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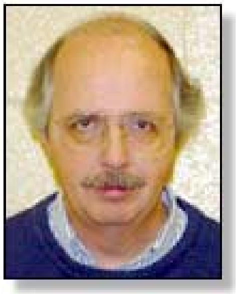

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Objective

The research investigated the feasibility to utilize optical fibers to convey and distribute solar light passively throughout residential/commercial structures. The primary objective was to use solar energy in the form of light to reduce the power consumption required for lighting the interiors of structures. The research method consisted of the performance of controlled illumination experiments by which the light transmission effectiveness of the proposed system was measured. These measurements included the concentration ratio of a simple configuration of a nonimaging solar concentrator, the efficiency of the coupling devices from fiber to concentrator and diffuser, and the loss in light intensity in the fiber itself.

Implications/Application to Industrial Technology

The research contributes to the Industrial Technology field by advancing applied research through the investigation and evaluation of large-diameter fiber optic cable for transmission of solar light. This applied research project couples contemporary fiber optic technology with laboratory-fabricated solar light concentrators. The intent is to develop a complex energy efficient lighting system for commercial and residential structures. This paper details the development and evaluation of this complex technological system. The combination of fiber optics and solar energy is an active area of applied research, and in fact has received increased attention from the U.S. Department of Energy. [Fang et al., Feuermann et al., Kribus et al., Liang et al., Rannels].

Principles and Methods of Light Concentration

Optical Fiber

Optical fibers now play an important part in the fields of both long-distance telecommunications and short-link networks (LAN's, etc.). More recently, designers have successfully applied less expensive, more mechanically robust fibers to various problems of illumination, such as safety lighting, background lighting, and medical lighting, among others. Typically, optical fiber for communications purposes uses glass fiber with very small core diameters. On the other hand, more recent development work has concentrated on improving the light-propagating properties of larger core diameter fiber made out of plastic. The research program describe above depends on the properties of plastic optical fiber, but it also depends a great deal on the means used to gather and concentrate the light from the light source, whether this source is artificial, as in the experiments reported on so far, or natural, as from sunlight.

The nearly lossless transmission of light through optical fiber can occur because of the structure of the optical fiber, shown in Figures 1 and 2. The inner core of the fiber has a higher index of refraction than the outer cladding of the fiber. Therefore, there exists a critical angle with respect to the long axis of the fiber at which light entering the core of the fiber is totally internally reflected. All light rays which are incident upon the front face of the fiber at any angle less than or equal to this critical angle will propagate undisturbed through the fiber [Snyder]. The critical angle defines a cone, with angular extent equal to twice the complement of the critical angle, within which light entering the fiber will be totally reflected at the interface between the core and the cladding. Equation 1 gives the value of the critical angle.

$$\theta_c = \sin^{-1}\left\{1 - \frac{n_{cl}^2}{n_{co}^2}\right\}^{1/2} \qquad (1)$$

where n_{co} is the index of refraction of the core material, and n_{cl} is the index of refraction of the outer cladding material.

Another measure of light acceptance commonly used in the optical fiber community is the numerical aperture, defined in equation 2.

Numerical aperture =

$$\sqrt{n_{co}^2 - n_{cl}^2} \qquad (2)$$

The important point to retain from the discussion above is that not all light incident on the fiber will necessarily get into the fiber, or propagate to the end of the fiber. Several things can lead to a loss of light intensity in the fiber. In the first place, if light does not enter the fiber within the acceptance cone, some light will be transmitted into the cladding or even radiated out of the fiber; this light power is lost to the user (Figure 3) [Snyder]. Even if light does enter the fiber within the acceptance angle defined above, the material in the core of the fiber contains impurities that, over the length of the fiber, absorb some of the light's power. For the glass fibers favored in telecommunications work, this loss in decibels (dB) is lower than a few dB/km. In the plastic optical fiber used in this research, the attenuation per length is greater, about 0.25 dB/m. However, for the lengths of fiber needed for the purposes of illumination, such losses are acceptable. The transmission coefficient as a function of length of fiber is given by equation 3.

$$T = 10^{-(\alpha \cdot d)/10} \qquad (3)$$

where a is the loss per meter in dB, and *d* is the distance along the fiber.

Another factor which influences total light transmission through the fiber is the effect of bends. When light rays propagating through the fiber encounter a bend, the angle that these rays make with the cladding can exceed the critical angle. If the critical angle is exceeded, the light will no longer undergo total internal reflection. Instead, the light will be partially reflected back into the core, and partially transmitted into the cladding, where it is lost. These so-called leaky rays steal power from the incident light beam. In cases of more extreme bends, some light will actually radiate out of the fiber, also stealing power from the incident light.

So far, the discussion of losses in optical fiber has focused only on the fiber's transmission properties. When one considers using optical fiber as a means of conveying light, it is equally necessary to understand, account for, and, if possible, overcome the loss of light power due to the inability of the

***Figure 1**. The end face of the fiber, showing the core and cladding - cladding has a lower index of refraction than the core.*

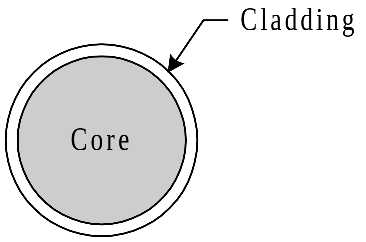


Figure 2. Incident ray within the critical angle of fiber optic cable.

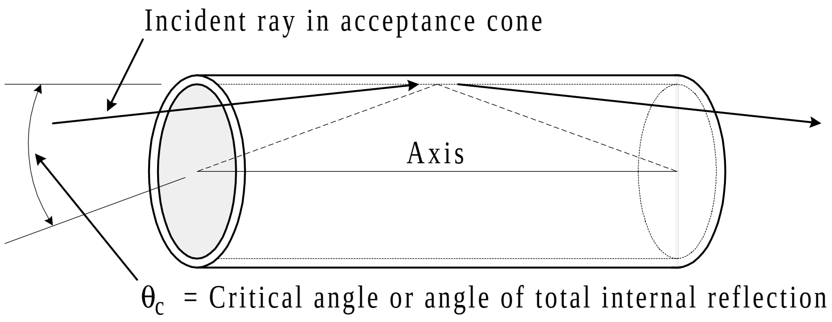
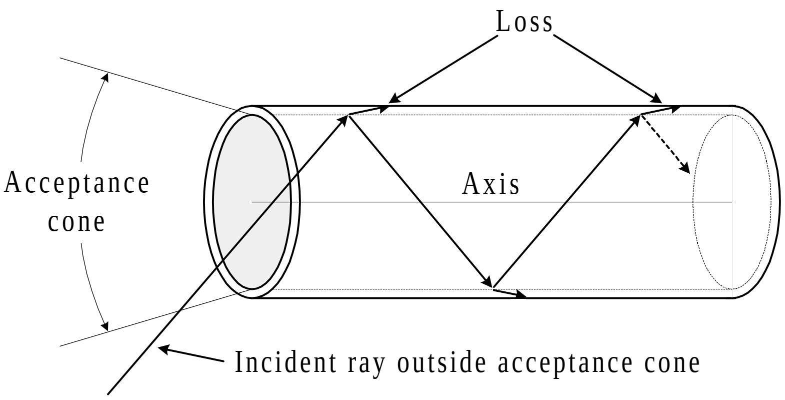


***Figure 3**. Effect on light ray that enters outside acceptance cone of fiber.*



fiber to accept all the light emitted from a source. There are two types of sources considered in optical work: collimated and diffuse. A diffuse source is one that emits light into all angles between $\pm 90°$. A collimated source is one that emits light into a narrow pencil of rays, so that essentially all rays are parallel to each other. A partially diffuse source emits light into a range of angles narrower than $\pm 90°$. Figure 4 below displays the mismatch between the acceptance angle of a typical optical fiber and that of a typical diffuse or partially diffuse source. Rays emitted from the source which are incident upon the fiber endface at angles greater than the critical angle will not become propagating rays in the fiber; instead, they will either be refracted into the cladding or they will reflect back out from the fiber. In either case, this represents a loss or attenuation of light. Even light rays from a well-collimated source such as the Sun can suffer this fate, especially as the Sun moves across the sky, thus causing more rays to be incident on the fiber at greater than the critical angle.

Light Gathering Techniques for Optical Fiber

Given the several ways in which light power can be lost, even before entering the fiber, it is apparent that simply letting the light shine upon the fiber endface will not ensure adequate levels of illumination. There are several ways around this difficulty. First, one could just try to focus the light using convex lenses onto the face of the fiber. In fact, with a collimated or partially diffuse light source, with tight control over the angle of incidence of the light from the source, one can get good magnification of light into the fiber. However, the aberrations of the image formed by lenses imply a need for precise tracking of the source by the lens-fiber combination. This adds greatly to the expense of a supposedly passive lighting system. Fresnel lenses are a lightweight variant of the conventional lens that have found application in efforts to concentrate solar energy for thermal applications. However, their tracking requirements mirror those of the conventional lenses.

About thirty years ago, a group of researchers looked afresh at the problem of concentrating solar radiation onto small areas in order to increase the temperatures achievable from solar energy. As reported in the work [Welford et al.] of Winston and others at the University of Chicago, the use of lenses and other optical components of imaging type (this would include mirrors as well) to concentrate solar radiation is inefficient due to the inherent aberrations of such components. To overcome these limitations, Winston's group developed ***non-imaging*** optics.

Non-imaging optics is a field that deals with the optimal transfer of light between a source distribution and a target distribution. The most common use of nonimaging optics is achieving maximal concentration of light. In the simplest terms, nonimaging optics strives to gather light rays that are incident on an opening or aperture of a given area, and to ensure that these rays manage to make their way to the exit aperture, which has a smaller area. ***As long as*** the entering rays become exiting rays, the definition of the concentration ratio is given as the ratio of the two areas in equation 4.

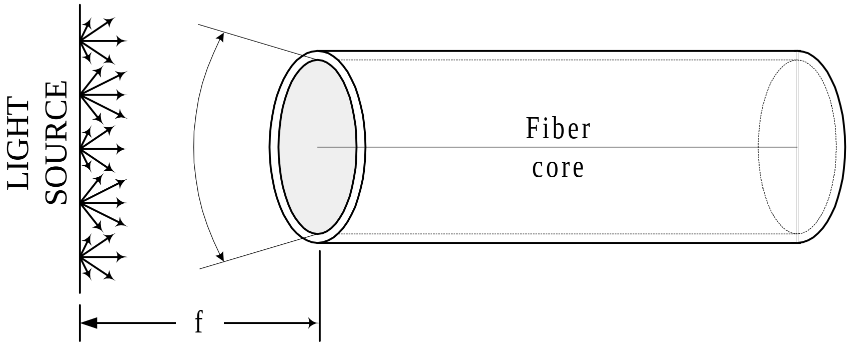
$$C = \frac{A_{inc}}{A_o} \qquad (4)$$

Of course, not all rays become exit rays, because of the Fresnel laws of reflection, and so it is necessary to analyze more closely how a concentrator of a desired concentration ratio will be made. The major results of the analysis are as follows:

- The concentration ratio, C, in Eq. 4 will depend on the angle of opening of the concentrating instrument (in this case, a truncated pyramid).
- The concentration ratio will depend on the number of reflections that an incident light ray will make with the inner surfaces of the concentrator.
- The concentration ratio will depend strongly on the angle of incidence of the incoming light rays.
- The concentration ratio will also depend, to a lesser extent, on the reflectivity of the inner surfaces of the concentrator.

The development of nonimaging concentrators has reached a very high stage of development, with several companies in the U.S. and abroad marketing commercial versions of advanced concentrator designs. Most of these are designed for the solar thermal energy market. The standard design for these applications is some variant of the compound parabolic concentrator (CPC) or the more recent compound elliptical concentrator (CEC) [Welford et al.]. The reliable fabrication of these designs, especially the precise control over the parabolic surface of the concentrator, requires expensive setups. The authors wanted to achieve modest concentration of light incident on an

Figure 4. Diffuse light source illuminating fiber core. Rays from points on the source that exceed the critical angle will not become propagating rays in the fiber.



optical fiber without engaging in expensive development cycles. Instead of designing CPC's, the authors decided to explore simpler designs first broached in the literature about twenty years ago [Burkhard-78a, Burkhard-78b]. These designs use truncated pyramids or hexagons, which are easier to fabricate reliably. The following analytic results will be specific to the truncated pyramid.

If one considers two sides of the pyramid (i.e., a trough), as shown in Figure 5, and imagines a light ray incident on the extreme left edge of the entrance aperture, then the concentration factor, C, can be shown from simple geometrical optics to be:

$$C = \frac{D_{inc}}{D_o} = \frac{\sin\left[(2n+1)\alpha + \theta\right]}{\sin(\alpha+\theta)} \quad (5)$$

In Eq. 5, the quantity D_{inc} is the width of the entry aperture, and D_o is the width of the exit aperture. To make contact with our previous expression (Eq. 4), the actual concentration ratio of the built concentrator will be the square of the C in Eq. 5. The angle a is the half-angle opening of the pyramid, and the angle q is the angle between the vertical (normal incidence) and the incident light ray. The index ***'n'*** is the number of reflections that the light rays can make with the interior walls of the concentrator and still exit through the aperture D_o. What Eq. 5 indicates is that all light rays which undergo up to and including ***n*** reflections will exit the concentrator. There is then a restriction on the angles and number of reflections. That restriction is that after ***n*** reflections, the light ray will have acquired no more than a 90° angle with respect to the vertical axis of the trough or concentrator:

$$2(n+1)\alpha + \theta \leq 90^\circ \quad (6)$$

In order to achieve a certain concentration ratio, these three quantities must be optimized. Once that is done, there will be a necessary relationship between the quantities α, θ, and n and the size (including the slope height) of the concentrator:

$$\frac{L}{D_o} = \frac{\sin\left[(2n+1)\alpha + \theta\right] - \sin(\alpha+\theta)}{2\sin\alpha \cdot \sin(\alpha+\theta)} \quad (7)$$

Figure 6 shows a model of the truncated pyramid that was constructed in our lab. The particular design had an apex half-angle, a = 10°, a slope height, L = 20", an entrance aperture, D = 6.875", and an exit aperture, D_0 = 1".

Finally, one must account for the fact that repeated reflections from the inner surfaces of the concentrator entails some loss of light power. This is so because no surface is perfectly reflecting, and thus some light energy is absorbed at each reflection. This is expressed as a reflection coefficient less than unity (r < 1). Believe it or not, it is possible to obtain closed-form expressions even for this case, but these equations are too lengthy to be of much help to the casual reader. A simple, heuristic argument will give a rough idea of the effect of a finite reflection coefficient. Each time a light ray strikes the surface, the power contained in the reflected light ray will be reduced from its initial value, e.g., P_{inc}, to a new value, given by $\rho \cdot P_{inc}$. Of course, this new light ray will suffer yet another reflection on its downward path into the concentrator, with a consequent reduction of its power to $\rho^2 P_{inc}$, and so on. It is clear that too many repeated reflections reduce the power available at the exit aperture of the concentrator.

Ensuring a high concentration ratio does not guarantee that all this light propagates through the fiber. The previous section pointed out that light rays entering the fiber would travel with low loss as long as these rays make an angle with the core-cladding interface that is less than the critical angle. The question then is: how much of the light exiting the nonimaging concentrator will enter the fiber "successfully" and end up traveling through the fiber all the way to the end?

To answer this question, it helps to think about how the concentrator transforms the angular distribution of light rays from its entrance to its exit. The design of the concentrator is such that the cone angle, a, is quite small, about 10° in our design. Furthermore, the design ensures that edge rays that undergo up to three reflections will make it to the exit aperture. In order to satisfy Eq. 6, the angle of incidence for those rays with three reflections should be no more than ~10°. So we have a relatively narrow distribution of rays at the entrance to the concentrator. At the exit end of the concentrator, rays that just barely satisfy Eqn. 6 will reflect off one edge of the aperture at nearly

Figure 5. Side view of truncated pyramid (trough) which shows angular relationships involved in estimating concentration ratio.

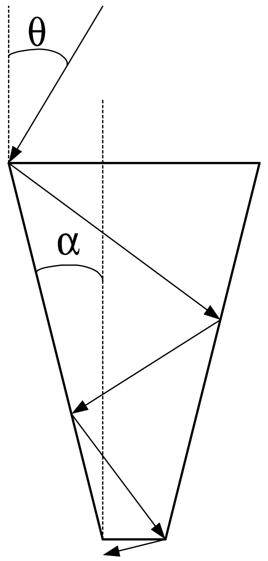
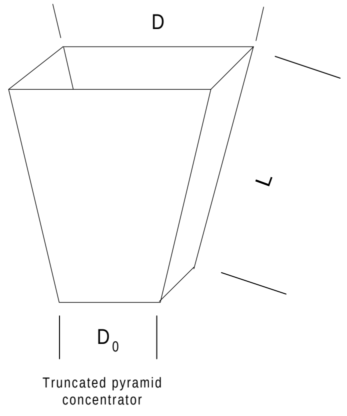


Figure 6. Model of truncated pyramid concentrator.



90°. This implies that the exiting light rays fill a wider range of angles than did the entering rays. In other words, the light at the exit aperture is more concentrated in intensity, but also more diffuse in angular extent. Therefore, because light entering the fiber must be within the acceptance cone of the fiber in order to be useful, some of the light from the concentrator will not be able to propagate through the fiber. The exact proportion of light that is outside the fiber's numerical aperture is difficult to calculate. However, one should bear in mind that while Eq. 6 states the possibility of light rays exiting the aperture at close to 90°, this applies to those rays which are incident at the top edge of the entrance aperture ***and*** which undergo ***n*** reflections. Other light rays will either suffer fewer reflections or strike further down the sides of the pyramid, with the result that their exit angles will be less than 90° by a considerable amount.

Experimental Results

The first set of experiments was designed to characterize the transmission properties of the plastic optical fiber purchased for this research. These experiments first measured the transmission losses through the 0.7" fiber while the fibers were held straight. A metal halide light source with a 4200 K blackbody temperature was used to illuminate the fiber endfaces. A light meter able to measure up to 200,000 lux was used to record the light levels at the illuminator and at the fiber end. This was done in an otherwise darkened facility. Next, these same fibers were bent at progressively greater angles of 30°, 45°, 60°, 90°, 135°, 150° and180°, in order to quantify the effect of bending on attenuation of light in the fiber. Because the proposed use of the fiber as a conduit for passive lighting in buildings could require the fibers to be bent at more than one site along its length, another series of experiments were done in which one length of fiber (~75' long) was tested while configured in a snakelike shape. The attenuation of the transmitted light was compared to the number of separate bends. The tables below give the results for the various tests.

The optical fiber that is reported on in the tables above is 0.7-in. diameter core, plastic, and has a length of 75 feet, or 22.9 meters. Supplied from the Lumenyte Corporation in California, the fiber has a published attenuation of about 0.25 dB/m. From Equation 3, one expects that the transmitted light intensity would be 26.82% of the incident light intensity. Table 1 indicates that our measured attenuation is about 23-25% up to a bend angle of 90°, and then falls slightly for greater bend angles. When multiple bends are made in the fiber, only slight fluctuations are found in the transmitted intensity. The slightly greater than expected attenuation shown in Table 1 could result from the partially diffuse nature of the metal halide illuminator, which results in some proportion of the light rays not fitting within the acceptance cone of the fiber. The fact that multiple bends seemed not to increase attenuation could be due to the fact that the radius of curvature for these bends was about 1.5 to 2.5 feet. This is much higher than the radius of the fiber, so optical waveguide theory calls for little effect on the loss.

In preparation for the test of the pyramidal concentrator, a profile of the illumination levels in the controlled lighting room was determined. The sources of illumination were standard fluorescent light fixtures and rows of 100-W incandescent bulbs. Contour plots of the light intensity indicate concentric circles of increasing light intensity. Light intensity increased from low levels on the outer edges of the facility to the highest light intensity directly above the concentrator. Finally, the concentrator was placed in the lit facility, and its concentration ratio determined. Preliminary results for the concentrator give a concentration ratio of 2.5:1. Although this is less than expected from initial calculations, a measurement of the reflectivity of our mirrored plexiglass gave a value of about 65%, instead of the 80% presumed initially. Other sources of error in the design and/or fabrication are being sought as explanations for the reduced concentration ratio.

Future Work: Improvements to the Non-Imaging Concentration Ratio

Previously, reference was made to the problem of exiting light rays from the

Table 1. Transmission loss versus bending angle of fiber.

Bend Angle	Incident Intensity (Lux)	Transmitted Intensity (Lux)
0°	15500	3350
30°	18000	4200
45°	18400	4570
60°	17250	4350
90°	16000	4110
135°	16100	3400
150°	16250	3300
180°	16100	3600

Table 2. Transmission loss vs. Number of 180° Bends.

Number of bends	Incident Intensity (Lux)	Transmitted Intensity (Lux)
1	16100	3600
2	16300	3400
3	15900	3390

non-imaging concentrator and their angular distribution. As will be recalled, this angular distribution exceeds the narrower acceptance angle of the optical fiber. Therefore, an undetermined amount of the light, collected by the concentrator, is not transferred to the fiber, and is thus not available for illumination purposes. Indeed, it is the opinion of the researchers that this “light spillover” effect at least partly accounts for the discrepancy between the expected concentration ratio and the measured value. Several researchers in the solar thermal energy field have proposed different approaches to the coupling problem between optical fiber and solar concentrators. Fang et al. have examined several combinations of nonimaging techniques, imaging optics such as lenses or mirrors , and fiber optics to maximize the irradiation of small target sizes by concentrated sunlight. Feuermann et al. have proposed a combination of miniature parabolic dishes that are illuminated through a single optical fiber, which in turn has light focused upon its entry aperture via reflections from a flat mirror.

Recently, several researchers in the passive solar energy community have proposed, designed, and tested combinations of non-imaging Fresnel lenses and other non-imaging concentrators in order to achieve several objectives: (1) the ability to design solar power collectors which do not need to track the sun’s position in the sky, and (2) the ability to uniformly irradiate small surfaces, as in photovoltaic applications [Leutz et al.-99a, 2000b]. Figure 7 below shows a basic schematic of the arched Fresnel lenses together with a second concentrator [Leutz et al.-99a, 2000b]. The present researchers have secured funding for optical bench equipment and flexible Fresnel lens material, and hope to report in the future on any improvements in concentration ratio derivable from such a combination scheme.

Conclusions

The conclusions and results reported herein represent only a first phase of research on the efficacy of this scheme for passive solar lighting. An initial design of a system incorporating a truncated pyramidal nonimaging concentrator and a large-core plastic optical fiber has been built and tested. Three separate series of tests have been performed on the optical fiber itself, and an overall test on the integrated fiber to concentrator link. The first series characterized the transmission coefficient of the 0.7-in. diameter fiber. For a 75-foot length, the transmission was found to be about 25%-30%, in accord with manufacturer’s specifications. The second and third series of tests tested the transmission through the fiber at various bend angles and with multiple bends. The transmission was found to be relatively insensitive to angle and to the number of 180° bends. Finally, the pyramidal concentrator-to-optical fiber link has been shown to yield some intensification (x 2.5) of light entering it. Further designs, including two-stage Fresnel lens-concentrator architectures and simulations are in the planning stages.

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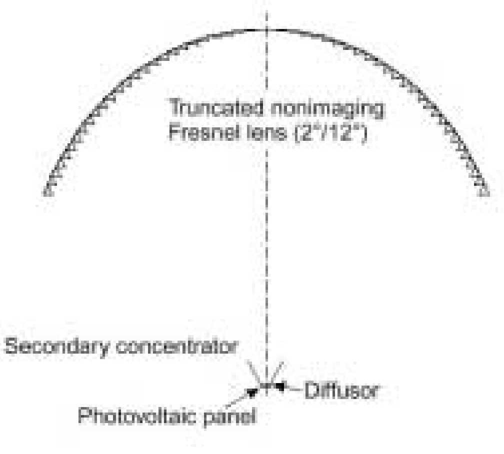

Figure 7. Schematic of non-imaging Fresnel lens aligned with a secondary concentrator.