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Review

Limitations in current day lighting related solar concentration devices: A critical review

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This study introduces the day lighting related solar concentration devices such as light pipes (or tubular daylight guidance systems), optical fibers for light transport, conventional solar concentrators and luminescent solar concentrators (LSC). The principles of study, advantages and disadvantages for application of these day lighting related devices have been explained. Daylight has a disadvantage of not being able to reach deeper areas in a building such as storerooms, basements and corridors and it also brings the heat gain with the light. Light pipes and optical fibers were expected to transfer daylight to unreached areas, but light pipes have their difficulties in wiring and the optical fiber needs a pointolite for the light transportation. Solar concentrators are only sensitive for the beam radiation and they function poorly in overcast sky conditions. Even under a clear sky condition, trackers are always needed for conventional solar concentrators. Static concentrators always come with a poor concentration rate without a tracker and the light concentrated by normal luminescent solar concentrators could not be transported by optical fibers to a remote place since the light produced by LSCs is not a pointolite. Future studies especially cross disciplinary researches on developing new solar concentration devices in mitigating those limitations as discussed in this study are highly recommended.

Key words: Day lighting related device, light pipe, optical fiber, LSC, solar concentrator.

INTRODUCTION

Besides the rapidly rising price of petroleum, anthropogenic activities, especially the burning of fossil fuels, have released pollutants into the atmosphere increasing global warming and depleting the ozone layer (Mills and Orlando, 2002) To improve the situation, there need to be a decrease in energy of which fossil fuel is used. As a result, there has been an increased interest in renewable energy systems. Solar energy is made widely available for thermal applications, day lighting and direct production of electricity (Muhs, 2000; Reisfeld and Jorgensen, 1982). Artificial lighting is one of the major sources of electrical energy costs in office buildings, both directly through lighting energy consumption and indirectly by production of significant heat gain, which increases cooling loads. Electric lighting represents up to 30% of building electricity consumption in commercial and office buildings (Crisp et al., 1998; Lam and Chan, 1995). The recent interest in energy efficiency and sustainability has led to the implementation of design strategies in buildings aiming at the achievement of the optimal utilization of daylight with minimum energy consumption for lighting and cooling (Hasdemir, 1995). Sun light as a clean energy source could contribute considerably to a solution of the energy problem if appropriate methods were developed to collect, concentrate, store and convert solar irradiation, which is diffuse and intrinsically intermittent (Reisfeld and Jorgensen, 1982). Daylight is an underused resource that has the potential to improve the quality of indoor lighting, as well as to substantially reduce energy costs.

However, daylight has a disadvantage that it may not able to reach many areas such as storerooms, basements and corridors. It also brings heat gain with the light (Bouchet and Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transport the daylight to the deeper parts in buildings. However, the light pipes have their difficulties for wiring so that daylight transportation

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through optical fibers is considered as the best approach so far (Enedir and John, 2006; Cariou et al., 1982). In building integration, one of the most important features of the remote light transportation is the wiring method and the wiring method is expected to be as simple as that of electrical wires (Enedir and John, 2006; Cariou et al., 1982; Kaino, 1992; Nihei et al., 1997). Only optical fibers are suitable for this requirement. However, the optical fiber needs a pointolite for it to transport (Cariou et al., 1982; Kaino, 1992; Nihei et al., 1997). Solar concentrators have been designed using optical approaches such as using mirrors and/or lens because of the high price for PV cells. Since they are only sensitive for the beam irradiation, they function poorly in the cloudy weather and the diffuse light conditions and a tracker is always needed (Compagnon et al., 1993; Page et al., 2003). Luminescent solar concentrators (LSC) and some static solar concentrators were then designed as the diffuse light solution and the static solution respectively (Weber and Lambe, 1976; Goetzberger and Greubel, 1977; Rapp and Boling, 1978). Static concentrators always come with a poor concentration rate without a tracker and the light concentrated by normal LSCs could not be transported by optical fibers to a remote place since the light produced by an LSC is not a pointolite (Compagnon et al., 1993; Page et al., 2003; Beckman et al., 2003; Kandilli et al., 2008). This study introduces the delighting related solar concentration devices such as light pipes (or tubular daylight guidance systems), optical fibers for light transport, conventional solar concentrators and luminescent solar concentrators (LSC). The principles of study, advantages and disadvantages for application of these day lighting related solar concentration devices are explained.

DAYLIGHT FOR ILLUMINATION

Lighting has a profound effect on the lives of people. It facilitates vision, which is the most important source of information on the world and it affects the basic biological functioning through its effect on human “body clocks” as stated by Webb (2006). Electric lighting is one of the world’s biggest end uses of electricity (Mills and Orlando, 2002). In developed nations, the electricity use for lighting ranges from 5 to 15% of total electrical energy use (Mills and Orlando, 2002). Because the energy for artificial lighting is often supplied by fossil fuel generation, it results in the large scale release of greenhouse gases (GHGs) (Mills and Orlando, 2002). Further, lighting is a major contributor to the peak demand for electrical power, which is often met by the high-GHG generators.

Sunlight is the universal and free sources of renewable energy available throughout the earth. The survival of life and health as well as the conditions of environmental comfort and prosperity are dependent on their effective utilization of sunlight (Muhs, 2000). People can benefit directly from sunlight through active or passive day lighting systems besides the electrical generation and thermal gain from the sunlight. In an energy efficient building design, it is always proper to reduce the energy consumption for artificial lighting (Muhs, 2000).

Solar energy utilization and specifically making use of the daylight in the buildings can be a very promising choice among the renewable energy options. Daylight is a kind of light source that most closely matches human visual response so that its quality is as high as to be the best for color rendering (Hasdemir, 1995). The luminous efficacy of sunlight is around 110 Lm W^{-1}, while the luminous efficacy of fluorescent lamps and incandescent lamps are around 75 Lm W and 20 Lm W^{-1}, respectively. Further, day lighting generates only 20 to 50% the heating that equivalent electric lighting does, significantly reducing the building cooling load (Hasdemir, 1995). A reduction of 65% of the total lighting energy consumption is achieved by active and passive systems that use daylight and control component (Hasdemir, 1995).

Electric lighting and daylight are compatible and complementary and should be used to bring out the best in the interior environment. Electric lighting can account for 25 to 40% of a commercial building’s energy requirements so that the combined savings from reduced lighting and cooling loads can be substantial (Franzetti et al., 2004). Franzetti et al. (2004) reports that energy saving could be as much as 52% along the window walls. The amount of daylight penetrating a building is mainly through window openings which provide the dual function not only of admitting light for indoor environment with a more attractive and pleasing atmosphere, but also allowing people to maintain visual contact with the outside world. People desire good natural lighting in their living environments (Chel et al., 2009).

Day lighting is an important issue in modern architecture because it affects the functional arrangement of spaces, visual and thermal comfort of occupants, structure and energy use in building (Chel et al., 2009). Danny et al. (2005) states that illumination levels on a bright sunlight may vary from 50,000 to 100,000 LUX. The first step of designing a building to utilize daylight for illuminating its interior is to acquire information on the amount of daylight available. However, the basic daylight luminance data are not always readily obtainable in many regions of the world (Unver et al., 2003).

Daylight has a significant positive impact on the people because it provides a sense of cheerfulness and brightness (Li and Lam, 2001). People spending the day in non-daylit buildings may therefore be in “biological darkness,” causing reduced performance (Leslie, 2003). The most powerful impact of day lighting is on the building’s occupants even though the potential for reducing energy costs and environmental emissions is substantial. However, the successful integration of such strategies requires data regarding daylight availability and illumination levels for every region in the world (Andre, 2002).

Lighting has often been the target of energy efficiency initiatives because of its high-energy burden and one of such initiative is daylight saving time. The principal reason for the application of daylight saving time was to shift human activity patterns to make better use of daylight and thus reduce the amount of electric lighting necessary to support these activities. Daylight saving time impacts the changes to traffic fatalities and the commercial activities as well (Aries and Newsham, 2008).

The energy consumption of lighting in buildings is a major contributor to carbon emissions and the heat gains produced from such lighting have an important influence upon heating and cooling loads (BRE. Energy Consumption Guide, 1997). With the aim of identifying how technological interventions might reduce emissions by 50% by the year 2030, a program is investigating the carbon emissions of UK buildings (Peacock et al., 2005). This program was based on the estimations made with respect to technological and building improvements that, although not necessarily readily available in 2005, should be obtainable within the next 21 years until 2030. Several building categories such as domestic, office and retail are being investigated. Several different types of building are defined that are indicative of that category within each category. For the buildings under investigation in this program, electrical lighting accounts for a substantial proportion of carbon emissions (Peacock et al., 2005).

The reduction of energy consumption is an important agenda in the world. There is an urgent need to search for renewable energy sources and modern technologies. A growing interest of illuminating engineers in the utilization of natural light is well recognized in last decades (Kocifaj, 2009). Paroncini et al. (2007) have summarized several reasons for preferring the natural light in designing the illumination systems, namely:

1. Solar energy is free.
2. The diffuse skylight is available for a whole day (also under overcast conditions).
3. Direct solar radiation is an extra supply, which increases the efficiency of light-guides dramatically.
4. Daylight is considered as the best source of light for good color rendering and it most closely matches human visual response.

Owing to an increasing awareness of the positive effects of daylight on the health and efficiency of humans, a wide range of day lighting systems was developed. Up to the year 2000, around 180 000 m^2 of day lighting systems were installed in Europe (Koster, 2000). Boyce (2009) claimed that the value of interior lighting means aesthetic, physiological and economic attributes. The aspect of environmental protection is always understood as a monetary term and analyzed in economics. The values of the aesthetic quality and the human well-being are difficult to quantify and they are only able to be estimated. To improve health and productivity of occupants, energy conservation and wider environmental benefits is the current interest in daylight (Boyce, 2009). The health conditions of working environments can be improved by daylight through physiological responses such as regulation of the diurnal cycle of body activity. Since up to 85% of office costs are staff salaries and in comparison energy costs are tiny, small increases in staff productivity are equivalent to large savings in energy. The visual environment has an affect on wellbeing, personal satisfaction and mood, all of which influence office productivity, but attempts to measure the relationship between productivity and lighting directly have not been successful (Boyce, 2009).

Electricity generation is one of the largest sources of carbon dioxide (CO_2), which comprises a significant amount of greenhouse gas emissions. The amount of CO_2 released into the atmosphere depends on the fuel mix used in generation (Carbon Trust, 2010). A monetary value of £0.0043 /kWh may be ascribed to this kind of pollution using the climate change levy (CCL) and the tax on energy bills (Department of Environment, Farming and Rural Affairs, UK, 2010).

The compliance to be based on a whole-building overall CO_2 emission is implemented in the UK via the energy-related parts of the Building Regulations (2010) and it is required by the European Energy Performance of Buildings Directive. Accordingly, the requirements in building codes have been shifted towards the control of CO_2 emissions (Carter, 2008). The provision of daylight within a building may influence CO_2 emissions if daylight is used as a substitute for electric light. The Building Regulations (2010) define a daylit space as being either within 6 m of a window wall, provided that the glazing area is at least 20% of the internal area of the window wall, or below roof-lights or similar provided that the glazing area is at least 10% of the floor area. No distinction is made in the regulations between roof-lights and daylight guidance. For thin roof constructions roof-lights and guides of similar aperture areas will deliver comparable amounts of light into a space, but for deeper roof constructions guides will generally have a superior performance. Smaller areas of external glazing may be needed using guides to produce a given daylight condition (Building Regulations, 2010). This may be beneficial in terms of the overall CO_2 emission (Carter, 2008).

Martin (2002) classified the conventional day lighting systems into shading systems and optical systems. Shading systems have been designed primarily to block direct sun and admit diffuse light, but may address other day lighting issues as well, such as redirection of direct or diffuse sunlight. The use of conventional shading devices to prevent overheating or glare effects also reduces the use of daylight for visual tasks indoors. Shading systems capable of redirecting diffuse light into the interior by rejecting or diffusing sunlight are developed to increase the use of daylight (Martin, 2002). Optical systems are day lighting systems without shading, they include: Diffuse light guiding systems, direct light guiding systems, scattering systems and light transport systems discussed as follows (Martin, 2002):

Diffuse light guiding systems

The overcast sky is much brighter in the zenithal area than in the horizontal part of the sky. The use of light guiding elements that redirect the light from these areas into the depth of the room allows an improved utilization of daylight. The zenith light is normally used near the window opening. Rooms are only well lit nearby the window because the high external obstructions shade the room against the diffuse skylight. This problem can be solved by diffuse light guiding elements, which include light shelf, anabolic integrated systems, anidolic ceiling, fish system and zenith light guiding elements and so on (Martin, 2002).

Direct light guiding systems

The direct light guiding systems include laser cut panel (LCP), prismatic panels, holographic optical elements in the skylight and light guiding glass and so on (Martin, 2002). When glare effects and overheating problems are avoided, rooms can be illuminated by direct sun light. Glare reduction needs the even distribution of light in the room without shadows and high contrasts in the working field. The avoidance of cooling loads can be realized by high efficient redirection and distribution of the sun light in a small part of the facade, while the rest of the facade is closed by conventional shading devices (Martin, 2002).

Scattering systems

Scattering systems include light diffusing glass, capillary glass and frosted glass and so on (Martin, 2002). Scattering systems are used to realize an even lighting distribution. They are very useful in sky light openings in top-lit rooms. Attached in vertical openings, they may produce huge glare problems. Their location has to be considered very carefully or they have to be shielded in some way to prevent glare problems. The physical and optical properties of daylight emitters are heavily influenced by the transport system to which they are connected. Carter (2004) introduced daylight emitters as combined emitters and discreet emitters. In combined emitters, light is extracted continuously along its length. On the other hand, discreet emitters operate in a manner similar to conventional luminaries. Carter (2004) further classified daylight emitters into hollow prismatic emitters, slit light guides and discrete emitters.

Hollow prismatic emitters

Light transport within hollow prismatic guides is by total internal reflection within the prismatic material (Whitehead et al., 1982). Imperfections in the prismatic structure and the presence of non-collimated light produce the emission. The loss is approximately 2% per 300 mm of pipe length and the effect is to cause the pipe to glow. A number of devices are used to control the light output from the emitter. An extractor, a strip or wedge of diffusing material may be placed inside the guide causing incident light to be scattered and escape through the walls. A reflective material may cover exterior surfaces of the guide that are not used as an emitter that redirects light inwards. Control of output along the length is achieved by varying the width and shape of the strip. Prismatic emitters have an appearance similar to large electrically powered diffusing area sources giving light with few shadows and little glare (Carter, 2004).

Slit light guides

These are tubes made of elastic polyethlemephate film, which has a high reflectance up to 95% except for a slit running the length of the tube (Carter, 2004). The high reflectance is achieved through the internal coating and the light transmission along the guide is by mirror reflection. The material is fabricated, erected *in situ* and air is pumped in under pressure to give the correct shape. However, light can be emitted through the transparent or diffusing slit (Aizenberg et al., 1975). The diameters for slit light guides range from 250 to 1200 mm and the angular size of the slit varies from 30 ton110° subtended by the axis (Aizenberg et al., 1975).

Discrete emitters

In daylight applications, many commercially available discrete emitters are incorporated at the ends of the light guides. The discrete emitters are made of opal or prismatic material of diameters corresponding to the light guides. They are generally circular flush, domed or square. For instance, a 600 mm^2 emitter that fits into suspended ceiling systems is reported (Carter, 2004). The square emitter is connected to a 500 mm mirrored pipe via a transition box and the light is distributed within the building interior by either a diffuser or an array of Fresnel lenses as shown in Figure 1 (Carter, 2004).

Light transport systems

Light transport is the feature that sets light pipes apart from other daylight redirection methods (Martin, 2002). Light transport systems such as light pipes and optical fibers allow daylight to be transported from outside by

Figure 1. Interior lit using a square lens discrete emitter (Carter, 2004: 223).

collating it and guiding it into the depth of the building. Transport elements deliver light from the collector to the point of exit and some devices have their own emitters. Daylight can be transported over long distances into floor areas or rooms without any window opening. At night time, artificial light could also be transported through this kind of systems (Hicks and Wright, 2000). By considering a major factor of the availability for low cost light redirection materials, four different transport methods, namely, beam/lens systems, hollow mirrored pipes, hollow prismatic pipes and solid core systems, are examined by Martin (2002).

Beam/lens systems

In these systems, light from the collector is collimated by a lens and transported via an arrangement of lenses and mirrors. A physical 'guide' between the lenses is not necessary optically, but may provide protection. These systems have two drawbacks that limit practical application. First, light-redirecting equipment such as lenses and mirrors tend to be more expensive than the other methods. Second, there are high levels of light loss in the optical processes. Whilst a clear lens can transmit a maximum of 92% of light, losses increase with dirt deposition on surfaces. Efficiency is also dependent on accurate alignment, so that in systems consisting of several components, losses due to misalignment become significant (Martin, 2002). The few examples of this type that have been realized are based on the study of Dugay and Edgar (1977). A building at the University of Minnesota, for example, uses heliostats on the roof to capture sunlight that is concentrated and collimated before being beamed through a vertical duct in the building containing lenses and mirrors to a working space 35 m below ground. Thirteen optical processes give a maximum system efficiency of 28% in a clean state. The main advantage of this approach is that concentrated sunlight permits the use of smaller ducts than other transport methods delivering the same light flux. However, high capital and maintenance costs combined with low efficiencies suggest that these methods would almost certainly be uneconomic compared with other transport methods (Dugay and Edgar, 1977).

Hollow mirrored guides

These use multiple specula reflections at the inner wall surface to transmit light. Overall light transmission is a function of the surface reflectance, the input angles of the incident light and the proportions of the guide in terms of the ratio of length to diameter. If the light paths are long compared with the axial width of the pipe, the number of reflections is necessarily large (Martin, 2002). Performance is particularly sensitive to reflectance of the mirror material with variations of as little as 0.1% causing noticeable changes. To attempt to minimize the number of reflections, light must enter the guide as a near collimated axial beam. Efficiency is as a function of both the ratio of effective length to diameter and the angle of incidence of the collimated incoming light. For the best case, efficiency was in excess of 50% for a length/diameter ratio of 40, corresponding to approximately 12 m of light travel in a 300 mm diameter guide, but efficiency rapidly diminishes as the alignment of incident rays and guide axis diverges. In practice, dirt and component misalignment will mean that efficiencies are likely to be somewhat lower than those in laboratory measurement are (Hicks and Wright, 2000). The recent introduction of visible mirror film, a reflecting material based on polymeric multiplayer optical stacks that has a specula reflectance of the order of 99%, in future will increase the economic light transport distance. The efficiency of a 12 m circular cross-section pipe of 300 mm diameter would rise to 70% using this material (Hicks and Wright, 2000).

Aizenberg et al. (1975) described the slit light guides, essentially a circular cross-section mirrored pipe with a transparent slit throughout its length that serves as a light emitter, in which light is totally reflected internally from a prismatic dielectric surface that traps the light and redirects it down the inside of the guide. Incident light is totally reflected internally twice at the prismatic surface, thus operating like a mirror for certain angles of incidence. Unlike a mirror, however, the prismatic structure is transparent to light at higher angles of incidence. The main lighting applications use acrylic or polycarbonate materials having a 90° prismatic ridge structure on the exterior surface. The devices redirect light down the inside of the guide when the prisms are orientated parallel to the axis provided that the incident light does not exceed 27.5° to the axis of the pipe. Overall reflectance is of the order of 98%. In theory, all light would be reflected by this process, but irregularities in the film cause a small proportion of light to exceed the maximum angle and leak out of the pipe (Aizenberg et al., 1975).

Solid core systems

The major lighting applications of solid core systems are optical fibers. These consist of two coaxial regions, an inner core that acts as the light transport medium and an outer cladding of lower refractive index that prevents leakage of from the core. The process of total internal reflection in an optical fiber is very efficient and light transport is essentially a function of length and not of diameter as in the case of mirrored or prismatic transport systems (Martin, 2002).

One of the very few examples of this technology in daylight guidance is the Himawari system (Eben, 1993). Sunlight is collected using a tracking Fresnel lens, self-powered by a solar cell, filtered and focused with a concentration of 1:10000 onto the ends of the optical fiber. A single 6 fiber 40 mm-long cable (made up of six or nine optical fibers) delivers 1180 lumens from 98000 LUX of direct sunlight over a distance up to 200 m from the collector, a distance far beyond the capabilities of the other transport methods. Notwithstanding this, these systems represent an extremely large capital investment that is unlikely to be justified for other than prestige buildings (Eben, 1993).

The huge number of different day lighting systems allows new and optimized ways of daylight utilization. But at least it has to be considered that the different systems have to be used in the right way and that the used system is adjusted to the building and matches the requirements of lighting for this special purpose. Otherwise, problems like overheating of rooms or glare may occur that would lead to refusal of the day lighting system and to stopgap solutions bringing the elements to a standstill to reduce these problems (Martin, 2002).

What makes day lighting a particularly challenging task is the permanent change of availability, brightness and angle of incidence due to weather conditions and the sun path. Other factors also play an important role, e.g. the reflectivity of nearby surfaces, the different levels of brightness due to the latitude, the different composition of direct and diffuse daylight due to air humidity and the use of different glazing (Kischkoweit, 1998). Daylight luminance ranges from 120000 Ev on a sunny day in the tropics to 5000 Ev with overcast sky in temperate climates even at high noon. The necessary average luminance level for most tasks in offices ranges from 500 Ev-2000 Ev and these levels are proposed for visually sensitive jobs such as designing. Owing to an ever-increasing amount of computer workplaces, the tolerance for higher or lower luminance, especially in office buildings, is limited. Veiling glare as well as disability glare has to be avoided (Kischkoweit, 1998).

Many options seem revolutionary: Zero-energy houses are possible even under poor climate conditions. Energy gains can be obtained with active and passive solar facades. Visual comfort can be increased significantly by daylight guidance systems. Architectural concepts might be affected, e.g. the division of windows into a fanlight, especially equipped with three-dimensional daylight guidance systems for an optimized light distribution without glare and a sun protected window at eye-level for visual contact with the outside world (Martin, 2002).

An important issue to be considered for day lighting is the user's behavior. Day lighting systems are mainly considered for office buildings. Typically, the full depth of office space is used for working. However, office staffs are generally fully concentrated on their tasks and do not find time to adjust day lighting systems regularly. Therefore, systems with a high demand of user participation may be a problem, for example, once day lighting systems are adjusted to full protection, which means fully closed, they are rarely opened again. Lighting needs are then fully covered by artificial lighting. However, automatic systems adjust venetian blinds automatically. To avoid being overdriven or turned off by the user, these systems must be highly reliable and robust (Laar and Friedrich, 2002).

Another important aspect is maintenance. Mechanical systems, especially when applied on the facade, are problematic. While everybody is used to the idea of regular car maintenance, it is not necessarily the same for buildings. The high costs caused by neglecting this item started to lead to a change in this attitude, but it still depends strongly on the individual owner. In addition, a regular cleaning of relatively unprotected systems (outside and inside the building) is necessary to maintain the full efficiency of the applied system. Therefore, systems integrated into the vertical facade, protected by glass on each side, are clearly advantageous. Furthermore, the development of the day lighting systems was generally focused on the temperate climate instead of the tropic climate (Laar and Friedrich, 2002).

Increasing the use of day lighting in buildings can offer significant savings in energy consumption as well as improving the internal environment (Martin, 2002). For example, Bouchet and Fontoynont (1996) suggested that as little as 50 LUX of daylight might provide significant relief from feelings of isolation for people working in underground spaces. However, there can be problems with glare and potential thermal discomfort due to direct solar gain with some day lighting systems. Natural light could be transported by light pipes and optical fibers in a building with little thermal effect (Bouchet and Fontoynont, 1996).

LIGHT PIPES FOR DAYLIGHT TRANSPORTATION

Daylight guidance redirects natural light into buildings areas that cannot be lit by conventional glazing. The most commercially successful type is light pipes, also called tubular daylight guidance systems, which comprise a clear polycarbonate domed light collector that accepts sunlight and skylight from the whole sky, a light transport tube lined with highly reflective silvered or prismatic material and a diffuser commonly made of opal or prismatic material light to distribute light in an interior (Carter, 2004). The usage of cylindrical tubes for light guiding becomes one of very attractive approaches for delivery the natural light into the interior spaces (Al-Marwaee and Carter, 2006). New technologies support production of light tubes with satisfactory high reflectance of inner surfaces (Elmaualim et al., 1999). This minimizes energy losses during guiding the light.

The development of efficient reflective and refractive optical materials made possible the first light pipes in Australia and the US some two decades ago. The systems were initially aimed at the domestic building market and subsequently at that for commercial buildings. More recently, light pipes were introduced into the European market where they have been the subject of heavy marketing based around manufacturers' claims of user appreciation of the delivered daylight and of potential energy savings (Carter, 2004). As illustrated in Figure 2, light pipe systems have three components, namely: (1) An outside collector (usually on the roof), generally a clear dome that removes UV radiation and acts as a cap to prevent dust and water from entering the pipe; (2) The light pipe itself; (3) An emitter or luminaries that releases the light into the interior (Oakley et al., 2000).

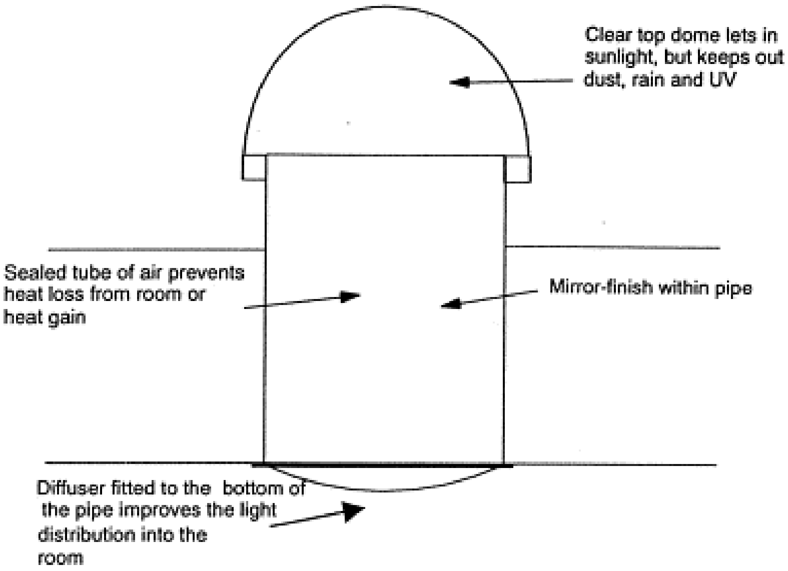

Figure 2. Schematic of a typical light pipe (Oakley et al., 2000: 91).

The majority of commercially available light pipes are simply empty tubes along which light can travel into the interior of a building or other dark spaces. They are available from a number of manufacturers and are versatile enough to be installed in straight or angled assemblies, enabling them to bring daylight into otherwise inaccessible rooms. The coating on the internal surface of the light pipe is composed of highly reflective materials such as anodized aluminum or coated plastic films such as Alcoa Everbrite and SilverLUX, which have reflectance greater than 95% (Shao et al., 1998).

Light pipes use the principle of high efficiency reflection and as a result straight light pipes perform better than angled ones as light energy decreases with increased reflections (Sweitzer, 1993). Each light pipe bend may reduce light output by approximately 8% (Monodraught, 1997). The light pipe also transmits less solar heat than windows, preventing internal heat gains in summer and heat loss in winter. Finally the diffuser distributes the light more evenly into the space the light pipe is illuminating.

Bouchet and Fontoynont (1996) produced a computer simulation predicting a minimum luminance of 100 LUX for over 70% of the period between 09:00 and 18:00 under overcast conditions. Shao et al. (1998) studied four different buildings in the UK and found that light pipes with moderate aspect ratios (up to 6) produced illuminances up to 450 LUX with internal/external luminance ratios of 1%. However, in cases where long and narrow light pipes with some bends were used the internal luminance fell to as low as 27 LUX with the ratio reduced to 0.09%. Light pipes guide light which enters to the intended exit in the ceiling at the interior of the building. Iluminance from sunlight (and coincidental skylight) through the light pipe can complement that from side lighting especially for the space in the deep interior of a building. Light pipes are effective for a facade which faces the sun all year round and has been presented as an effective means to complement side lighting (Beltran et al., 1997).

For a tropical location, the sun may traverse in the northern or southern hemisphere depending on the day of the year. Aperture of light pipes faces either east or west to utilize the sunlight in the morning or in the afternoon. For such a situation, sunlight is utilized only for a few hours for a facade each day and for the rest of the time electric lighting will be used to supplement side lighting (Surapong et al., 2000). Carter (2008) presents some photos of the uses of light pipes explored in actual buildings in UK as shown in Figure 3 to 5. Exterior views of two installations are shown in Figure 3. Interior views of the same installations illustrated in Figure 4 show the circular opal diffuser, or square lens panel output devices. Figure 5 provides a general view of guides in roof space.

Tubular light guidance systems are classified here by their light collection method (Carter, 2004). The collector is usually located at roof level to gather light from the zenithal region of the sky and is either mechanical devices that actively focus direct daylight (usually sunlight) or are passive devices that accept sunlight and skylight from part or the whole sky hemisphere (Carter, 2004).

Zenithal systems with active collection

A tracking mirror or Fresnel lens (heliostat) usually on a roof collects concentrates sunlight. A second mirror or

Figure 3. External views of two installations (Carter, 2008: 526).

lens directs a concentrated beam of sunlight into a light guide. Diffuse daylight is much less suitable as a light source since there are theoretical limits on the concentration achievable (Rabl, 1980).

Collimated light is necessary to achieve the necessary concentration for efficient transport. The size of the tracking mirrors or lenses required can be large. It is estimated that a total mirror area of about 40 m^2, or a

Figure 4. Internal views of two installations (Carter, 2008: 526).

lens area of half this value, would be required to light a 1000 m^2 office to 500 LUX (Ngai, 1983). Collectors of this size would have high capital cost, require costly control systems and maintenance and have implications for the external appearance of the building. The majority of light transport systems used for active collector systems are hollow mirrored or hollow prismatic pipes light pipes. Two detailed examples of light pipes, namely: Sun lighting

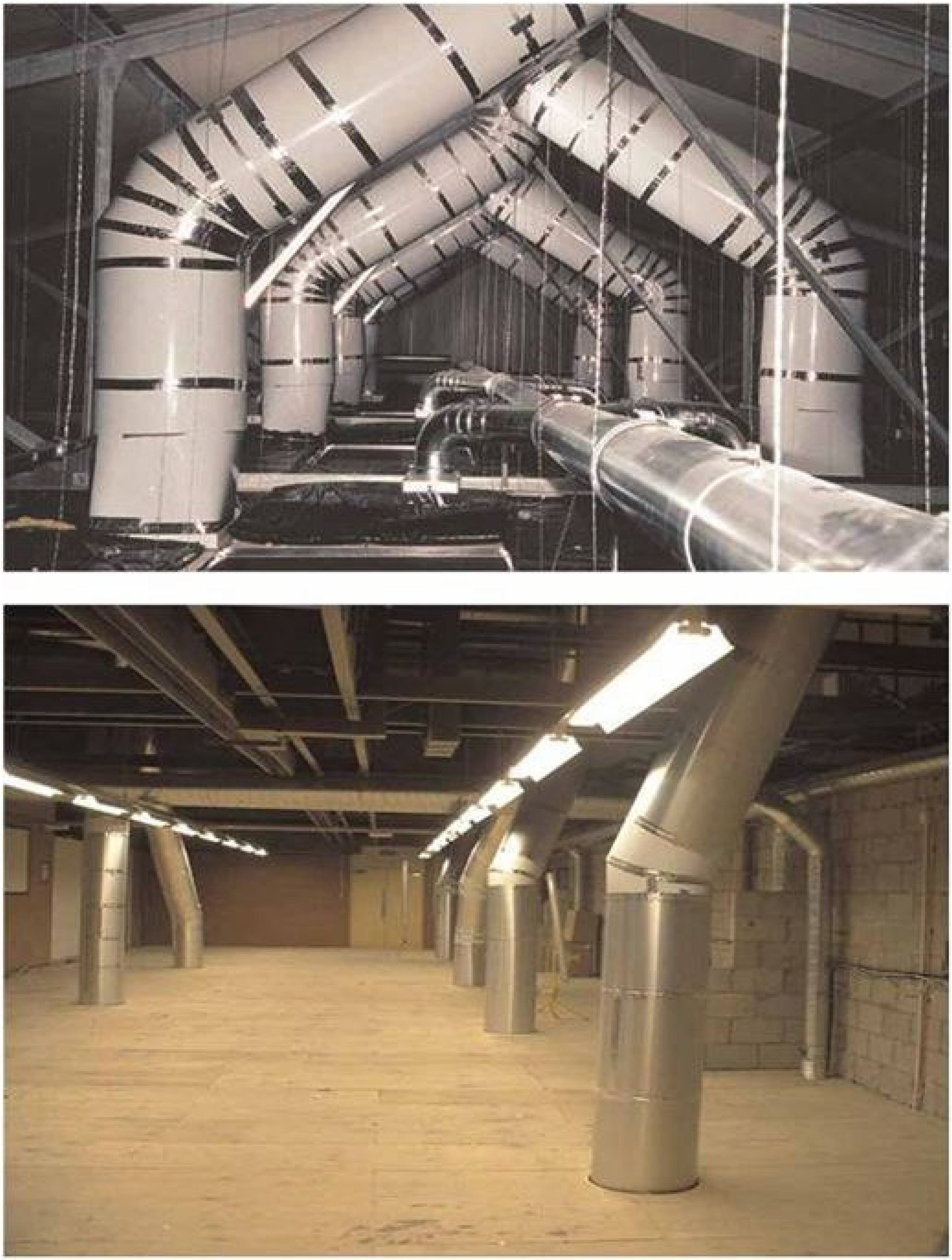

Figure 5. General views of guides in roof space (Carter, 2008: 526).

system and Arthelio are described as follows (Carter, 2004):

Sun lighting system

An installation in Austria uses sunlight to provide lighting to an underground room with a size of 7.8 m length, 4.5 m width and 2.4 m height (Pohl and Anselm, 2001). A sun tracking heliostat and a redirection mirror redirect light to a concentrator as shown in Figure 6. Two adjustable Fresnel lenses increase the concentration of incoming sunlight by a factor of 35 for transport in a 300 mm diameter tubular prismatic hollow guide (Figure 7). The emitter located in a windowless basement consists of two elements. A component similar to a mirrored louvered

Figure 6. Sun lighting system redirection mirror (Carter, 2004:224).

down light electric luminaries provides glare-free light to a task area. Diffuse ambient light is provided by light from the prismatic walls of the emitter. In addition, users can adjust a mirror to direct sunlight onto the task area thus creating a visual link to outside conditions. Supplementary fluorescent lamps are incorporated in the reflective optical component, which can be dimmed according to outside conditions and provide lighting after dark. The installation delivers glare-free light with working plane luminance between 100 and 1200 LUX given

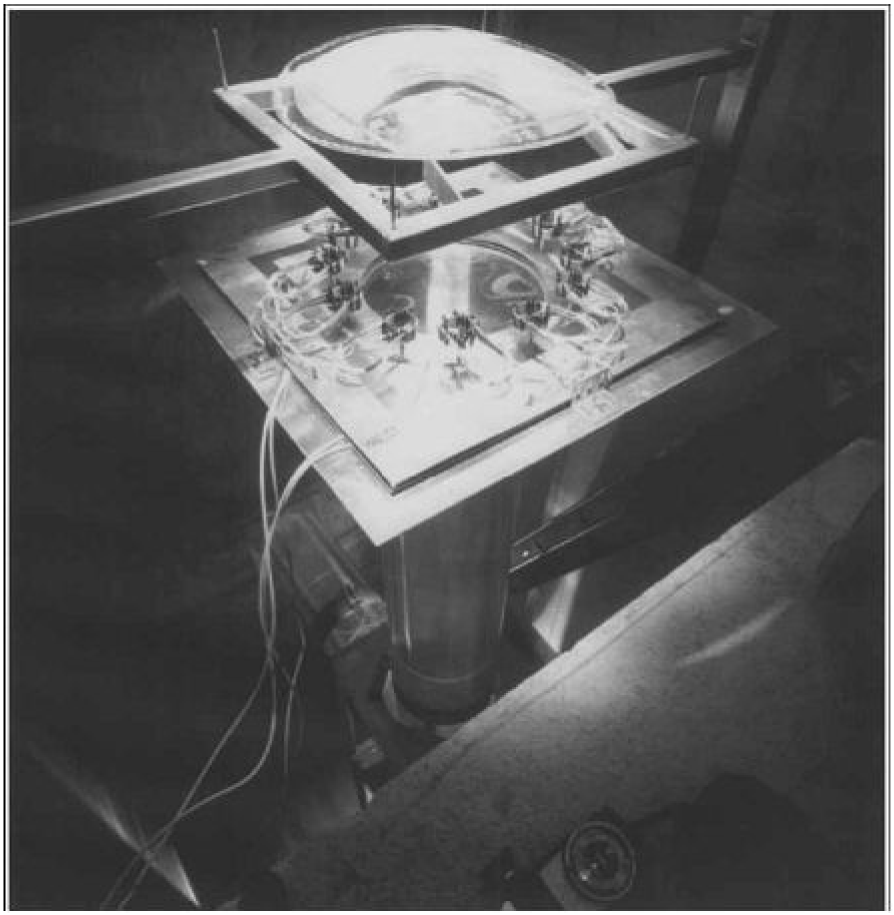

Figure 7. Sun lighting system concentrators (Carter, 2004:225).

sunny conditions with a 30% overall system efficiency. Energy savings were measured by a combination of continuous monitoring of power consumption and simulation of the performance of the system located in various parts of Europe. The results indicated power savings of 40 to 60% compared with a conventional electric lighting system. The quoted capital cost of £225 /m^2 is of the order of ten times that of an electric lighting installation providing comparable lighting conditions. However, this kind of device is highly dependent on the direct sunlight and a tracker is always needed (Pohl and Anselm, 2001).

Arthelio

The Arthelio study developed systems combining daylight and electric light and culminated in the construction of two large installations: A staircase connecting three floors of an office building in Berlin and a working area of a single-storey warehouse in Milan (Mingozzi et al., 2001). The Berlin installation has a two-axis automatically controlled 6-m^2 plane mirror directing sunlight horizontally toward four 1*1.4 m Fresnel lenses, which concentrate the light by a factor of 100 and hence to a mixing box (Figure 8). The mixing box allows introduction of light from 1000 W dimmable sulphur lamp to supplement and directs collimated light into two 12 m long, 30 cm diameter hollow prismatic light guides with a specula reflectance of 97%. Light leakage from the guides is regulated by a series of white diffuse hollow tube extractors inside the guide (Mingozzi et al., 2001).

The mixed light supply means that the appearance of the tubes varies with time of day and season. The Milan installation uses a single-axis light-capture head based on a Fresnel lens with an acceptance angle that enables sunlight to be collected from the majority of the sun path at the latitude of the installation. The sunlight is then reflected into a 13 m long, 90 cm diameter circular guide via an anidolic mirror. The guide is lined with prismatic material with a specula reflectance of 97%. A diffuser unit, shaped like a truncated cone and located at the end of the duct, distributes the light over some 14 m^2 of working area beneath the pipe. Connected to the diffuser unit are two horizontal prismatic light guides powered by

Figure 8. Arthelio Fresnel lens (Mingozzi et al., 2001: 16).

100 W dimmable sulphur lamps. These provide a uniform luminance over the working area by a control system that tops up or replaces the daylight as necessary. The system delivers in the order of 200 to 250 LUX on the working plane and luminance beneath the diffuser is more than 2% of the external luminance from sunlight/daylight and sunlight. The combination of dimming and the presence of a detection system give estimated savings of 67% over the fluorescent installation it replaced. No capital costs are quoted for either project (Mingozzi et al., 2001).

Passive zenithal systems

These are the most commercially important form of daylight guidance system. They consist of a light transport section with, at the upper end, some device for collecting natural light whilst preventing ingress of wind and rain and, at the lower end, a means of distribution of light within the interior. The collector is usually a clear polycarbonate dome that may include a refractive redirection device. Modifications to the basic systems include: Cutting the upper end of the tube at an oblique angle inclined toward the equator; laser-cut deflecting panels to redirect light in an axial direction and reflectors known as 'light scoops' located outside or inside the collector dome to intercept direct sunlight, increasing the flux output under a clear sky plus sun, but having a negative effect under overcast conditions. The transport section is a rigid or flexible hollow mirrored or prismatic guide and may include bends or elbows (Carter, 2004).

Studies of achieved conditions and user views in buildings equipped with light pipes suggest that daylight guidance devices are recognized as sources of daylight, but are thought to be generally inferior to windows in the delivery of daylight (Al-Marwaee and Carter, 2006; Ejhed, 2001). Little authoritative work on either energy savings realized, or the general economic viability of light pipes, has been published. Fontoynont (2005) compared theoretical long-term costs of various methods of office lighting and concluded that whilst the costs of light pipes were similar in magnitude to electric lighting, they were more expensive than conventional windows or roof lights.

Muneer and Jenkins (2004) compared the costs of lighting a number of theoretical small rooms using light pipes. Their results suggested that light pipes may be an economic investment particularly if the economic value of daylight was included, but the limited nature of the study did not permit the viability of actual installations to be investigated. The innovative nature of light pipes has posed two major problems for designers (Carter, 2008). The first is that there is little accumulated experience of how they are accommodated within a building. As conduits of daylight, light pipes penetrate the exterior envelope of a building but, unlike windows, may also pass through internal structural or construction elements. They thus make demands in terms of structural support and fire protection (fire compartments, fire stopping and internal and external spread for flame) that other lighting systems do not. In this respect, they are akin to mechanical ventilation systems. In addition, the internal space required to accommodate light pipes components and associated ducts may affect building space planning and cause loss of rentable floor area (Carter, 2008).

The second problem relates to the availability of design guidance and data. Design guidance for conventional glazing sets out desirable window properties, room proportions and surface treatments and allowable daylight levels and distributions to give satisfactory conditions for users. Similarly, electric lighting codes attempt to create comfortable conditions using recommended planar luminance levels and limits on surface and source luminance. Little independent specialist design data have been developed for light pipes to date and manufacturers' websites are the main source. These usually offer little more than output device spacing and installation advice. They are usually based on optimal conditions-the most favorable possible system configuration and assumed daylight resource, which are rarely found in practice. They also use a proliferation of methods of describing system performance, often incomplete and with little indication of the source of that data. This means that evaluation of the range of alternatives on the market is at best very difficult and in some cases impossible. Indeed, unsubstantiated claims about system performance by a minority of daylight guidance manufacturers threaten to discredit the whole technology. This state of affairs sits uneasily in a lighting industry where standardized methods of design data production and exchange (e.g., utilization factors, luminous intensity tables, daylight factors and glare ratings) have

Figure 9. Example picture of light transmitted through optical fibers (Enedir and John, 2006: 1614).

existed for many years (Carter, 2008).

OPTICAL FIBER FOR LIGHT TRANSPORTATION

According to Enedir and John (2006), since the early 1990s, fiber optic cables using an artificial light source have been used in remote-source lighting systems. Using this technology, light travels from its source to one or more remote points through fiber optic cables, one example picture for light transportation through optical fibers is presented in Figure 9. The technology has been used in many applications such as museums and retail displays and in architectural applications to emphasize the features of a building or to outline its exterior contours; other applications have involved lighting exit signs and aisles in theatres and aero planes etc. to name but a few.

The idea of concentrated solar energy transport by optical fibers was put forward in 1980 by a group of French investigators (Cariou et al., 1980). Owing to the unavailability of high quality optical fibers and the high cost of their design, this project limited itself to theoretical analysis only. With the present day availability of fiber-optic techniques, solar energy can be transmitted by high quality optical fibers of large core diameter and large numerical aperture. With flexible fiber optic solar energy transmission and concentration, a solar laser or any other light powered tool will be able to be moved out of its actual pumping position in the focusing area of the primary parabolic mirror and will find new applications (Cariou et al., 1980).

Wherever the remote lighting system has been introduced in an architectural project, it was mentioned clearly the practical advantages it breeds. In addition, the main light generators being put away at some distance, in a dry place, gives clear evidence about the safety higher degree of the system. Actually, in important projects where optical fibers take aim to satisfy more complex lighting design purposes, like illumination, safety is appreciated but is not certainly seen as the stimulus of the system choice. Additionally, the practical location of the effective light sources is valued but in terms of lower cost services. In fact, the main advantage aimed for while selecting a remote lighting system instead of an ordinary one, relates to some extent to the considerable cut down upon the effective running costs (Milanesi et al., 1993).

Under such circumstances is the Commercial Fair Tower in Franckfurt. This tall building is crowned by a pyramid previously enhanced by external lighting provided by some 353 fluorescent tubes. These have been now replaced by optical tubes supplied with the necessary light by only 76 metallic vapor lamps (250 W). With this new lighting design scheme long term savings are to be realized not only upon the diminution of the effectively operating lamps but also upon the services as the generators are placed within the building (Djamila, 1996).

During the past 30 years a new type of optical fiber has been researched, namely the Plastic Optical Fiber (POF). The situation of this transmission medium had remained rather stagnated for years because of its high attenuation and the lack of demand of specific commercial applications. However, since the development of the graded index plastic optical fibers in 1990 and the later attainment of the low-attenuation per fluorinated fibers in 1996, plastic optical fibers have received a lot of interest, which is expected to give rise to a great deal of applications in the next several years (Joseba and Jon, 2001).

Because of its high frequencies, the optical portion of the electromagnetic spectrum is currently being used by employing optical fibers as transmission media. Specifically, the well-known plastic optical fibers with PMMA core were introduced in the 1960s, although the first optical fibers that were used were made of glass. In the past several decades, concurrent with the successive improvements in glass fibers, POFs have become increasingly popular, owing to their growing utility (Kaino, 1992; Nihei et al., 1997).

Although POFs have been available for some time, only quite recently have they found application as a high-capacity transmission medium, thanks to the successive improvements in their transparency and bandwidth (Murofushi, 1996). By the end of 20th century, they are advantageously replacing copper cables in short-haul communications links by offering the advantages intrinsic to any optical fiber in relation to transmission capacity, immunity to interference and small weight. In addition, POFs serve as a complement for glass fibers in short-haul communications links because they are easy to handle, flexible and economical, although they are not used for very long distances because of their relatively high attenuation. These characteristics make them especially suitable as a means of connection between a large net of glass optical fiber and a residential area, where distances to cover are generally less than 1 km. An example would be Internet access from home or from an office. For this purpose, POFs allowing for increasingly better features regarding distance and transmission speed have been manufactured (Murofushi, 1996).

As had been already mentioned, POFs present some important advantages over their glass counterparts. Specifically, their large diameter typically 0.25 to 1 mm, allows low precision plastic connectors to be used, which reduces the total cost of the system. In addition, POFs stand out for their greater flexibility and resistance to impacts and vibrations, as well as for the greater coupling of light from the light source to the fiber. Because of these merits, varied applications with POFs have been developed and commercialized, from their use as a simple light transmission guide in displays to their utilization (Joseba and Jon, 2001). The following paragraphs introduce a brief view on the mechanical properties, thermal properties and chemical resistance for plastic optical fibers:

Mechanical properties for plastic optical fibers

Several authors have studied the mechanical properties of POFs. These studies have been focused on the attenuation induced by bends and tensile or torsion stresses (Blyler, 1999; Zubia et al., 1997). In contrast to glass fibers, POFs are made of plastic materials. Another difference is that it is nearly two orders of magnitude lower than that of a silica fiber less than 2.1 Gpa for a PMMA POF (Blyler, 1999). For this reason, even a 1 mm diameter POF is sufficiently flexible to be installed according to typical fiber configurations. For the same reason, the minimum bend radius for POFs is smaller, since plastic is more ductile and much less stiff than silica. Similar results have been obtained for polycarbonate POFs, for which POF lies in the range between 1.55 and 2.55 Gpa (Guerrero et al., 1998).

Thermal properties for plastic optical fibers

As POFs are made of polymer, they can operate at temperatures up to 80 to 100°C. Above this limit, POFs begin to lose their rigidity and transparency. The operation temperature can be increased up to 125°C or even to 135°C by using a jacket made of cross-linked polyethlylene or of a polyolefine elastomer (Nihei et al., 1996).

On the other hand, the resistance of POFs to high temperatures strongly depends on the degree of moisture. This behavior is due to the strong OH absorption band in the visible range. Fluorinated fibers do not absorb water, so the attenuation rate through them is not altered significantly by the degree of moisture (Naritomi, 1996). High bandwidth POF also has a high thermal stability. No distortion in bandwidth is observed even after more than 10000 h of aging at 85°C (Sato et al., 2000).

Chemical resistance

Most of the study on POFs' chemical resistance deals with the behavior of POFs when they are in contact with those liquids typically found in cars. For example, polycarbonate POFs without jacket only resist 5 min immersed in 85-octane petrol. However, these POFs are able to withstand oil and battery liquid for a long time (Guerrero et al., 1993). The polyethylene jacket of a fiber cord serves to protect the POF when it is dipped into chemical products. When using this jacket, PMMA POFs are protected against liquids such as water, NaOH, sulfuric acid (34.6%), or engine oil. In any of such liquids, the attenuation remains constant when the coated POF is dipped into the liquid at 50℃ for 1000 h. Fluorinated POFs (CYTOP), do not show changes in their attenuation when they have been dipped for 1 week into chemical acids such as 50% HF, 44% NaOH and 98% H_2SO_4 or organic solvents such as benzene, hexane, MEK and CCL_4 (Daum et al., 1994).

The continuous lighting industry progress and the perseverance of lighting designers have also allowed relying totally upon the remote lighting system to meet quantitative and qualitative lighting conditions within very spacious environments. A successful experiment has been carried out in the Congress Palace of Madrid (Djamila, 1996). Two auditoria (900 and 2000 seats) are exclusively lit by optical fibers scattered evenly in the ceilings and seeing to the standard of the design objectives required; an illumination level in accordance with the expected comfort lighting norms, a good color rendering, a uniform lighting and a pleasant luminous internal environment. Furthermore, heat output due to lamps is extracted in the generators and therefore nuisance caused by lighting appliances is not noticeable giving hence additional satisfaction with the adoption of this system (Djamila, 1996).

The use of concentrated solar energy and its transport in optical fibers is studied by Cariou et al. (1982). Transmission properties of fibers as well as geometrical conditions of the association between fibers and concentrator were investigated. It was shown that modules where one fiber is associated with a small parabolic mirror might supply 2 W with efficiency greater than 70%, whilst the concentration on the exit end of a 10 m long fiber may exceed 3000. Such a device has been achieved and the experimental results are in good agreement with the preliminary study (Cariou et al., 1982).

CONVENTIONAL SOLAR CONCENTRATORS

Sunlight holds considerable unrealized potential for application in energy efficient room lighting designs. There are currently few existing systems that efficiently utilize sunlight to provide sufficient room lighting to remote non-daylit rooms. Anidolic optics can be used for lighting of a room with an immediate day lighting aperture (Compagnon et al., 1993; Page et al., 2003). Recently, systems involving concentrating collectors (Beckman et al., 2003), heliostats (Pohl and Anslem, 2002), or mirror light pipes (Garcia-Hansen and Edmonds, 2003) have been developed for illumination of remote rooms. A fatal disadvantage of conventional solar concentrators is while systems using mirrors or lens may be advantageous for large-scale room lighting, they chiefly rely on beam solar irradiation and require tracking mechanisms to avoid astigmatism and other light losses experienced during collection of solar energy so that they lose their functions in cloudy and diffuse conditions (Ries et al., 1995). Figure 10 presents an example of the heliostats solar concentrator and light transmission through optical fibers developed by Kandilli et al. (2008).

Solar concentrators were early brought into consideration as alternative ways to reduce the cost of photovoltaic electricity and solar heat due to the relatively high material and production costs of solar cells and solar thermal absorbers. One approach is to use concentrators that increase the irradiance on the modules or absorbers and thus the electricity or heat production per unit receiver area, which in turn reduces the area needed for a given output (Maria et al., 2004).

Concentrating systems use lenses or reflectors to focus sunlight onto the solar cells or solar thermal absorbers. High concentration of solar radiation requires tracking of the sun around one axis or two axes, depending on the geometry of the system. The higher the concentration, the more concentrator material per unit area of solar cell or thermal absorber area is generally needed. It is therefore more appropriate to use lenses than reflectors in highly concentrating systems, because of their lower weight and material costs. Lenses, typically point-focus or linear-focus Fresnel lenses with concentration ratios of 10 to 500 are most often manufactured out of inexpensive plastic material with refracting features that direct light onto a small or narrow area of photovoltaic cells or on a linear thermal absorber. The cells are usually silicon cells. Single or mono-crystalline silicon approaches accounted for 93% of the annual cell production in 2002 (Schmela, 2003). Cells of GaAs and other compound materials have higher conversion efficiencies than silicon and can operate at higher temperatures, but they are often substantially more expensive (Swanson, 2000). Concentrator module efficiencies range from 17% and upwards and concentrator cells have been designed with conversion efficiencies in excess of 30% (Yamaguchi and Luque, 1999; Fraas et al., 1990). However, concentrator systems that utilize lenses are unable to focus scattered light, limiting their use to areas with mostly clear weather (Yamaguchi and Luque, 1999).

In areas with a lot of diffuse irradiation, as well as for moderate (5 to 20×) and low (less than 5×) concentration

Figure 10. One example of the heliostats solar concentrator and light transmission through optical fibers (Kandilli et al., 2008: 23).

ratios, reflectors are often more cost effective than lenses and therefore the most common type of concentrator. Below 5× concentration, it is possible to construct cost-effective static concentrators; both for photovoltaic and solar thermal systems (Whitfield et al., 1995; Hellstrom et al., 2003). These are mostly two-dimensional parabolic troughs or plane booster reflectors. Plane mirrors in front of the collector area increase the collected energy with 20 to 50% and reduce some of the diurnal variation (McDaniels et al., 1975). Reflectors for solar energy applications should fulfill a number of requirements (Maria et al., 2004):

1. They should reflect as much as possible of the useful incident solar radiation onto the absorbers.
2. The reflector material and its support structure should be inexpensive compared to the solar cells or thermal absorbers onto which the reflector concentrates radiation.
3. The high reflectance should be maintained during the entire lifetime of the solar collector or photovoltaic module, which is often longer than 20 years.
4. If cleaning is necessary, the surface should be easily cleaned without damaging its optical properties and the maintenance should not be expensive.
5. The construction must be mechanically strong to resist hard winds, snow loads, vibrations, etc.
6. The reflector should preferably be lightweight and easy to mount.
7. The reflector material should be environmentally benign and should not contain any hazardous compounds.
8. The visual appearance of the reflector should be aesthetical, since solar concentrators often are large and must be placed fully visible on open spaces so that the concentrator aperture is not shaded by objects in the surroundings.

The optical requirement that must be fulfilled for reflector materials in solar thermal applications is a high reflectance in the entire wavelength range of the solar spectrum (300 to 500 nm). In lighting and photovoltaic applications, photons with lower energy than the band gap of the solar cell, which corresponds to wavelengths longer than about 1100 nm for a silicon cell, do not contribute to the photoelectric conversion but only to overheating. Hence, metals that are free electron-like are suitable as reflectors for solar thermal applications, but not optimal for lighting and photovoltaic applications. There are no known metals that combine a low reflectance in the near-infrared with a high reflectance in the ultraviolet and in the visible (Mwamburi and Roos, 2000).

Among the Drude metals, silver and aluminum are the best solar reflectors with a solar hemispherical reflectance of approximately 97 and 92%, respectively (Granqvist, 2003). Due to its lower cost, the material, which is most often used for solar reflectors today, is anodized aluminum. However, if the anodized aluminum is not protected, for example by a glazing, a plastic foil, or a lacquer, its optical performance degrades severely in only a couple of months (Bouquet et al., 1987). The degradation of silver is essentially as rapid as that of aluminum (Czanderna, 1981). Due to the limited corrosion resistance of the free electron-like metals, they are often used in back surface mirrors, evaporated on the back of a glass or polymer substrate that protects the metal from oxidation. Among the state-of-the art in solar reflector materials are Polymethylmethacrylate (PMMA) or backsurface-silvered low-iron glass (Schissel et al., 1994). However, glass mirrors tend to be brittle and heavy. Front surface mirrors, on the other hand, are often bendable and of lightweight, but more susceptible to chemical attack (Roos et al., 1989).

A solar reflector is not subject to the same high temperatures and thermal cycling as a solar absorber. Nevertheless, environmental conditions impose stringent demands on the material, whose surface will deteriorate more or less upon exposure to the environment. Loss of solar reflectivity can result from erosion or oxidation of the surface, dirt accumulation on the reflector and action of cleaning agents (Duffie, 1962). While degradation caused by accumulation of dust on the reflecting surface is essentially reversible, surface oxidation is not. The optical performance of solar reflectors thus depends on the mechanical and chemical properties of the surface and the protective coating, if such is present. For flexible reflective foils, a support of sheet metal may be necessary, while only a simple frame construction is needed if the reflector is self-supporting, which is the case for corrugated sheets. When installing booster reflectors, the cost of the reflector material, the frame and support construction, as well as mounting and installation of the reflector must be taken into account. Maintenance should also be included in lifecycle cost (Morris, 1980).

Mora et al. (2009) reported using porous silicon photonic mirrors (PSPM) as secondary reflectors in solar concentration systems. The PSPM were fabricated with nanostructured porous silicon to reflect light from the visible range to the near-infrared region (500 - 2500 nm), although this range could be tuned for specific wavelength applications. The PSPM are multilayer of two alternated refractive indexes (1.5-2.0), where the condition of a quarter wavelengths in the optical path was imposed. The PSPM were exposed to high radiation in solar concentrator equipment as shown in Figure. 11. As a result, it observed a significant degradation of the mirrors at an approximated temperature of 900oC. In order to analyze the origin of the degradation of PSPM, it was modeled the samples with a non-linear optical approach and study the effect of a temperature increase. It concluded that the main phenomeno involved in the breakdown of the photonic mirrors is of thermal origin, produced by heterogeneous expansion of each layer (Mora et al., 2009).

Poulek and Libra (2000) developed a tracking ridge concentrator using proven tracker hardware. This system combines simple low-cost tracker with flat booster mirrors but unlike V-trough concentrator (Klotz, 1995; Nann, 1991) by the new ridge concentrator the mirror has been eliminated as shown in Figure 12. On single axis trackers, both horizontal and polar, the mirrors have to be extended beyond PV panels to ensure uniform illumination of panels at seasonally variable elevation of the sun. On polar axis trackers with seasonally adjustable slope of the axle the extended mirror is not needed. Unlike V- concentrator trough concentrators, no additional mirror supporting structures are needed. However, it could only double solar energy gain of PV panels in comparison with fixed ones (Poulek and Libra, 2000).

To obtain cost-effective photovoltaic modules, Uematsu et al. (2001) have developed static prism array concentrator modules consisting of prism concentrators about 4 mm thick assembled unidirectional under a 3.2-mm-thick cover glass as shown in Figure 13. Calculating the optical collection efficiency for the annual solar irradiation in Tokyo, it found that the theoretical efficiency of the modules is 94.4% when the geometrical concentration ratio is 1.88 and that it is 89.1% when that ratio is 2.66, respectively. Fabricating prism-array-concentrator modules with a geometrical concentration ratio of 2.66, it only obtained a maximum optical collection efficiency of 82% with a flat reflector and 81.7% with a V-grooved reflector (Uematsu et al., 2001).

In order to remove the trackers, a static solar concentrator is proposed by Masato and Toshiro (2005) to match the aesthetic features of towns. The concentrator consists of vertical plate solar cells and white/transparent switchable bottom plate, which is operated with external power. The bottom is switched to be a diffuse reflection white surface when the cell generates electric power and switched to be a light transmissible transparent surface when the cell does not deliver power. The light collection of this concentrator was analyzed by using multiple total internal reflection model and ray tracing simulation. However, the results are not significantly satisfying for a static solution for solar concentration (Masato and Toshiro, 2005).

LUMINESCENT SOLAR CONCENTRATOR (LSC)

The luminescent planar solar concentrator was proposed in the late 1970s (Weber and Lambe, 1976; Goetzberger and Greubel, 1977; Rapp and Boling, 1978) consisting of a transparent plastic sheet doped with organic dyes.

Figure 11. DEFRAC-Spanish acronym of device for the study of highly concentrated radioactive fluxes (Estrada et al., 2007: 1308).

Sunlight is absorbed by the dye and then re-radiated isotropically, ideally with high quantum efficiency and trapped in the sheet by internal reflection. A stack of sheets doped with different dyes can separate the light. Solar cells can be chosen to match the different luminescent wavelengths to convert the trapped light at the edge of the sheet (Goetzberger and Greubel, 1977).

Luminescent Solar Concentrators (LSCs) have attracted the attention of a large number of scientists and engineers since the first proposal by Weber and Lambe (1976). The operation of the LSC, which can be considered as a peculiar kind of light guide, is based on the following principles. One or more high quantum yield species are dissolved in a rigid highly transparent medium

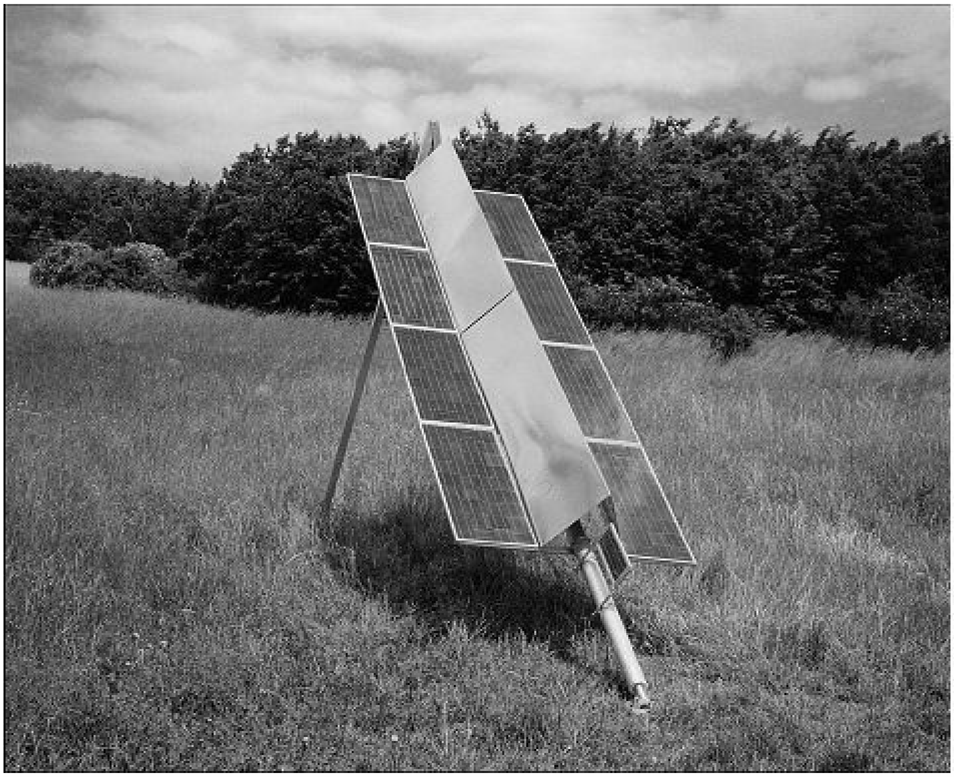

Figure 12. Photograph of the polar axis tracking ridge with 8*55 Wp PV panels (Poulek and Libra, 2000: 201).

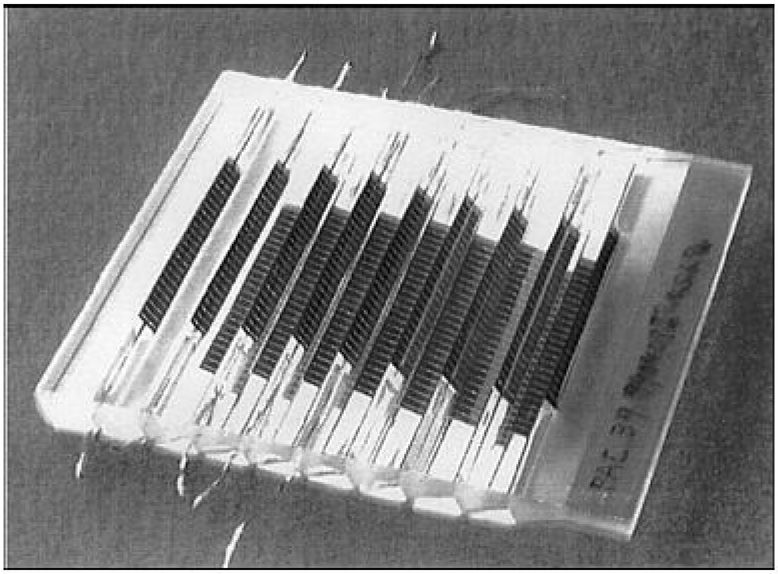

Figure 13. Photograph of a static prism-array concentrator module (Uematsu et al., 2001: 420).

of high refractive index. Solar photons entering the plate are absorbed by the luminescent species and reemitted in random directions. Following Snell's law, a large fraction of the emitted photons will be trapped within the plate and transported by total internal reflections to the edge of the plate, as illustrated in Figures 14 and 15,

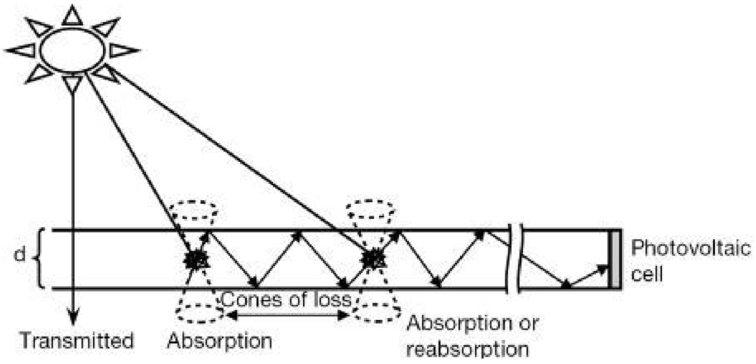

Figure 14. Schematic representation of luminescent solar concentrator (LSC) (Hammam et al., 2007: 245).

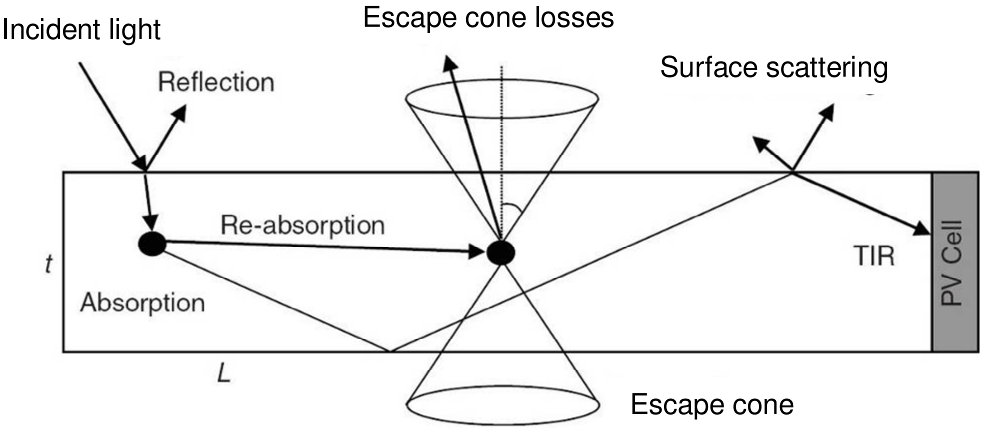

Figure 15. More in detailed example of schematic representation of luminescent solar concentrator (LSC) (Richards, 2006: 2335).

where they will be converted by appropriate photovoltaic cells (Richards, 2006; Reisfeld, 2001; Batchelder et al., 1979; Hammam et al., 2007).

Conversion of the incident solar spectrum to monochromatic light would greatly increase the efficiency of solar cells. Since LSC were proposed in 1970s, solar cells were attached to it. LSCs consist of a highly transparent plastic, in which luminescent species, originally organic dye molecules, are dispersed. These dyes absorb incident light and isotropically emit it at a red-shifted wavelength, with high quantum efficiency. Internal reflection ensures collection of part of the emitted light in the solar cells at the sides of the plastic body. The energy of the emitted photons ideally is only somewhat larger than the band gap of the attached solar cells, to ensure near-unity conversion efficiency (Goetzberger and Greubel, 1977). A large fraction of the emitted photons loses from the escape cones. The size and form of the cross section could impact on the proportion of photons trapped by the LSC plate and the reduction of the cross sectional area of the luminescent plate could increase the photon loss (Richards, 2006; Reisfeld, 2001; Batchelder et al., 1979; Hammam et al., 2007).

LSCs were developed as an alternative approach to lower the costs of PV. As both direct and diffuse light is concentrated by a factor of 5 to 10, without the need for expensive tracking, smaller silicon or other solar cells can be used. As the cost of the transparent plastic is expected to be much lower than the area cost of the solar cell the cost per Watt-peak is lower compared to the cost of a planar silicon solar cell (Batchelder et al., 1979; Hammam et al., 2007).

The development of the LSC was initially limited by the performance of the luminescent dyes available some decades ago. Nevertheless, efficiencies of up to 4% have been reported for a stack of two plates (40×40×0.3 cm), one being coupled to a GaAs solar cell and the other to a Si solar cell (Wittwer et al., 1984). Particular problems were the poor stability of the dyes under solar irradiation and the large re-absorption losses owing to significant overlap of the absorption and emission. Within the full spectrum project (Luque et al., 2005), the performance of both quantum dots and organic dyes are being evaluated as the luminescent species in the LSC. The important characteristics of organic dyes are that they: (1) Can provide extremely high luminescence quantum efficiency (near unity); (2) Are available in a wide range of coolers and, (3) New molecular species are now available with better reabsorption properties that may also provide the necessary UV stability. Quantum dots have advantages over dyes in that: (1) Their absorption spectra are far broader, extending into the UV; (2) Their absorption properties may be tuned simply by the choice of nanocrystal size, and (3) They are inherently more stable than organic dyes. Moreover, there is a further advantage in that the red-shift between absorption and luminescence is quantitatively related to the spread of quantum dot sizes, which may be determined during the growth process, providing an additional strategy for minimizing losses due to reabsorption (Barnham et al., 2000). However, as yet quantum dots can only provide reasonable luminescence quantum efficiency: Luminescence quantum efficiency more than 0.8 has been reported for core-shell quantum dots (Peng et al., 1997).

Advantages over geometric luminescent concentrators include that solar tracking is unnecessary and that both direct and diffuse radiation can be collected and, in addition, the sheets are inexpensive. However, the development of this promising concentrator was limited by the stringent requirements on the luminescent dyes, namely high quantum efficiency, suitable absorption spectra and red shifts and stability under illumination (Goetzberger et al., 1985; Wittwer et al., 1981). Concentration ratios of 10× were achieved (Goetzberger et al., 1985; Wittwer et al., 1981). A typical measured electrical efficiency with a two-stack concentrator with GaAs solar cells was 4%, whereas the original predictions were in the range 13 to 23% (Goetzberger and Greubel, 1977).

Barnham et al. (2000) have proposed a novel concentrator in which the dyes are replaced by quantum dots. The first advantage of the quantum dots over dyes is the ability to tune the absorption threshold simply by choice of dot diameter. For example, colloidal InP quantum dots, separated by dot size, have thresholds, which span the optical spectrum (Micic et al., 1997). Secondly, high luminescence quantum efficiency has been observed. CdSe/CdS hetero-structure dots have demonstrated luminescence quantum yields of above 80% at room temperature. Thirdly, since they are composed of crystalline semiconductor, the dots should be inherently more stable than dyes (Chattena et al., 2003).

The disappointing results obtained with dye concentrators were probably mainly because of reabsorption, which was considered, but not modeled at the time of the original calculations (Goetzberger and Greubel, 1977). Barnham et al. (2000) have argued that there is a further advantage in that the red shift between absorption and luminescence is quantitatively related by the thermodynamic model to the spread of quantum dot sizes, which can be determined during the growth process. The ability to limit the overlap between the luminescence and absorption by the choice of quantum dot size distribution is a significant improvement compared to dye concentrators (Micic et al., 1994).

Goldschmidt et al. (2009) demonstrated how the collection efficiency of fluorescent concentrator systems is increased by two independent measures. One approach is to combine different dyes to enlarge the used spectral range. A system using the combination of two materials had an efficiency of 6.7%. The other approach is to increase the collection efficiency by the application of a photonic structure, which acts as a band stop reflection filter in the emission range of the dye. A relative efficiency increase of 20% with a commercially available filter was achieved. With the achieved efficiency of 3.1% and concentration ratio of 20, the realized fluorescent concentrator produces about 3.7 times more energy than that of the used GaInP solar cell produced on its own. Photonic structures are especially beneficial for larger systems. Goldschmidt et al. (2009) clarified the role of a white bottom reflector and its interaction with the photonic structure. The white bottom reflector increases the efficiency by two mechanisms. It increases the absorption of light in the fluorescent concentrator as it reflects non-absorbed light back into the fluorescent concentrator and it directly reflects light towards the solar cells. The second mechanism is especially important for small distances from the solar cell (Goldschmidt et al., 2009).

An LSC day lighting system has been produced by Earp et al. (2004), which transports sunlight to remote areas of a building using a stack of pink, green and violet LSCs and clear PMMA (poly methyl methacrylate) light guides. In direct sun of intensity 100,000 LUX, prototypes with collector area of 1.2×0.135×0.002 m deliver 1000 lumen of near white light with a luminous efficacy of 311 Lm W^{-1} and a light-to-light efficiency up to 6%. The light-to-light efficiency of the violet sheet is 0.29% and that of the green sheet is 5.8%. The light-to-light efficiency of the pink sheet is 1.5%. Surface effects such as excess adhesive and variations in flatness are thought to be causing unnecessary light loss, which can be avoided by careful LSC production (Earp et al., 2004). A limitation in the wiring for long distance light transportation has emerged in this LSC system.

CRITICAL DISCUSSION

Table 1 summarizes the limitations in current day lighting related solar concentration devices. In building integration, one of the important features of remote light transportation is the wiring method and the wiring method is expected to be as simple as that of electrical wires

Table 1. Summary of limitations in current daylighting related solar concentration devices.

Methods and devices	Problems and limitations
Direct day light	It may not able to reach many areas such as store room, basement, hallway, and it also brings heat gain with the light
Light pipes	Difficulties in wiring
Optical fiber	Needs a pointolite for it to transport
Various solar concentrators	They are only sensitive for beam irradiation, they do not function well in cloudy weather and diffuse conditions and a tracker is always needed
Luminescent solar concentrators (LSC)	Light concentrated by normal LSC could not be transported by optical fibers to a remote place since the light produced by LSC is not a pointolite.
Static solar concentrators	Poor concentration rate without a tracker

(Enedir and John, 2006; Cariou et al., 1982). As illustrated in Table 1, only optical fibers are competent for this requirement. For instance, an LSC developed by Earp et al. (2004) is transported by polymer sheets instead of the optical fibers because the light produced by the LSC is not a pointolite. The polymer sheets have a disadvantage in wiring, which brings difficulties in building integration. It is also not energy-efficient to further concentrate the rectangular light produced by the LSC into a pointolite for the transportation through optical fibers to a remote place in a building.

There are two groups of solutions that are practiced in the building sector for general energy issues, namely: The building energy saving approaches and the renewable energy application approaches. As an approach for energy saving, daylight has a disadvantage of not being able to reach many areas of a building such as store rooms, basements and corridors and it also brings heat gain with the light (Bouchet and Fontoynont, 1996; Shao et al., 1998). Light pipes were designed to transport daylight to unreached areas, but light pipes have their difficulties for wiring, so that optical fibers are considered as the best approach for the daylight transportation so far. However, the optical fiber needs a pointolite for the light transportation. Various solar concentrators have been designed using optical approaches such as mirrors or lens for the solar energy concentration. Since they are only sensitive for the beam irradiation, they function poorly in the cloudy weather and the diffuse light conditions and even if they are under a clear sky condition, trackers are always needed. Luminescent solar concentrators (LSC) and some static solar concentrators were then designed as the diffuse light solution and the static solution, respectively. Static concentrators always come with a low concentration rate without a tracker and the light concentrated by normal LSCs could not be transported by optical fibers to a remote place since the light produced by an LSC is not a pointolite.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

This study has introduced the delighting related solar concentration devices such as light pipes (or tubular daylight guidance systems), optical fibers for light transport, conventional solar concentrators and luminescent solar concentrators (LSC). The principles of study, advantages and disadvantages for application of these day lighting related solar concentration devices have been explained. Daylight has a disadvantage of not being able to reach deeper areas in a building such as storerooms, basements and corridors and it also brings the heat gain with the light. Light pipes and optical fibers were expected to transfer daylight to unreached areas, but light pipes have their difficulties in wiring and the optical fiber needs a pointolite for the light transportation. Solar concentrators are only sensitive for the beam radiation and they function poorly in overcast sky conditions. Even under a clear sky condition, trackers are always needed for conventional solar concentrators. Static concentrators always come with a poor concentration rate without a tracker and the light concentrated by normal luminescent solar concentrators could not be transported by optical fibers to a remote place since the light produced by LSCs is not a pointolite. Future studies especially cross-disciplinary researches on developing new solar concentration devices in mitigating those limitations as discussed in this study are highly recommended.

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