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EFFICIENT OPTICAL COUPLINGS FOR FIBER-DISTRIBUTED SOLAR LIGHTING

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ABSTRACT

Optical couplings in large core optical waveguides have many similarities with those in conventional optical fibers but pose some unconventional challenges as well. The larger geometry, looser manufacturing tolerances and reduced dimensional stability compound the problems associated with making low-loss couplings in large core waveguides.

The individual factors contributing to coupling losses are discussed to develop an understanding of the extant loss mechanisms. Individual methods and materials employed to mitigate the impact of each of the dominant loss mechanisms are discussed in detail.

A combination of endface geometry control, axial alignment constraint and refractive index matching are employed to produce highly efficient optical couplings in large core waveguides. The combination of these elements has significantly reduced the insertion losses due to connector couplings. Prior to implementing the current methods losses of 15% and greater were common but these have been reduced to 2%-5% with the current methods.

INTRODUCTION

Although the concept of transmitting the sun's light through an optical fiber for illumination is simple, lighting systems based on this approach will be somewhat more complex. The sun's light must first be collected and launched into a fiber. From there, it must be transmitted, perhaps divided and ultimately allowed to flow into a luminaire for useful distribution into the area to be lighted.

Large core (12.6mm) plastic optical fiber is being used in the development of hybrid lighting systems that will combine natural and artificial light. What is, for simplicity, called an optical fiber is actually configured as an optical waveguide, with a central core surrounded by cladding material of lower index of refraction. The deployment of efficient hybrid lighting systems will require the ability to connect all of the various subsystem components in a way that minimizes any degradation of luminous efficiency. When the sun's energy is collected and launched into a fiber, any subsequent connection of that fiber to another system component (e.g. another fiber, a splitter or a luminaire) will cause some of the light to be lost. The quality of the systems that are ultimately deployed will directly depend on the ability to connect all of the components in a way that wastes as little of the collected light as possible.

Optical couplings and their associated losses

In order to develop methods for minimizing connection losses, it is important to first understand why they occur. In a fiber-distributed lighting system, the minimum amount of loss that can occur is the small amount of absorption that takes place as the light passes through a straight section of un-interrupted fiber. Here the light is completely contained by the core and cladding of the fiber and it is only the material properties of the fiber core and cladding that cause a little of the light to be absorbed along the way.

A casual observation of almost any fiber connection will look almost like a continuous section of fiber. If we could take a microscopic look at the connection, however, we would see a very different situation. At every coupling of a fiber to another fiber (or to another component) the containment of the light crossing that interface is momentarily lost. The light completely exits one fiber, passes through the free space between the two fibers and must re-enter the other fiber. Unlike a continuous section of fiber, this introduces several ways in which light can escape and also creates additional resistance to the flow of the light. To minimize the optical losses, the coupling must approximate an uninterrupted fiber as closely as possible. The ends must be in intimate contact, the axial alignment of the two ends must be preserved and the optical index variation across the gap between the fibers must be negligible.

Endface preparation

The first step in making an optical fiber coupling is the preparation of suitable fiber endfaces. Each endface must have a shape that enables it to mate well with another similarly prepared endface and it must be polished to reduce the scattering of light as it passes through the surface. The best shape for reliable coupling and reduced losses is a flat endface that is perpendicular to the axis of the fiber. Figure 1 illustrates the benefits of preparing this type of endface and the losses that can occur with other types of fiber ends.

In addition to furthering the objective of achieving flat and perpendicular endfaces fixtured polishing methods are also more repeatable and less dependent upon the skill level of the individual performing the polishing. The endface profile measurements presented in the graph in Fig. 3 show quantitatively, the improvement in profile and repeatability.

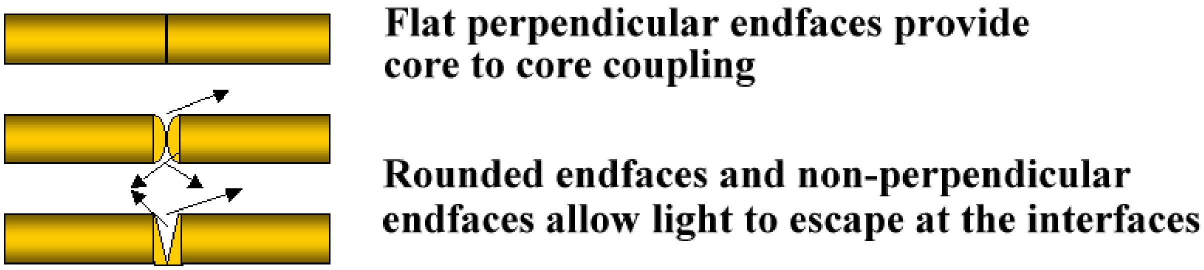

Fig. 1. Effects of endface shape on optical couplings

Hand polishing is commonly used to produce fiber ends that are adequate for getting light into or out of a length of fiber. However, hand polishing produces less than optimum results for fiber couplings. Fixtured polishing that produces flat and perpendicular endfaces can facilitate the production of low-loss couplings. A hard aluminum lap with adhesive backed aluminum oxide abrasive sheets applied to it provides a suitable surface for generating good quality endfaces. The fixture that maintains the fiber perpendicular to the surface of the lap is aligned with a digital displacement gauge to ensure perpendicularity across the range of travel across the lap. A very coarse abrasive is used to grind the initial surface and progressively finer abrasives are used to remove the surface damage produced in the grinding step. Once the flat and perpendicular end is well developed, final polishing can be achieved in very brief unfixtured hand polishing steps using very fine aluminum oxide abrasives on a soft rubber-polishing pad mounted in an electric drill. The material removal in the polishing steps is minimal and does not significantly degrade the surface geometry. A comparison of the endfaces produced with a freehand polishing method and a fixtured polishing method is shown in the photo in Fig. 2.

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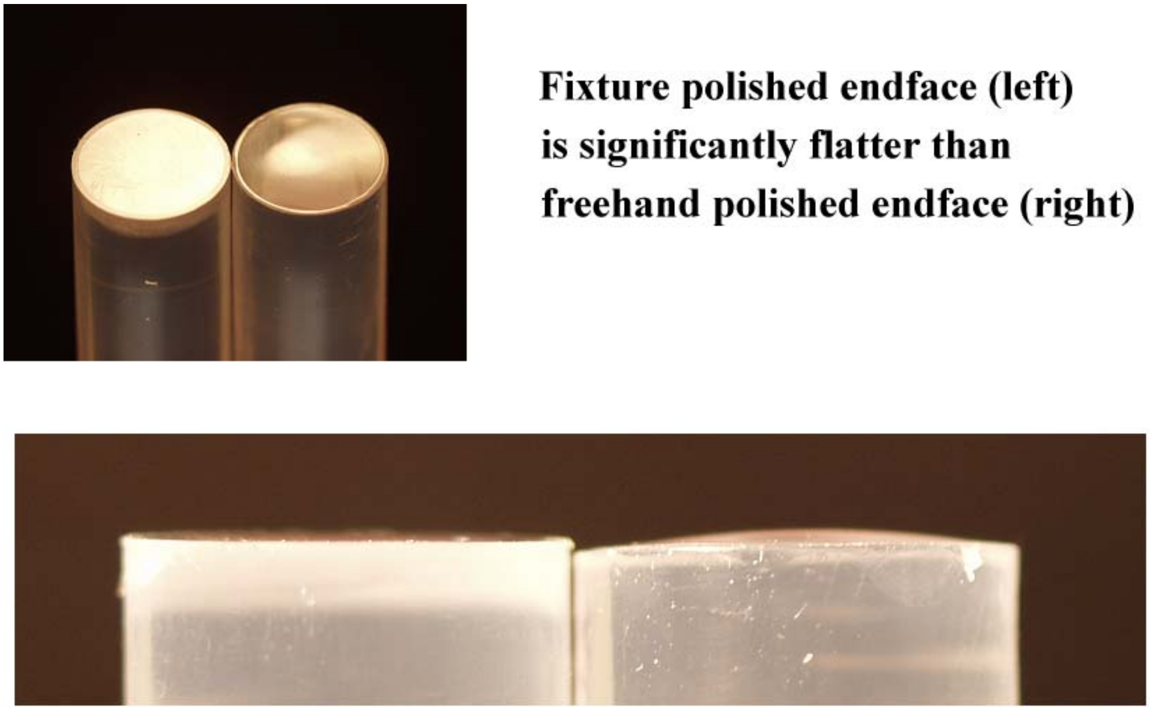
Axial alignment and connector design considerations

Although all of the examples in Fig. 1 are shown with good axial alignment, it is intuitive that any axial misalignment will also create an opportunity for light loss to occur. The manufacturing processes for the large core plastic fiber products allow a fairly large tolerance (about 1mm total) in the variation in the fiber diameter. This complicates the process of maintaining alignment within a connector. Fortunately the variations within a given batch of fiber are usually much smaller than the manufacturer's specified maximum tolerance. However, they are significant enough to require some effort to ensure axial alignment.

Some of the commercial connectors that have been used failed to provide enough mechanical support to the coupling to maintain the axial alignment. One method for improving the performance of these connectors has been the addition of an elastomeric bushing. Heavywalled vinyl tubing was used for one version of this bushing and offered promising results. The tensile properties of the bushing tended to hold the fibers in alignment. Also, the bore of the connector was modified to provide a mild interference fit when the fibers and bushing were in place. The elasticity of the bushing combined with the interference fit tended to provide a self-centering means of placing the two fiber ends into good axial alignment.



Fixture polished endface (left) is significantly flatter than freehand polished endface (right)

Fig. 2. Endfaces prepared using fixtured (left) and freehand (right) methods

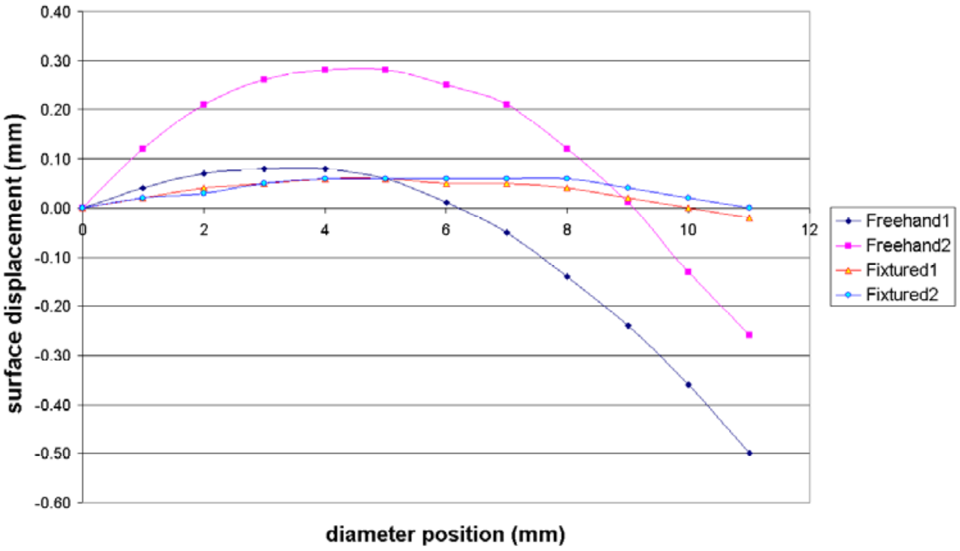


Fig. 3. Measured surface profiles of freehand and fixtured polishing results

There is another aspect of the large core plastic fibers that complicates the axial alignment. That is the lack of straightness in the fiber. The fibers are typically shipped in coils and tend to retain curvature from the coiling process. Even over a short section this can be significant enough to affect the axial alignment. One improvement over the commercial connectors that have been tested so far is to increase the length of the connector body. Some prototypes with this modification have been produced and initial tests indicate significant improvement in the axial alignment and resistance to lateral strain once assembled.

Reflective losses and index matching media

There is another loss mechanism that occurs due to material properties and can contribute significantly to coupling losses. No matter how well the fiber endfaces are prepared, there will still be some gap between the two coupled fibers. Whether the gap is less than one micron or more than one hundred microns, there will be about a 4% loss as the light leaves the first fiber and enters the air gap. There will be another 4% loss of the remaining light as it enters the second fiber. These losses are due to the difference in the optical properties (specifically the index of refraction) of the air and the fiber core material and are referred to as "Fresnel reflection" losses. These reflections alone will cause about 8% of the light to be lost at each connection, no matter how well the endfaces are prepared and no matter how well they are aligned. Any other losses due to misalignment and scattering will result in still more attenuation.

The only way to avoid the reflective losses is to make the gap between the fibers look as much like the fiber core material itself as possible. There are commercially available compositions designed to perform just this task. These are known collectively as "index matching media" and can be purchased as fluids or gels, which are used to displace the air in the gap between the fibers. If an index matching medium can be found that exactly matches the index of refraction of the fiber core, theoretically the reflective loss would be zero. In optical fiber communications systems it can be extremely important to eliminate even the smallest reflections that occur at the fiber coupling interfaces. Consequently, great effort and expense is justified to obtain an index matching medium with an exact match to the fiber core. In practice, however, even a relatively poor match is sufficient to make the losses negligible for lighting applications. The core of the fibers used in the hybrid lighting research have an index of refraction of about 1.50. Figure 4 shows the calculated reflective losses as a function of the number of couplings. The calculated losses with no index matching medium are compared with the calculated losses using a commercially available gel with an index of 1.46. The gel with an index of 1.46 lowers the fresnel reflection loss per coupling from 7.8% down to 0.03%. Over 99% of the light is maintained after eight couplings with the gel. By contrast, without an index matching medium, the same number of couplings would cause almost half of the light to be lost due to fresnel reflections.

The actual choice of an appropriate index matching medium for lighting applications is dictated more by its mechanical properties than its index of refraction. Many media, from glycerin to super-glue, would provide an acceptable index match and offer significant flexibility in coupling design options.

Preliminary tests have been conducted with three types of index matching media, fluids, gels and adhesives. All of the materials show good optical characteristics but vary in their ease of use and mechanical properties. The fluids appear to be the least useful for most hybrid lighting applications because they can seep out of the connections unless some reservoir is provided around the coupling to reliably contain them. The gels, by comparison, stay in place and are very easy to work with. There are a variety of adhesive options with different properties. Both cyanoacrylates and epoxies have been tested with good results for permanent or semi-permanent applications.

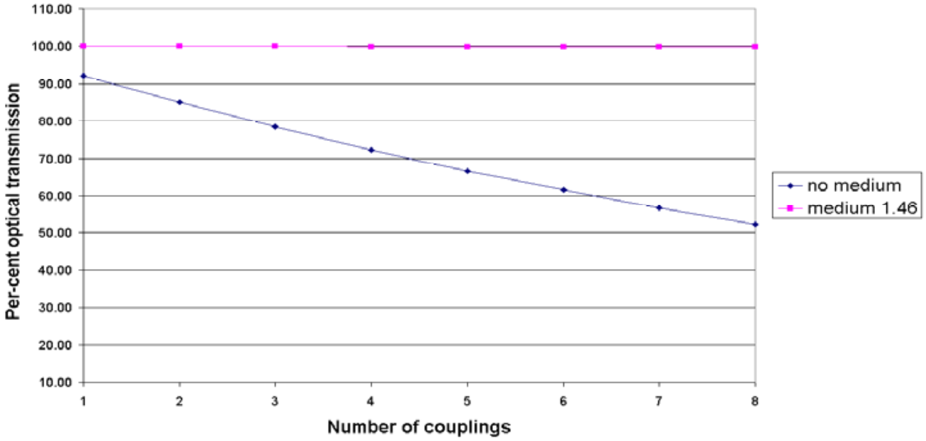


Fig. 4. Comparison of calculated losses with and without index matching gel

CONCLUSIONS

The losses associated with the use of couplings for fiber distributed solar lighting systems are largely attributable to the combined effects of endface geometry, axial alignment and Fresnel reflection loses. Significant progress has been made in the development of polishing methods that rapidly, reliably and repeatably result in high quality endface surfaces. This is expected to significantly reduce the amount of light that can escape at the fiber couplings. Similarly, the use of improved connectors to reduce axial misalignment of the fiber ends appears to be reducing the losses associated with that loss mechanism.

There has been an initial learning curve associated with the effective use of the index matching media but the results that are presently being obtained with these products are extremely encouraging. The effectiveness of the index matching media is so impressive that it may reduce the amount of polishing that is required. Experiments have shown that even endfaces that have only a preliminary polish (resulting in a frosted appearance) look perfectly clear and perform as well as highly polished endfaces, when mated to a similarly prepared endface surface with an index matching medium in between.

It has been difficult to reliably quantify the isolated impacts of each of the individual mechanisms associated with coupling losses. This is largely due to the variability in the results obtained with uncontrolled endface geometries, axial alignments and reflective losses. Prior to taking steps to control these various losses, connector losses on the order of 15% per coupling were common. The collective measures that have been taken to control these losses have, however, led to a measurable reduction of in coupling losses. With the existing degree of development in endface preparation, connector designs and the use of index matching media, losses are routinely being contained to between 2% to 5% per coupling.

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