single spot. Incident light from different heliostats will be

reflected in different directions. However, it might be possible to achieve some kind of resemblance of collimated light rays. With the right shape, size and adaptation to the heliostat array of the receiver mirror it should be possible to provide outgoing rays more parallel than the incoming. Though, probably some light will be lost due to dispersion.

#### *Getting the light into the fibers*

Naturally more light will be lost due to dispersion if the receiving fiber ends are placed at a distance from the mirror rather than quite close. On the other hand light losses in the fiber due to attenuation are much higher than light losses in free air. This means that it might be viable to place the fiber entrances away from the actual receiver with the cold mirror, if the length of light transmission, and thereby the losses, could be kept down by this.

Wherever the fiber ends are placed they should be mounted tightly together in a bundle. Any space between them is area receiving light that will be wasted. That applies also to the space made up by the cladding and other non-transmitting parts of the fibers. To get rid of these losses the fiber ends could be modified to fit more closely together. Each fiber end could be polished to form a hexagonal column. When these columns are joined together a compact fiberoptic bundle is obtained without any dead space. This has been tried with glass fibers [Liang et al, 1998] and it is not known to the authors of this report how and if it would work with plastic fibers and solid core fibers.

If the fibers are of plastic or solid core type, some kind of protection against ultraviolet rays will be needed. This could be in the form of a UV filter placed in front of the fiber ends. This would mean that an extra source of light loss is introduced.

#### *In both new and existing buildings*

The strategy of this design idea makes it tempting to utilise existing structures in buildings. A chimney for example could be the tower for the central receiver. Unutilised roof or wall areas could host heliostats. The fact that the collected light undergoes several reflections makes it possible to adapt the system to the building in question and to locate the actual collector and the fiber ends separate from each other. This gives some degree of freedom to the designer.

If a new building is to be designed with this kind of lighting system, the aspect of locating the different parts of the system could be considered in the planning phase. This could make way for smart ways of utilising the building structure to support the central receiver lighting system.

In already existing buildings it should be possible to utilise unused spaces of the exteriors to host the daylighting system. As mentioned before a chimney could be used as the site of the receiver and also other unused areas could be utilised.

#### *Performance*

Performance calculations for this type of system are complicated due to the amount of complex components (heliostat array, focusing receiver, and etcetera). Because of this no calculations have been done, though, Sukhatme describes a calculation method for central receiver systems intended for power production [Sukhatme, 1996].

### *Benefits and drawbacks of this system*

The positive and the negative with this system is that it is highly adaptable to the individual building. The location of the heliostats, the receiver and the entrance to the fibers is flexible and could be decided considering the structure of the building in question. However, this demands much work and calculations for each building where this system is going to be used. Possibly it will also demand specially designed parts for every new site. Specially adapted shaped cold mirror in the receiver to match custom made heliostats placed in a unique array. Having some different standard versions of each part that in combinations will cover most situations might control this costly fact.

The other big question for this system is if will cope with the high concentration levels. Is it possible to design this system so that the cold mirror and the fibers can endure the highly concentrated light and still be functional to provide lighting?

### **Array of small parabolas**

This system would in most aspects be very similar to the system suggested by the Hybrid Lighting partnership. The main difference is that the small parabolas suggested here provide only one light guide with light, instead of eight. This makes it possible to design smaller parabolas with a lower profile. These could be placed in arrays that would be served by one solar tracker, minimizing the cost for trackers.

One disadvantage with this concept is that every single fiber will require engines to turn the parabola around two axes. In the Hybrid Lighting concept eight fibers requires two engines, so the engine density will be eight times higher for an array of small parabolas. Possibly this could be avoided if a number of parabolas could be linked together and rely on only one engine. This could work for turning the parabolas in east-west direction, but for turning them to adjust for the solar altitude seems complicated to do like that.

Another thing to consider when designing this kind of system is the risk that parabolas will block each other. If the roof has a favourable inclination and orientation (south), blocking should be easy to avoid for the mid part of the day. In the morning and late afternoon however, blocking is probably hard to avoid if the parabolas are not placed very sparse.

# Discussion

## The central ideas for daylighting with fiber optics

When developing a system for fiber optic daylighting there are many design strategies that can be in conflict with each other; passive or active, basic or advanced, small or large, etcetera. One fact that speaks for small and basic, and perhaps also for passive, solutions is that other new alternative energy technologies have had an important starting help from enthusiasts and interested house-owners. For the development of wind power, solar power and for solar heating the existence of enthusiastic hobby builders have probably had great importance.

The fact that there are people willing to build and install their own system on their house increases the consciousness, the knowledge and the popularity of the technology. This opens up the market and makes it easier to sell such systems and to develop new and better ones.

These theories speak for the suggested system with one-axis turning troughs. This is the least advanced of the suggested concepts, the troughs are possible to install as modules and it is a system that does not demand major changes in the building's exterior. Of course there is a lot of development that could be done to make the system suit the enthusiastic house-owner, but it might be a good base to start with. Regardless of this, it seems to be good idea to develop some kind of system that appeals to the enthusiasts. More advanced systems in a larger scale can be developed to suit other applications such as commercial buildings, factories, etcetera.

Regardless of the size of an installation, a system lacking moving parts and advanced equipment for tracking the sun would most probably be the most cost effective and easiest to maintain. It should also be less prone to wear out or suffer from malfunctions that put it out of work. When the authors of this report were visiting the German Museum of Technology in Berlin, the only functioning daylighting system out of four was the passive one.

The authors of this report spent a lot of time pondering the possibilities to design a passive daylighting system that would transmit the collected light with optical fibers. For this kind of strategy the crux will always be how to get the collected light into the fiber. It is certainly possible to design a passive light collector that will collect sunlight or daylight and possibly also concentrate it. The problem is that the collected light should for all hours be directed to a very specific point, the entrance to the optical fiber. This can, as far as we know, hardly be done without using some moving parts in the collector. But still it remains worth considering if a solution could be found.

In general it seems like a viable design concept should be simple and include as few elements as possible. Every extra optical element means extra losses and every extra moving part most likely means that system will be harder to maintain and more sensitive.

## The varying weather decides the daylighting design

It is not so much the amount of available daylight as it is the infrequency of it that decides how a daylighting system should be designed. If all daylight hitting the

facades and roofs of our buildings could be utilised for lighting, electrical lighting would soon become merely a backup system for daylighting. It is not lack of light that makes daylighting systems difficult to design; it is the fact that daylight is partly diffuse, variable (both over seconds and over the year), unpredictable and have a strong direct moving light source (the sun).

These properties should be considered and utilised to design the ideal daylighting system.

## **Lighting control and illumination thermostats**

A key issue for fiber optic daylighting is how to combine daylighting with artificial lighting. It is clear that artificial lighting will be needed to cover for cloudy days, the dark winter season and during the night.

With fast reacting light sensors and electronic dimming ballasts electric lamps can compensate for the lower daylight level when a cloud passes the sun. This kind of control strategy can also manage different lighting situations for different parts of a room. The space can be divided into different control zones with independent sensors and luminaires.

An ideal system would manage to evaluate the current lighting situation composed of daylight through windows and such, daylight through light guides and electric light. With the data from this ongoing evaluation it would smoothly adjust the electric light output so that the room receives the illumination level desired by the inhabitants. Possibly some smooth fluctuations could be allowed to support the windows ability to give a feeling for the time of the day and the weather situation. This will be a contact link to the outside.

The inhabitants could decide the illumination level and degree of fluctuations by an “illumination thermostat”, a control system similar to today’s thermostats for heating. Possibly also other light properties such as for example colour could be controlled by this system.

## **Alternative light sources**

This is an issue that was among the objectives of this project, but has not been included in the studies. Instead of the sun or an electric lamp some other light source, e.g. a gas flame, could be used.

This might be a viable solution for lighting systems at remote locations where there is no electric grid. A central gas burner could be installed and the light from its flame could be concentrated into optical light guides. The IR portion could be utilised for producing hot water or electricity by IR sensitive photovoltaic cells. The light guides would transmit the produced light to the desired spots to provide illumination for work, reading, and etcetera.

One question that arises is if this in any way would be a better solution than having small gas fired lamps at each lighting spot and a battery charged by wind power or solar cells for the electricity that is needed.

## Future work

As mentioned before in this report, the main issue for designing a fiber optic daylighting system is how to get the light into the fiber. The main objective for future work should be because of this development of efficient light collector designs and doing accurate calculations of their performance. An efficient, reliable and preferably cheap light collector is the base for any further development of a functioning fiber optic daylighting system.

A vital issue when designing light collectors is the amount of available daylight. Since it seems to be most viable to collect direct sunlight only for fiber optic systems it is important to have data for sun hours at the location of interest. Maybe a location with weather and climate typical for some interesting locations should be studied. How many sun hours are there per year, how often and in which ways does the weather situation change, what is the intensity of the sun light, etcetera.

This leads to another major issue; how should periods of insufficient sunlight be dealt with? These can be long and predictable periods like the winter in northern latitudes or during nighttime. Or it can be periods that are short and unpredictable like during a day with overcast or just a cloud shading the sun for a few seconds.

A system that cannot provide sufficient illumination continuously will hardly be considered for installation anywhere, which means that this issue must be solved in some way. A fiber optic daylighting system cannot work alone; there must be some kind of backup or combination with another light source. Because of this it should be an objective of future research to come up with light sources that can be used in combination with fiber optic daylighting systems and efficient ways of combining these daylight and artificial light.

This study is mostly dealing with generic concepts and ideas. Therefore it would be interesting to further investigate especially some of the vital topics. Examples of such topics would be:

- A detailed study of the available daylight and its regularity at a chosen location.
- Developing the design of one of the suggested systems in this report, e.g. the 1-axis turning trough, and doing a detailed calculation of its efficiency.
- Doing an economical evaluation of this system.

Hopefully we will see some development in the area of daylighting, active and passive, that increases both the use of it and awareness of it for people in common.



# References

## *Books*

- Cutnell and Johnson (1995) *Physics* (3<sup>rd</sup> ed.). New York: John Wiley & Sons, Inc. ISBN:0-471- 59773-2.
- Gordon G. et al. (1957) *Interior Lighting for designers* (3<sup>rd</sup> ed.). New York: John Wiley & Sons, Inc. ISBN: 0-471-50970-1.
- Duffie, J.A. and Beckman, W.A. (1991). *Solar engineering of thermal processes* (2<sup>nd</sup> ed.). New York: John Wiley & Sons, Inc. ISBN: 0-471-51065-4.
- Harderup, Eva (1995). *Klimatdata för fuktberäkningar*. Lund: University of Lund. ISBN: 91-88722-03-1. (Swedish).
- Hopkinson, R.G., Petherbridge, P. and Longmore, J. (1966). *Daylighting*. London: Heinemann.
- Nordell, B. and Söderlund, M. (1998). *Solvärme och värmelagring* (2<sup>nd</sup> ed.). Luleå: Luleå university of technology. (Swedish)
- Peterson, F. and Wettermark, G. (1985). *Solenergi: teori, forskning & praktisk användbarhet*. Stockholm: Ingenjörsläroverket AB. ISBN: 91-7284-206-7. (Swedish)
- Pritchard, D.C. (1995). *Lighting*. (5<sup>th</sup> ed.). Harlow: Longman scientific & technical. ISBN: 0-582-23422-0.
- Robbins, C.L. (1986). *Daylighting: design and analysis*. New York: Van Nostrand Reinhold, cop. ISBN: 0-442-27949-3.
- Sukhatme, S.P. (1996). *Solar energy: principles of thermal collection and storage*. (2<sup>nd</sup> ed.) New Delhi: Tata McGraw-Hill Publishing Company Limited. ISBN: 0-07-462453-9
- Tregenza, P. and Loe, D. (1998). *The design of lighting*. London: E & FN Spon. ISBN: 0-419-20440-7.

## *Reports*

- Heschong Mahone Groupe(1999) *Daylighting in schools*. Fair Oaks: Heschong Mahone Groupe. Condensed Report

Karlsson, Björn (Vattenfall Utveckling AB) and Wilson, Gunnar (Finsun Energy AB). *Mareco design for horizontal, vertical or tilted installation.*

Nicklas, M.H. and Bailey G.B. (1997). *Analysis of the performance of Students in daylight Schools.* Analysis Report.

Nicklas, M.H. and Bailey G.B (1997). *Energy performance of daylight schools in North Carolina.* Condensed Report

Sze-Hui Au, Leony (1999). *Innovative Daylighting Systems.* Cardiff University : Honours Thesis

#### *Conference articles*

Earl, D.D. and Muhs, J.D. (2001). Preliminary results on luminaire design for hybrid solar lighting systems. *Solar Energy: The Power to Choose.* Washington, DC, USA.

Muhs, Jeff. (2000a). Design and analysis of hybrid solar lighting and full-spectrum solar energy systems. *SOLAR2000 Conference.* Madison, Wisconsin, USA.

Plympton P. et al. (2000) Daylighting in Schools: Improving Student Performance and health at a Price Schools Can Afford. *SOLAR2000 Conference.* Madison, Wisconsin, USA.

#### *Articles*

Abul-Jabbar N. Khalifa et al. (1998). Effect of two-axis sun tracking on the performance of compound parabolic concentrators. *Energy Convers. Mgmt.* Vol. 39 No 10. pages 1073-1079. Great Britain: Elsevier Science.Ltd.

Arboiro J.C. and Sala G. (1997). ‘Self-learning Tracking’: a New Control Strategy for PV Concentrators. *Prog. Photovolt. Res. Appl.* Vol. 5 pages 213-226.

Kaase H. et al. (2000). Arthelio, ein Grossforschungsprojekt der Technischen Universität Berlin. *Licht* 3/2000. pages 326-331 (German)

Lam J.C. and Li D.H.W. (1998) An analysis of Daylithing and Solar heat for coolingdominated office buildings. *Solar Energy.* Vol. 65 No. 4. pages 251-262. Great Britain: Elsevier Sci. Ltd.

Liang, Dawei et al. (1998). Fiber-optic solar energy transmission and concentration. *Solar Energy Materials & Solar Cells.* Vol 54. Pages 323-331. North-Holland: Elsevier Science. ISSN: 0927-0248.

- Littlefair (1990). Innovative daylighting: Review of systems and evaluation methods. *Lighting Research and Technology*. Vol 22. n 1. pages 1-17. London: Hodder Arnold. ISSN:1365-7828
- Maruyama, T. and Osako, S. (1999). Wedge-shaped light concentrator using total internal reflection. *Solar Energy Materials & Solar Cells*. Vol 57. Iss 1. pages 75-83. North-Holland: Elsevier Science. ISSN: 0927-0248.
- Müller T. et al. (2000). Arthelio, kombinierte Einspeisung von Tageslicht und Kunstlicht in Hohlleiterbeleuchtungssysteme. *Licht* 11-12/2000. pages 1216-1219.
- National Lighting Product Information Program. (1998). Photosensors. *Specifier Reports*. Vol. 6. Nr. 1. Rensselaer Polytechnic Institute
- Nostell P. et al. (1998). Ageing of solar booster reflector materials. *Solar Energy Materials and Solar Cells*. Vol. 54 pages 235-246. Amsterdam: Elsevier Sci. B.V.
- Ogbonna, J.C. et al. (1999). An integrated solar and artificial light system for internal illumination of photobioreactors. *Journal of Biotechnology*. Vol 70. n 1. pages 289-297. Amsterdam: Elsevier Sci B.V. ISSN: 0168-1656.
- William-Olsson, Margareta. (2002). Solbrist kan orsaka benbrott. *Göteborgs-Posten*. 2002-05-15.
- Promotional material, catalogues and similar*
- Arbetskyddsstyrelsen. (1979). *Belysning och belysningsplanering*. Solna: Arbetskyddsstyrelsen. (Swedish)
- Ljuskultur. (1990). *Belysning inomhus – Riktlinjer och rekommendationer 1990*. Stockholm: Ljuskultur. (Swedish)
- Flux. (2001). *Produkt Lista 2001 Fiberoptik* (sic!). Stockholm: Flux AB. (Swedish)
- Philips. (1998) *Fiber Optic lighting systems*. Philips
- Roblon. *Fiber optics guide*. Roblon Fiber Optics
- Schott. *Green light for long lightguides*. Schott Glas Fiber optic Division Mainz
- SunLab. (2000). *Solar Two demonstrates clean power for the future*. Washington: U.S. Department of Energy. Also at URL: <http://www.energylan.sandia.gov/sunlab/files/stfuture.pdf>. (2002-04-28).

## Webpages

- 3M (2002). Indoor Application Examples. 3M. URL:  
<http://www.3m.com/about3m/technologies/lightfiber/jhtml/indoor.jhtml>. (2002-03-20)
- Acept W<sup>3</sup>-Group. (1999). Light and optics. *Patterns in Nature*. URL:  
<http://accept.la.asu.edu/PiN/rdg/color/color.shtml>. (2002-03-26).
- Abrisa. Abrisa USPG Optical coatings. *Abrisa USPG Glass & Coatings Worldwide*. URL: <http://www.abrisa.com/coat.asp>. (2002-04-28).
- Advanced lighting systems(1999). Technical Solid Core Information. Advancedlighting URL:  
<http://www.advancedlighting.com/Technical%20%20Solid%20Core%20Information.htm>. (2001-10-15)
- Beckmann (2000) Parabolic Reflecting Antennas. Gran Valley Stats University. URL:  
<http://www2.gvsu.edu/~w8gvu/geo/geo.html>. (2002-04-11)
- Belcher M.C. and Helms R.N (1999).Lighting- the electronic Textbook Table of Contents. University of Kansas URL: <http://www.arce.ku.edu/book/contents.htm> (2002-03-20)
- Bourne M. (2002). interactive mathematic. URL:  
<http://www.np.edu.sg/~bms/index.htm> (2002-04-12)
- Colwell (2002) Converging Lenses. Physics online LAB. URL:  
<http://online.cctt.org/physicslab/content/Phy1/lessonnotes/converginglenses/converginglenses.asp>. (2002-04-16)
- Denton Vacuum (2001) Hot/ Cold Mirrors. Denton Vacuum. URL:  
<http://www.dentonvacuum.com/coatings/mirrors.html>. (2002-05-01)
- Department of Physics and Astronomy, Arizona. (1999). Fresnel Lenses. Patterns in nature State University. URL:  
<http://accept.la.asu.edu/PiN/rdg/fresnel/fresnel.shtml>. (2002-04-16)
- Dordai, Philippe C, NCARB. (2000). Integrated Solutions for Daylighting. Lightforum. URL:  
<http://archlighting.com/library/design/daylighting/integratedsolution.html>. (2001-12-05)
- Edmund Industrial Optics (2001). Cold Mirrors. Edmund Optics URL:  
<http://www.edmundoptics.com/IOD/DisplayProduct.cfm?Productid=1900>. (2002-05-01)

- Energy Efficiency and Renewable Energy Clearinghouse. (1996). Daylighting for Commercial and Industrial Buildings. *Lightforum.com*. URL: <http://www.lightforum.com/design/daylight4.html>. (2002-03-25).
- Fiberoptics Technology Incorporated. (2001). Optical fiber principles. Fiberoptics technology incorporated URL: <http://www.fti.thomasregister.com/olc/fti/fiber1.htm>. (2001-11-15)
- Giddings J.M. (1996). Triangles and Parabolas. University of Georgia. URL: <http://jwilson.coe.uga.edu/EMT669/Student.Folders/Giddings.Jemma/Parabolas/Parabolas.html>. (2002-05-10)
- Heliobus AG. (2001). We bring daylight into the darkness!. URL: <http://www.heliobus.com/E/index.htm>. (2002-03-25).
- Henderson Tom (2001). The Anatomy of a Lens. The Physics Classroom. URL: <http://www.glenbrook.k12.il.us/gbssci/phys/Class/refrn/u1415a.html>. (2002-04-12)
- Kupo. (2000). URL: <http://www.dichroic.com.tw/>. (2002-04-28).
- Laforet Engineering Co. Ltd. (2001). A new way to make sunlight available to living things – Himawari. URL: [http://www.himawari-net.co.jp/e\\_page-index01.html](http://www.himawari-net.co.jp/e_page-index01.html). (2002-02-27).
- Lechner, N.M. (1987a). Introduction to daylighting: Part I. *Lightforum.com*. URL: <http://www.lightforum.com/design/daylighting/introday1.html>. (2002-04-27).
- Lechner, N.M. (1987b). Introduction to daylighting: Part II. *Lightforum.com*. URL: <http://www.lightforum.com/design/ALM017.html>. (2002-03-25).
- Lechner, N.M. (1987c). Introduction to daylighting: Glazing. *Lightforum.com*. URL: <http://www.lightforum.com/library/design/daylighting/glazing.html>. (2002-02-22).
- Lechner, N.M. (1987d). Introduction to daylighting: Toplighting. *Lightforum.com*. URL: <http://www.lightforum.com/library/design/daylighting/toplighting.html>. (2002-02-22).
- Lumenyte International Corporation. (2002). Lumenyte International Corporation. URL: <http://www.lmyte.com/default.htm>. (2002-03-25)
- Mathematics department at Texas A&M University(2000). Using Reflection to Discover Parabolas. Texas A&M University URL:

- [http://www.math.tamu.edu/~jmorgan/Right\\_Angle\\_Nov\\_95/Parabola.htm](http://www.math.tamu.edu/~jmorgan/Right_Angle_Nov_95/Parabola.htm).  
(2002-04-11)
- Mills Evan. (2000). Windows as Luminaires. Lightforum. URL:  
<http://www.archlighting.com/library/design/daylighting/windowluminaires.html>.  
(2001-12-05)
- Muhs, Jeff. (2000b). Hybrid solar lighting doubles the efficiency and affordability of solar energy in commercial buildings. *CADDET Energy Efficiency*. URL:  
[http://www.caddet-ee.org/nl\\_pdf/004\\_02.pdf](http://www.caddet-ee.org/nl_pdf/004_02.pdf). (2002-03-25).
- NASA. (2001). Reflections In The Mirror. National Aeronautics and Space Administration. URL: [http://nasaexplores.com/lessons/02-012/k-4\\_2.pdf](http://nasaexplores.com/lessons/02-012/k-4_2.pdf). (2002-04-16)
- Nave Carl R. (2000). Fresnel Lens. HyperPhysics. URL: <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/fresnellens.html>. (2002-04-17)
- Oak Ridge National Laboratory. (2001). Hybrid lighting research and development program. URL: <http://www.ornl.gov/hybridlighting/>. (2002-02-27)
- Optical Coatings Japan (2000) Mirrors. Optical Coatings Japan. URL:  
<http://www.techmark.nl/ocj/mirrors.htm>. (2002-05-01)
- Optical Components, inc. (2001) Dielectric Reflectors, Hot & Cold Mirrors. Optical Components, inc. URL: <http://www.ocioptics.com/dielmir.html>. (2002-05-01)
- Poly Optics Australia. (2000). Poly Optic Solid Core Fibre. URL:  
[http://www.fiberopticlight.com/fiber\\_info.html](http://www.fiberopticlight.com/fiber_info.html). (2002-03-25).
- Roblon. (2001).Fiber Optics. URL: <http://www.roblon.com//fiber.htm>. (2002-03-24)
- Rodenstock. (2002). Rodenstock UV/IR- filter. Rodenstock. URL:  
<http://www.dito.se/rodenuvir.html>. (2002-05-10)
- Saskatchewan Education (2000) Optical Unit VI: Optics. Physics 20. URL:  
<http://www.sasked.gov.sk.ca/docs/physics/u6b2phy.html>. (2002-04-16)
- Schott (2002)Technical specifications. Schott-Fostec URL:  
<http://www.us.schott.com/fostec/english/products/tecnicalspecs/fibers/fibers.html>  
. (2001-10-15)
- Sellers James A. (2001) Definition. Krell Institute. URL:  
<http://www.krellinst.org/UCES/archive/resources/conics/node51.html>. (2002-04-11)

- SMHI. (2002). Solskenstid – Året. *SMHI*. URL:  
<http://www.smhi.se/sgn0102/images/p18.gif>. (2002-05-09). (Swedish).
- Smiley Fawn (2000) Durant Middel School. Lightforum. URL:  
<http://www.archlighting.com/library/design/daylighting/durantms.html>. (2002-01-17)
- Solatube. (2001). Solatube – The miracle skylight. URL:  
<http://www.solaglobal.com/home.htm>. (2002-04-28)
- Svenska Fotbollförbundet. (2002). Bra ljus krav för elitlicens. *Svenskfoboll.se*. URL:  
<http://www.svenskfotboll.se/t1.asp?p=7141&x=1&a=43222>. (2002-03-07).  
 (Swedish)
- Telecom Glossary (1996).Optical fiber. URL: [http://www.its.bldrdoc.gov/fs-1037/dir-025/\\_3720.htm](http://www.its.bldrdoc.gov/fs-1037/dir-025/_3720.htm). (2001-12-05)
- Thayer B.M (2000). A Daylit school in North Carolina. Watt Watchers of America  
 URL: <http://p2.utep.edu/Ws/resources/daylight.cfm>. (2002-03-28)
- TIR Lighting Solutions. About light guides. URL: [http://www.tirsys.com/gl-technology/b\\_tech.html](http://www.tirsys.com/gl-technology/b_tech.html). (2002-03-25).
- U.S. Department of Energy (2002) Daylighting for commercial, Institutional, and Industrial Buildings. Energy Efficiency and Renewable Energy Clearinghouse (EREC). URL:  
<http://www.eren.doe.gov/consumerinfo/refbriefs/cb4.html>. (2002-03-25)
- Weston Harley (2001) Why are satellite dishes parabolic? University of Regina. URL:  
<http://mathcentral.uregina.ca/RR/database/RR.09.95/weston1.html>. (2002-04-11)
- Whitehouse, David. (1999). Turning night into day. *BBC News*. URL:  
[http://news.bbc.co.uk/hi/english/sci/tech/newsid\\_271000/271224.stm](http://news.bbc.co.uk/hi/english/sci/tech/newsid_271000/271224.stm). (2002-05-02).
- Williams Bill (1999). A History of Light and Lighting. Bill Williams Lighting Design for Architecture and the Arts: URL:  
<http://www.escape.ca/~williams/history/hol.htm>. (2002-03-18)

### *E-mail*

Colsmann-Freyberger, Claus. BSR Solar Technologies GmbH, Lörrach, Germany.  
 (2002-02-11, 21)

Furuune, Hiroyuki. La Foret Engineering Co. Ltd, Japan. (2002-02-07,13)

Laymance, Leesa. Oak Ridge National Laboratory, USA. (2002-03-04)

Muhs, Jeff. Director. Oak Ridge National Laboratory, USA. (2002-02-25)

Rosemann, Alexander. Department of lighting technology, Berlin University of Technology, Germany. (2001-11-28, 12-06, 2002-02-25)

Signer, Rudolf. Heliobus AG, St. Gallen, Switzerland. (2002-03-09).

*Oral*

Rosemann, Alexander. Doctor of engineering. Division of lighting, Berlin university of technology. (November 2001).

Jakobiak, Roman. Architect. IBUS (Institut für Bau-, Umwelt-, und Solarforschung), Berlin. (November 2001).

## Appendix A: Lighting dimensions and units

Light is a form of electromagnetic radiation that can be detected by human senses; by the eyes. The light dimensions are related to the eye's sensation from different kinds of light.

There are also other kinds of electromagnetic radiation, such as heat radiation, x-rays and radio waves. What differs each of these and light from each other are the wavelength. Visible electromagnetic radiation, light, occupies the wavelengths 380 – 760 nm [Arbetarskyddsstyrelsen, 1979]. Though the eye's sensitivity is different to the different wavelengths within the visible area and the sensitivity also changes with the level of light.

### *Luminous flux ( $\Phi$ )*

The luminous flux is the total flow of light from a source. It is the radiated power evaluated according to the human eye's sensitivity. The unit is lumen (lm).

Normally we talk about the Wage of a lamp, whilst the real measure of light output would be in lm. The W value merely gives the total electrical input. This input is transformed to more than light, for example heat radiation. The relationship between the light output and the electrical input is defined as luminous efficacy, measured in lm/W. This can also be compared with the amount of visible light in sun- and daylight. Some examples of typical values are shown in table A1.

*Table A1: Typical values for some common lamp types compared with sun- and daylight [Tregenza and Loe, 1998; Robbins, 1986; Hopkinson et al, 1966]*

Lamp	Electrical input	Light output	Luminous efficacy
Incandescent lamp	100 W	1360 lm	13.6 lm/W
Fluorescent tube	58 W	5200 lm	90 lm/W
High-pressure sodium lamp	400 W	48 000 lm	120 lm/W
Sunlight (solar altitude: 7.5 – 25°)			90 – 117 lm/W
Daylight (overcast – very clear)			110 – 175 lm/W

### *Luminous intensity (I)*

The intensity of light, from a source or an illuminated surface, in a certain direction is defined as luminous intensity with the unit candela (cd). It can be calculated as the luminous flux in lumens divided by the angular size (solid angle) of the beam in steradians. One candela is equal to one lm per steradian.

A spotlight used in home for illuminating for example a Figure can have a luminous intensity of 3000 candela (Tregenza and Loe, 1998).

### *Illuminance (E)*

The illuminance is a measure of the amount of light falling on a surface, luminous flux density. The unit is lux (lx), equal to one lm per m<sup>2</sup>. Some typical values of illuminance are given in table A2.

Table A2: Typical values of illuminance [Tregenza and Loe, 1998].

From a candle 1 m away	1 lx
On desks in a general office	500 lx
On the ground from an overcast sky	10 000 lx
On the ground from the sun and bright sky in summer	100 000 lx

Standards for lighting are mostly given as required illuminance in lux. Some examples of Swedish standards are given in table A3.

Table A3: Some recommended and one required illuminance levels in Sweden [Ljuskultur, 1990; Svenska Fotbollförbundet, 2002].

Domestic kitchens, working area/general	500 lx/200 lx
Elementary schools, class room	300 lx
Schools, adult education, class room	500 lx
Offices, computer workplace, working area/general	750 lx/300 lx
Football fields, required in Sweden's highest league	800 lx

It should be noted that lighting standards are not only about illuminance. Other aspects such as for example glare, contrasts and reflexes are also considered.

#### Luminance (L)

The luminance states how much light a surface emits or reflects per area, in the unit candela per m<sup>2</sup> (cd/m<sup>2</sup>). This is the measure that best describes how bright we perceive a surface to be. Though the apparent brightness is also dependent on the eye's adaptation state.

Some examples of values for illuminance are given in table A4.

Table A4: Examples of illuminance [Tregenza and Loe, 1998].

White paper on an office desk	130 cd/m <sup>2</sup>
Overcast sky	3000 cd/m <sup>2</sup>
White paper in strong sunlight	25 000 cd/m <sup>2</sup>

#### Corresponding units

Table A5: Overview of light dimensions and units;  $\omega$  = solid angle,  $\varepsilon$  = solid angle of emitted beam,  $A$  = area in m<sup>2</sup>,  $P$  = electrical power in W [Ljuskultur, 1990].

Dimension	Symbol	Equation	Unit
Luminous intensity	I	$\Phi = I \cdot \omega$	candela (cd)
Luminous flux	$\Phi$		lumen (lm)
Luminance	L	$L = \frac{I_{\varepsilon}}{A \cdot \cos \varepsilon}$	candela/m <sup>2</sup> (cd/m <sup>2</sup> )
Illuminance	E	$E = \frac{\Phi}{A}$	lux (lm/m <sup>2</sup> ) (lx)
Luminous efficacy	U	$U = \frac{\Phi}{P}$	lumen per W (lm/W)

## Appendix B: Calculation of clear sky solar beam radiation

The calculations in this appendix are based on formulas and data given by Duffie and Beckman in the book Solar Engineering of Thermal Processes [Duffie and Beckman, 1991].

The solar constant,  $H_{sc}$ , is the energy radiated from the sun, per unit time, as received on a unit area of surface perpendicular to the direction of propagation of the radiation. This is a nearly fixed value, which is measured outside the earth's atmosphere at mean earth-sun distance. Different investigations have resulted in slightly differing values for the solar constant. In this report the solar constant is set to the value that has been adopted by the World Radiation Center (WRC):

$$H_{sc} = 1367 \text{ W/m}^2 \quad [\text{B1}]$$

Since the earth moves in an elliptical path around the sun, the earth-sun distance varies and so does the intensity of the extraterrestrial solar radiation. At the  $n$ th day of the year the extraterrestrial solar radiation as measured on a plane normal to the radiation is

$$H_{on} = H_{sc} \left( 1 + 0.033 \cos \frac{360n}{365} \right) \quad [\text{B2}]$$

Thus  $H_{on}$  varies in the range 1322-1412  $\text{W/m}^2$  during the year.

Dependent on the location on the earth, day of the year and time of the day, the sun's position on the sky varies. And because of that so does the intensity of the incident radiation. The zenith angle,  $\theta_z$ , is the angle between the vertical and the line to the sun; incident solar beam radiation.

$$\theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad [\text{B3}]$$

where  $\phi$  is the latitude,  $\delta$  the declination and  $\omega$  the hour angle. The declination is the angular position of the sun at solar noon with respect to the plane of the equator. It varies between  $-23.45^\circ$  and  $+23.45^\circ$ , with north as positive. For the  $n$ th day of the year it can be calculated:

$$\delta = 23.45 \sin \left( 360 \frac{284 + n}{365} \right) \quad [\text{B4}]$$

The hour angle,  $\omega$ , is the angular displacement of the sun east or west of the local meridian due to rotation of the earth. Since the earth turns  $15^\circ$  per hour the hour angle can be calculated, with afternoon positive:

$$\omega = 15(\text{solar time} - 12) \quad [\text{B5}]$$

The local solar time can be calculated, as it is dependent on the local time, the time zone's time meridian,  $\alpha_{\text{timemeridian}}$ , and the longitude,  $\alpha_{\text{location}}$ , of the location:

$$\text{Solartime} = \frac{\alpha_{\text{location}} - \alpha_{\text{timemeridian}}}{15} + \text{clocktime} \quad [\text{B6}]$$

For “clock time” this equation does not use the daylight saving time, but merely the standard time of the time zone.

Even if the sky is clear the atmosphere absorbs and scatters parts of the direct solar radiation. How much is dependent on both the zenith angle and the location on the earth. The fraction of the beam radiation that is transmitted through the atmosphere can be calculated:

$$\tau_b = a_0 + a_1 \exp\left(\frac{-k}{\cos\theta_z}\right) \quad [\text{B7}]$$

The constants  $a_0$ ,  $a_1$  and  $k$  for the standard atmosphere with 23 km visibility are found from  $a_0^*$ ,  $a_1^*$  and  $k^*$ , which are given for altitudes below 2500 m by

$$a_0^* = 0.4237 - 0.00821(6 - A)^2 \quad [\text{B8}]$$

$$a_1^* = 0.5055 + 0.00595(6.5 - A)^2 \quad [\text{B9}]$$

$$k^* = 0.2711 + 0.01858(2.5 - A)^2 \quad [\text{B10}]$$

where  $A$  is the altitude in km. To allow for change in climate, correction factors are applied to the constants  $a_0^*$ ,  $a_1^*$  and  $k^*$ . The correction factors  $r_0 = a_0/a_0^*$ ,  $r_1 = a_1/a_1^*$  and  $r_k = k/k^*$  are given in table A1.

*Table B1: Correction factors for the climate.*

Climate type	$r_0$	$r_1$	$r_k$
Tropical	0.95	0.98	1.02
Midlatitude summer	0.97	0.99	1.02
Subarctic summer (Luleå)	0.99	0.99	1.01
Midlatitude winter	1.03	1.01	1.00

Using the factors calculated above, the incident beam solar radiation on a horizontal plane for a clear sky could be calculated:

$$H_{b,c} = H_{0,n} \cdot \tau_b \cdot \cos\theta_z \quad [\text{B11}]$$

Since the light collectors investigated in this report will not be horizontal, but rather continuously tracking the sun to be normal to incoming radiation, the value calculated above needs to be adjusted. Unless the sun is in zenith, that is.

To attain the value of the solar radiation power incident on a non-horizontal solar collector  $H_{b,c}$  should be multiplied with the geometric factor,

$$R_b = \frac{\cos \theta}{\cos \theta_z} \quad [\text{B12}]$$

Where  $\theta$  is the angle between the normal of the solar collector and the incident solar beams. In the case of a tracking solar collector that is normal to the incident radiation  $\theta$  is always equal to zero. That is, the geometric factor for such a tracking solar collector is:

$$R_{\text{tracking}} = \frac{1}{\cos \theta_z} \quad [\text{B13}]$$

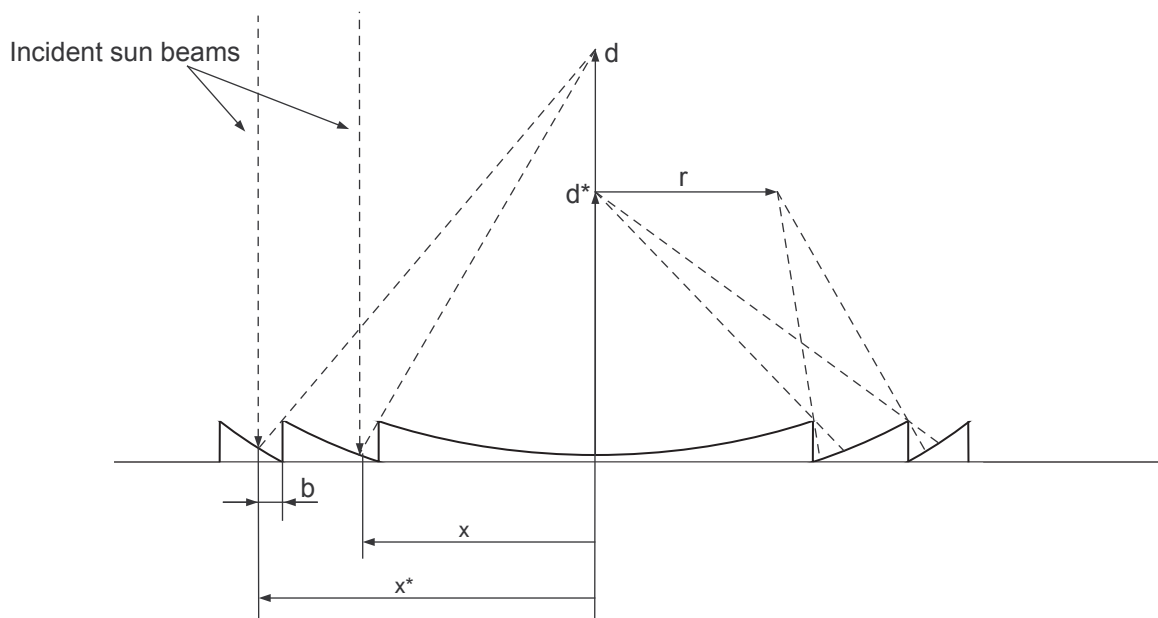
This means that the beam solar radiation power received could be calculated as:

$$H_{b,t,c} = H_{0,n} \cdot \tau_b \quad [\text{B14}]$$



## Appendix C: Rough calculation of blocking losses for a Fresnel mirror

A Fresnel mirror does not focus all of the incoming light. Some of the reflected rays will be blocked. The Fresnel structure that focuses the rays is also somewhat self-shading. Below is a picture showing how this works in principle.



*Figure C1: The principle for how the Fresnel reflector partly blocks itself. The ineffective area,  $b$ , cannot be viewed from the secondary reflector. How large this area will be is dependent on the distance between the primary and secondary reflector,  $d$  and  $d^*$ , how wide the secondary reflector is,  $r$ , and which part of the primary reflector that is considered (distance from centre,  $x$  and  $x^*$ ).*

### *Prerequisites and assumptions*

These are rough calculations that will provide an estimation of the size of the losses. The calculations are adapted to the 2-axial turning trough design. They are based on figures from the Hybrid Lighting-project, HL, [Muhs, 2000b] and Poly Optics Australia, POA, [Poly Optics Australia, 2000].

$A = 0.3 \text{ m}^2$ . The collector area needed for 1 fiber. HL uses  $0.25 \text{ m}^2$ .

$\gamma = 80^\circ$ . Maximum incident angle for beams to the fiber. POA's solid core fiber has an acceptance angle of  $85.7^\circ$  (calculated from the refractive indexes of the materials).

$l = 1 \text{ m}$ ,  $w = 0.3 \text{ m}$ . Length (x-axis) and width (y-axis) of the primary reflector (PR).

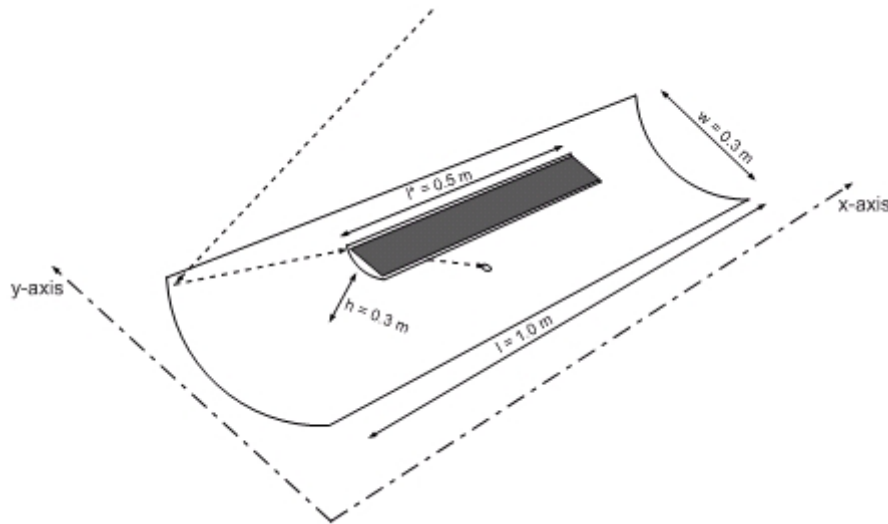
$h = 0.3 \text{ m}$ . Distance between PR and secondary reflector (SR).

$l^* = 0.5 \text{ m}$ . Length of the SR.

The SR is assumed to be non-focusing along the x-axis and specular reflecting for visible light.

Each section of the Fresnel surface is assumed to be a flat sloped surface rather than a piece of a parabolic surface.

The depth of the Fresnel structure is set to 10 mm.



*Figure C2: The design of the trough with measures used in these calculations.*

### Calculations

Below is a figure that shows the geometry for how the sun beams are concentrated.

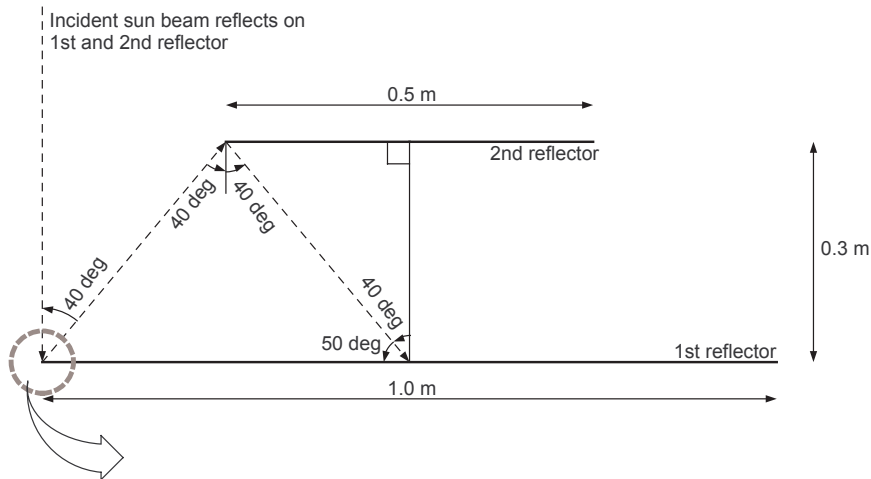


Figure C3: Sunbeams hitting the rim of the Fresnel shaped PR will be reflected under an angle of  $40^\circ$  to hit the rim of the SR. The SR reflects the beam onto the fiber end placed in the centre of the PR. The part within the dotted circle is shown in figure C4.

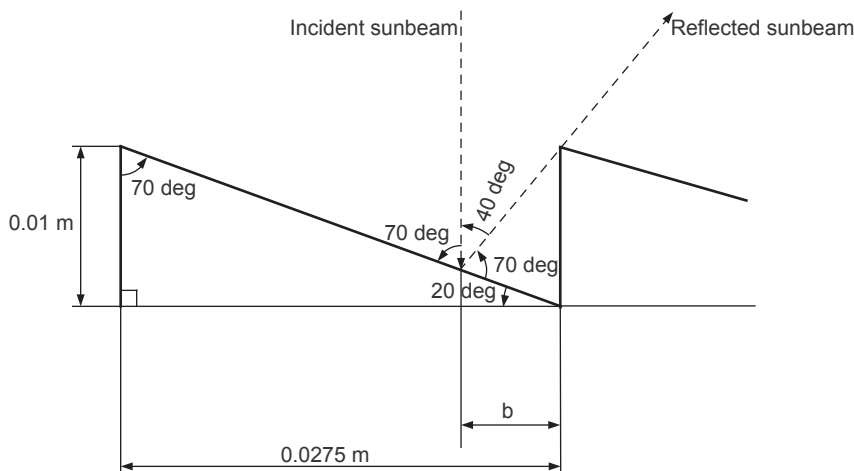


Figure C4: The parabolic sections have been approximated to straight lines with the inclination needed to give the correct reflectance angle. To achieve a reflectance angle equal to the incident angle at the PR rim, an inclination of  $20^\circ$  is required. Since the depth of the structure has been set to 0.01 m, the length of the rim section will be 0.0275 m. From this the blocked part,  $b$ , can be calculated.

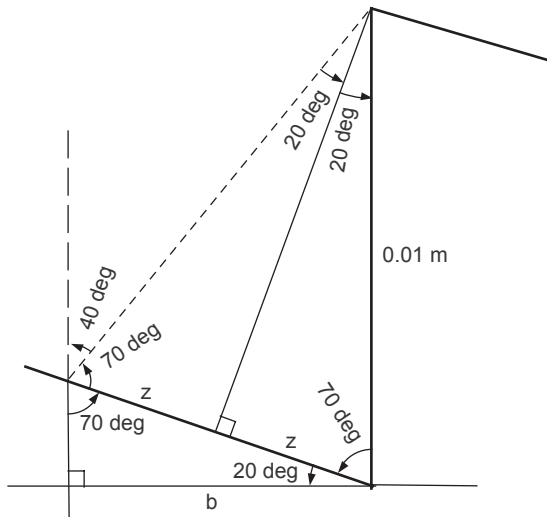


Figure C5: A close-up of the blocked part of the Fresnel section. The unknown angles are given by the geometric laws, e.g. equal triangles.

Calculation of the blocked reflector width

$$\frac{z}{0.01} = \sin 20^\circ \Rightarrow z = 0.01 \cdot \sin 20^\circ \quad [C1]$$

$$\frac{b}{2z} = \sin 70^\circ \Rightarrow b = 2z \cdot \sin 70^\circ \quad [C2]$$

$$\frac{b}{0.0275} = \frac{0.00643}{0.0275} \approx 23\% \quad [C3]$$

➔ The blocked portion of the PR rim will be about 23 %, i.e. 23 % of the reflected light will be lost due to self blocking of the Fresnel structure.

The same calculations carried out for the area right between the rim and the centre of the PR (0.25 meter from the centre) shows that there will be an 8 % loss.

Naturally the loss due to the Fresnel structure at the centre will be zero.

As a rough estimation the value for the area 0.25 m from the centre can be used. Thus, the mean loss due to the self-blocking of the Fresnel structure will be 8 %.



## Appendix D: Lighting performance for 1-axis turning troughs

Light losses in this system, as for any system, occur in several steps. Below is a list of these steps and the losses for each of them.

The prerequisites for this rough performance calculation are that an office space of 100 m<sup>2</sup> is to be provided with 500 lux illumination. The primary reflector has a width of 0.35 m and the width of the secondary is 0.05 m. A 14-mm solid core fiber from Poly Optics Australia is used. It has a core diameter of 13.2 mm and an acceptance angle of more than 85°. The attenuation is claimed to be 5.3 % per m [Poly Optics Australia, 2000].

### *1. Blocking*

The secondary reflector will block the view of the sun for the primary reflector. As a result of this only 0.30 of the primary reflector's width will be effective in collecting sunlight.

### *2. Reflection*

The collected sun beams first hit the primary collector where they are reflected. The alumina foil, from 3M with product number 5400, mentioned earlier and recommended by Nostell et al can be used as reflective material. The specular reflectivity of this is 81 % after more than six years of ageing. Before the ageing it was 85 % [Nostell et al, 1998]. In this calculation it is assumed that 81 % of the light is reflected onto the secondary reflector.

### *3. Reflection/separation*

At the secondary reflector the sunlight hits a cold mirror that transmits the infrared radiation, but reflects the visible and ultraviolet wavelengths. Here a cold mirror from Kupo is used. It has 97 % reflectivity for visible light and 88 % transmissivity for infrared [Kupo, 2000]. This might change with ageing, but since no investigations for that have been found it is assumed that 97 % of the light is reflected.

### *4. Entrance*

At the entrance to the fibers there will be losses both because of reflections at the fiber end surface and because of an ultraviolet filter that is necessary. Without the UV filter the fiber material can degrade and lose its light guiding properties. To block the ultraviolet radiation a UV filter with 88 % transmission of visible light is used [Kupo, 2000].

The light loss due to surface reflection will be about 4 % [Fiberoptics Tech. Inc., 2001]. This is a figure valid for glass fiber, which should have a higher entrance reflection since it has a higher refractive index. Therefore it should be safe to assume that 96 % of the light that hits the fiber entrance will penetrate it.

### *5. Exit*

The light needs to be further concentrated and this can be done by concentrating the light from several fibers using a Fresnel lens. This means that the light will have to exit the first fiber, be concentrated through a plastic Fresnel lens and then enter a new

fiber. The exit loss is the same as the entrance loss and occurs due to reflection; 96 % of the light will be transmitted through the end of the first fiber.

#### *6. Fresnel lens*

The lens is made of plastic. The sources of losses when using a Fresnel lens have not been thoroughly investigated, but there should be an entrance loss of 4 % and also an exit loss of 4 %. The value suggested for acrylic plastic by Rosemann [Rosemann, 2001].

#### *7. Entrance*

After the Fresnel lens the concentrated light will enter a new fiber that conduits it to the luminaire. This will cost another 4 % of the remaining light.

#### *8. Exit/luminaire*

At the exit of the final fiber yet another 4 % of the transmitted light will be lost. Losses due to the luminaire design are unknown and neglected.

#### *9. Attenuation*

There will also be losses due to attenuation along the fiber length. It is assumed that a total of 10 metres fiber will be needed. According to Poly Optics Australia the attenuation is 5.3 % per meter; 94.7 of the light will remain after 1 m of fiber [Poly Optics Australia, 2000]. This means that  $0.947^{10} = 0.58$ , or 58 %, will be remaining after 10 m.

#### *Total transmission and loss*

Multiplying the percentage of light transferred at each source of loss gives the total transmission rate of 32.7 % or a loss of 67.3 %. That is, approximately 1/3 of the light collected can be utilised for illumination.

It should be known that some aspects have been left out of the calculation and some favourable circumstances have been assumed.

Firstly it is assumed to be twelve o'clock, when the sunbeams hit the collector, and thereby the fibers, under the optimal angle. Additional losses will occur earlier and later the same day when the sun beams enter the fiber under an angle closer to the acceptance angle. When the entrance angle is just about the same as the maximal accepted angle the additional losses might be 50 % or even higher. This would lower the total transmission to about 16 %.

As mentioned above (in the section *Getting the light into the fiber*) an acceptance angle of 80° will allow for sunlight collection for 5 hours. These will be evenly distributed around noon if the collector is oriented to the south. This means that the high losses mentioned above will occur in the beginning of the operation period, about 9.30, and at the end of it, about 14.30.

One aspect that might lower the total losses is that it might be possible to design the uv-filter so it fits smoothly on the first fiber entrance. This would mean that the light enters the filter and the fiber in one step, rather than first entering the filter, then travel through air and then enter the fiber. This could lower the losses and it might also be possible to design similar solutions for other part of the system, such as the Fresnel lens.

### *How much light will be delivered?*

Based on this performance calculation and the calculations of available light (chapter Conditions for daylighting) the amount of delivered light can be calculated. It is assumed to be a clear day. The amount of delivered light and the needed collector area to illuminate 100 m<sup>2</sup> of office floor with 500 lux is presented in table D1.

*Table D1: Delivered light per collector area and needed area to supply a 100 m<sup>2</sup> office with 500 lx illumination. This means that 500 lx\*100 m<sup>2</sup> = 50 000 lm is needed. The extra loss for unfavourable incident angle at 9.30 has been estimated to be 50 %. The amount of incoming light has been calculated with the method shown in the chapter Conditions for daylighting.*

Location	Date [DD/MM]	Time [HH:MM]	Incoming light [lm/m <sup>2</sup> ]	Delivered light/m <sup>2</sup> collector [lm]	Collector area needed [m <sup>2</sup> ]
Luleå	21/03	9:30	49700	8100	6.2
Luleå	21/03	12:00	54900	18000	2.8
Copenhagen	21/03	9:30	62200	10200	4.9
Copenhagen	21/03	12:00	67300	22000	2.3
Luleå	21/06	9:30	78000	12800	3.9
Luleå	21/06	12:00	80400	26300	1.9
Copenhagen	21/06	9:30	81200	13300	3.8
Copenhagen	21/06	12:00	83800	27400	1.8
Luleå	21/12	9:30	0	0	-
Luleå	21/12	12:00	16800	5500	9.1
Copenhagen	21/12	9:30	20300	3300	15.1
Copenhagen	21/12	12:00	28800	9400	5.3

For both Luleå and Copenhagen it seems to be possible to employ this kind of system at least from the vernal equinox and presumably until the autumnal equinox. The maximum ratio between used collector area and illuminated floor space would be 6.2 % for Luleå, 9:30 at the vernal equinox.

At midwinter a system located in Copenhagen would need 15.1 m<sup>2</sup> of collector area to provide illumination for a 100 m<sup>2</sup> office, 9:30 in the morning.

### *Roof area*

In order not to shade each other the collector trough will have to be placed with a certain space in between in the north-south direction. Because of this the required roof area will be larger than the collector area.

The needed spacing between the troughs is dependent on the latitude of the location and the inclination of the roof. The optimal inclination for a solar collector in Sweden is approximately 45° from the horizontal plane [Nostell et al, 1998]. Lower latitudes need less inclination and thus installations further south in Europe will need less inclination for the collector. For any inclination, the worst case for the system will be when the sun is at the horizon. The troughs are turning and thereby face the incoming

radiation at an optimum. But if no internal shading among the troughs is accepted, this situation will need the most spacing between them.

The ratio between the collector area and the needed roof area will be same as the ratio between a rectangle's vertical side and the diagonal. Thus, the ratio will be the square root of 2, if the roof inclination is  $45^\circ$ . This means that the required roof area in this case will be about 40 % larger than the collector area. So using the values for collector area from table D1 it is possible to derive that the required roof area would be in the range of 2.5 – 22 % of the illuminated floor space.