

Photocuring in Areas Where You Typically Cannot Get Light

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Abstract

This paper describes a technique for photo-curing and/or performing photochemistry in areas where it is difficult, if not impossible to get actinic radiation by normal, conventional means. The technique involves the use of a Light Diffusing Fiber (LDF) to deliver the actinic radiation.

In most cases of photo-curing, the actinic radiation (usually UV or visible light) is delivered to the photo-curable material by direct exposure to a light source or exposure to reflected light from a light source. The light may be focused, de-focused, collimated, or otherwise manipulated with lenses, reflectors, prisms, gratings, etc. The light sources typically are lamps, LEDs, excimers, lasers, etc. The light can even be directed down a fiber or waveguide such that the light emits out the opposite end of the fiber and is available for photo-curing and/or performing photochemistry. However, there are cases where it is desirable to photo-cure or perform photochemistry on a material when the material is in an area where it would be impossible to direct light. The light might be blocked by any opaque, absorbing or highly scattering material or object. An example would be trying to photocure a material that is between two pieces of metal, curing inside an opaque tube or pipe, curing under an opaque paint or highly absorbing coated layer, etc. Using LDF is a means to deliver light and allows for the facile photo-curing of materials in these hard-to-get-light-to areas due to the small diameter and flexibility of the LDF.

An LDF is an optical fiber that is intentionally designed such that when light is input into the core on one end of the fiber, the light leaks out the sides of the fiber along its length. Such fibers are often also called “leaky” fibers or light scattering fibers. Since light is emanating out the sides of the fiber along its length, this light can be used to perform photo-cure and/or photochemistry along the whole length of the fiber. Glass core optical fibers with their small size and flexibility can readily be placed into tight areas or areas where it may be difficult to otherwise get actinic light. The LDF fiber or fibers can be placed in or near photo-curable materials and then when powered with light affect cure or do photochemistry in these areas.

Introduction

Optical fibers are used for a variety of applications where light needs to be delivered from a light source to a remote location. Optical fibers are specifically designed to efficiently deliver light from point-to-point over long distances. Most of the light injected into one end of

the fiber exits the opposite end with only insubstantial amounts exiting peripherally through the sides of the fiber along its length. Thus, standard optical fibers function as a point source and are not well suited as an extended illumination source. However, optical fibers can be designed with light scattering centers in the core of the fiber that provide very efficient scattering of light through the sides of the optical fiber along its length. This type of fiber is called a light diffusing optical fiber (LDF). Visible light transmitting/emitting LDF's are under consideration in a number of applications such as specialty lighting, signage, and display applications where a select amount of visible light needs to be provided in an efficient manner to specified areas. Since LDF's are silica-based, they are very efficient at transmitting/emitting light across the UV, visible, and near IR wavelength range. This study specifically looks at powering LDF's with UV light in order to induce photocuring.

Both the small size and the scattering mechanism employed in the fiber afford a very small, flexible and efficient illumination source¹. The fibers are about the size of normal silica transmission optical fibers. The glass core diameter can vary from about 100-200 microns, and the polymer clad thickness is ~50-70 microns, making the OD of the fiber less than 150-250 μm . For high power or UV applications, the fiber can employ a glass cladding as well to more efficiently emit these wavelengths. The efficiency of coupling light sources may also be adjusted to accommodate a variety of light sources, both lambertian and laser sources. Coupling efficiency of single fibers with laser sources is very high, but will decrease when using a lambertian source such as an LED. This latter coupling problem may be addressed by the use of a low index polymer cladding to increase the numerical aperture (NA) of the fiber so that it can range from 0.35-0.53. In addition, the LDF's may be bundled together to effectively increase the core size to more effectively couple light from LED's and similar light sources. The extraction of light from the fiber is very uniform and may be tuned to scatter more or less light through the sides by controlling the number of scattering sights within the core of the fiber. The emitted light may also be converted to different colors by the use of phosphor coatings or altered by using light sources of different colors if so desired.

The light diffusing fiber has a silica core in which a section contains scattering sites with submicron size.^{2,3} These scattering centers effectively scatter the propagating light almost independently of the wavelength of light used. As mentioned earlier, the magnitude of scattered light may be controlled and depends on the size of the scattering centers and their relative area compared to the fiber core. The absorption losses within the fiber are negligible, and the scattering losses can be as high as 5-7 dB/m. When fiber is bent or turned sharply, loss of light can also occur as a secondary mechanism however, in the case of LDF, these bending losses are also small with minimum bending diameters as small as a 5mm radius.

The large core size and high NA of the fibers allow low loss coupling of light from inexpensive laser sources, such as visible or near infrared (NIR) laser diodes with efficiencies higher than 85%. Coupling from other types of lasers with reasonable beam quality can also be done with very high efficiency. The relatively low cost of blue diode lasers (405 or 445nm) creates an economically feasible route to scattering visible light with different colors by placing one or more phosphors in the coating of the fiber. In addition, other scattering materials also can be placed in the coating to provide a fiber with a uniform angular scattering distribution. Several of these fibers can be bundled together to couple extended light sources, such as LED or high

brightness lamps, into the fiber. Bundles with ~40 fibers have been demonstrated with coupling efficiency ~30% to LED sources. Figure 1 shows an example of a bundle of LDF's being powered simultaneously from one light source.



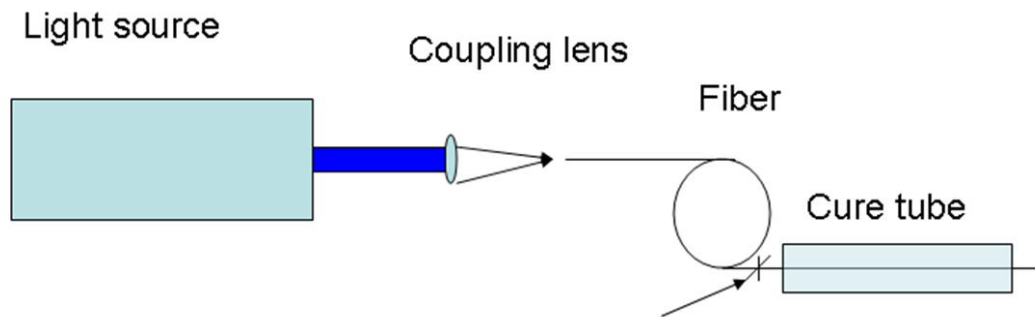
Figure 1. Example of a bundle of LDF's being powered simultaneously from one light source.

The flexibility of thin glass fiber LDF's enables them to be deployed in complex configurations and shapes in special light applications. In this study, the small, flexible LDF fiber or fibers are placed in or near photocurable materials that are in areas inaccessible to the traditional ways of delivering light. Then, when the LDF is powered-up with actinic radiation (in this case, UV light) photocure and/or photochemistry can be performed in these areas⁴.

The idea to use side emitting optical fibers to conduct photocuring is not new. In earlier patents describing optical fiber photocuring,^{5,6} fibers were made to lose light by bending or weaving them to create microbends, tailoring the thickness of the cladding to allow evanescent wave transmission, removing the cladding at intervals along the fiber, and removing the coating or deliberately damaging the coating or cladding along the fiber. Technical articles from the University of Nottingham⁷⁻⁹ also describe the use of side emitting optical fibers to conduct photocuring. However, most of these fibers are plastic fibers or plastic clad silica fibers with surface modifications used to scatter or disperse the light. These fibers possess some characteristics that may cause issues when used in photocuring. Plastic fibers typically suffer from higher absorption losses than silica fibers especially in the UV wavelength range. Also, it is difficult to control the scattering losses by surface modification when the fiber is submerged in a high refractive index media such as an adhesive. Our design of light diffusing fiber has small scattering centers which are gas filled voids introduced into the core of the fiber causing high refractive index contrasts. The scattering sites efficiently fill the core space, have high scattering cross-sections, and are located away from the surface of the fiber.³ The amount of the loss through scattering can be accurately controlled by the placement, size, and amount of scattering sites in the core. In the past, air bubbles, air holes, and air gaps have been used to make side emitting optical fibers but only in polymer fibers or polymer clads.¹⁰⁻¹²

Results and Discussion

For demonstration experiments, we used 250 μ m LDF fiber and the light source was a Hippo Spectra Physics laser operating in the 355nm wavelength with 2.3 W of power, repetition rate 30kHz, and pulse width \sim 10 ns. The laser was coupled to the fiber with efficiency \sim 60%. The fiber was placed inside a \sim 30 cm long non-transparent plastic tube filled with the adhesive composition of Example 8 in US 7,256,221, or Norland 61 optical adhesive and radiated for different amounts of time depending on type of adhesive used from 10 to 60 min (See Figure 2).



Connection of delivery and Light Diffusing Fiber

Figure 2. Setup for using a light diffusing optical fiber for UV adhesive cure inside opaque tube.

After the irradiation step, the tube was cut open and the degree of cure was evaluated. The polymer cured up to \sim 3-4mm away from center of the fiber as shown in Figure 3.

Different light sources could be used in this method. They can be either CW or pulsed. Also, since the fiber can deliver multiple wavelengths, it is possible to couple an additional visible light source for inspection of the adhesive during the filling process. The fiber has relatively high strength, so it is possible to evaluate the degree-of-cure of the adhesive in the tube by pulling on the fiber. Fiber designs with less UV loss (lower absorption) are proposed by using glass clad instead of low index polymer clad. Since the LDF is very small, it can be left in place after cure with minimal effect.



Figure 3. This is a picture of a photocured polymer that was cured inside a 4mm i.d. opaque tube. An LDF fiber was placed into the center of the tube filled with a photocurable polymer. The LDF was powered with a 355nm laser. After irradiation, the polymer was completely cured around the fiber.

Figure 4 shows a schematic where an LDF is embedded in a UV curable lens potting compound that was dispensed around the perimeter of a silica lens. When the LDF fiber is powered-up with UV light, the potting compound cures and bonds the lens to the metallic optical mount.

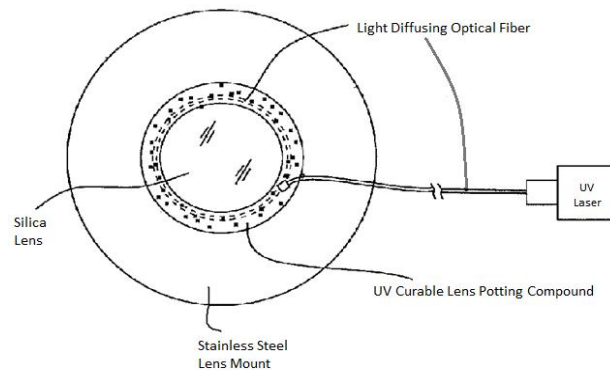


Figure 4. Schematic where an LDF is embedded in a UV curable lens potting compound that was dispensed and cured around the perimeter of a silica lens.

Figure 5 is a side-view of a case where an LDF allows for UV cure of the lens potting compound in a lens assembly where there is not access of UV light to the potting compound by the conventional ways of delivering UV light. In this figure, an opaque coating is on the silica lens edges and an opaque shield is over the potting compound. The opaque coating and shield are to protect the potting compound from degradation by scattered short wavelength UV radiation during operation of the lens assembly. The LDF is embedded in the UV curable potting

compound around the perimeter of the lens as shown and when powered-up with UV light, the potting compound photocures.

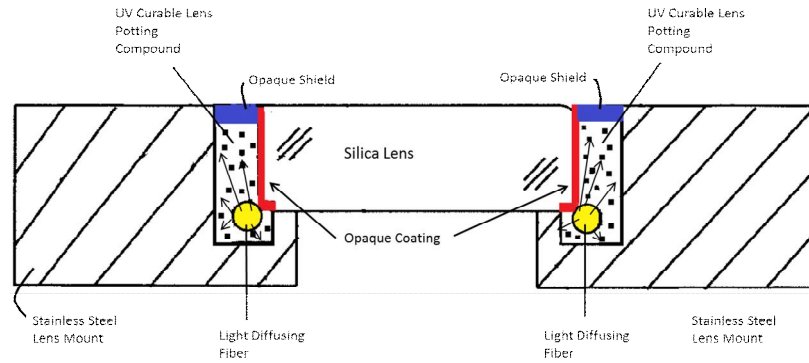


Figure 5. Side-view of a case where an LDF allows for UV cure of the lens potting compound in a lens assembly where there is not access of UV light to the potting compound by the conventional ways of delivering UV light.

Figure 6 shows a schematic where a sandwich structure is formed by two opaque planar elements with a layer of photoreactive material in between. The opaque planar elements may be for example, glass sheets that are substantially opaque to actinic light (e.g., by virtue of anti-reflection coatings, opaque paint, etc.), metal, plastic or other materials that substantially prevents actinic light from reaching all parts of photoreactive material. Trying to perform a photoreaction of photoreactive material through the opaque planar elements of the sandwich structure is problematic using conventional free-space illumination techniques

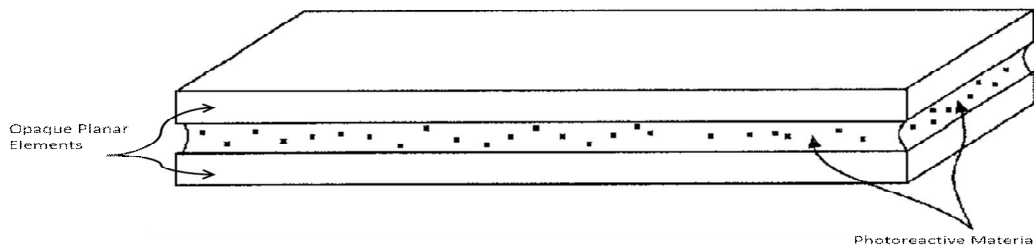


Figure 6. Schematic where a sandwich structure is formed by two opaque planar elements with a layer of photoreactive material in between.

Figure 7 is a cross-sectional view of the sandwich structure of Figure 6, wherein an LDF-based actinic illumination system is integrated for performing a photoreaction in the sandwiched photoreactive material. Figure 8 is a top-down view of sandwich structure of Figures 6 and 7 and shows a serpentine configuration of light diffusing optical fiber embedded in the photoreactive material. The light-diffusing fiber is configured so that scattered actinic light can reach all parts of the photoreactive material so that the photoreaction, such as photocuring, takes place over the entire photoreactive material.

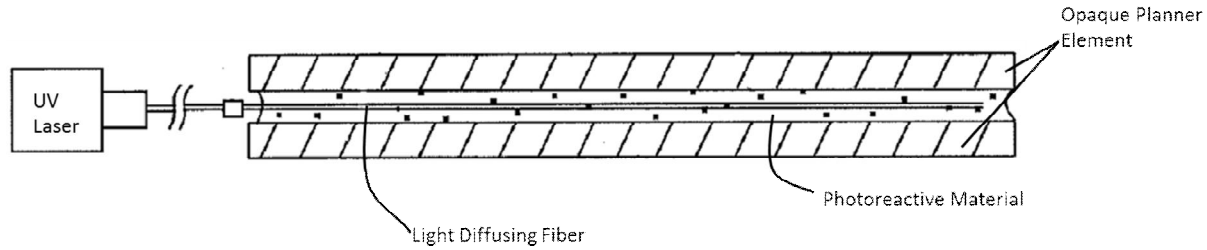


Figure 7. Cross-sectional view of the sandwich structure of Figure 6, wherein an LDF-based actinic illumination system is integrated for performing a photoreaction in the sandwiched photoreactive material.

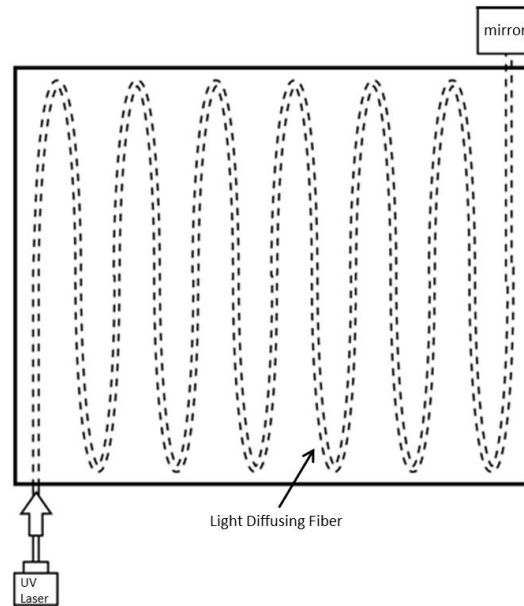


Figure 8. Top-down view of sandwich structure of Figures 6 and 7. It shows a serpentine configuration of light diffusing optical fiber embedded in the photoreactive material. The light-diffusing fiber is configured so that scattered actinic light can reach and cure all parts of the photoreactive material.

Figure 9 shows a transparent mold with upper and lower mating halves. The inside of the mold has a particular shape and is filled with photocurable material. Light diffusing optical fiber is coiled or wrapped around the mold outer surface. When the LDF fiber is powered up with UV light, the photocurable material inside the mold cures to form a molded body that is removed when the mating halves are separated.

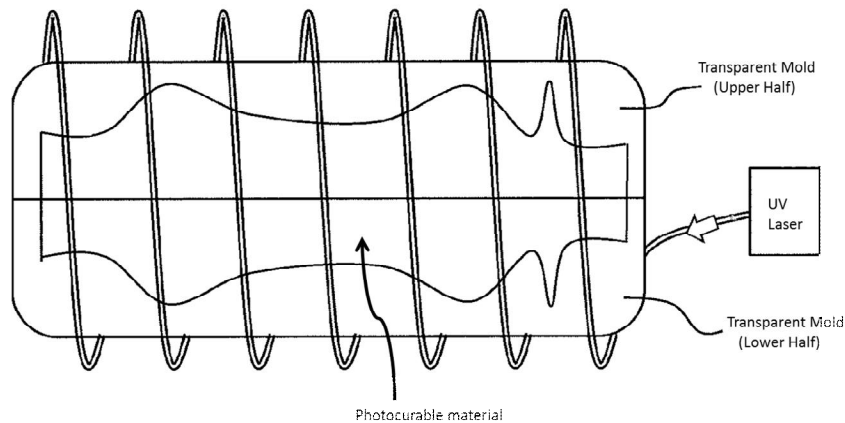
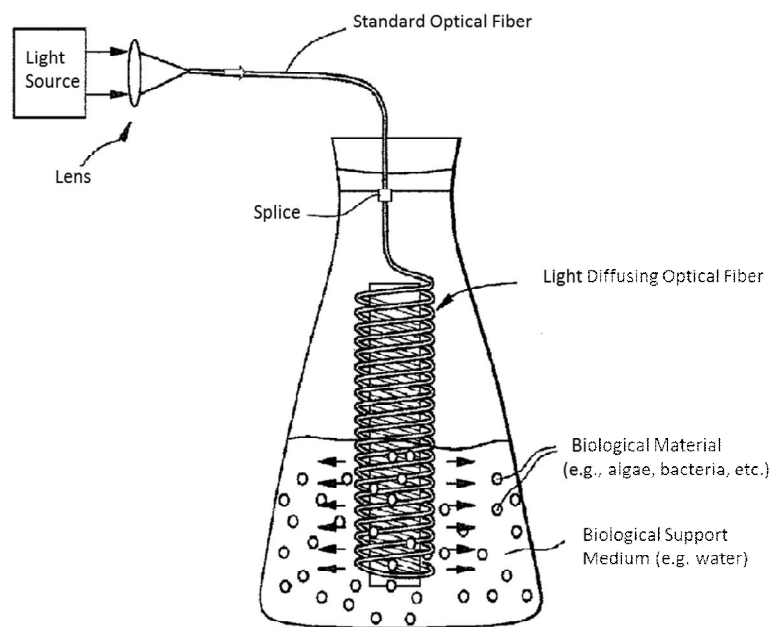


Figure 9. Transparent mold with upper and lower mating halves. The inside of the mold has a particular shape and is filled with photocurable material. Light diffusing optical fiber is coiled or wrapped around the mold outer surface. When the LDF fiber is powered up with UV light, the photocurable material inside the mold cures to form a molded body that is removed when the mating halves are separated.

In addition to photocure, given their flexibility and unique ability of LDF's to transmit and dispense light, LDF's can also be used for other purposes. For example, Figure 10 illustrates an example illumination system used in a biological growth system. A coil of light diffusing optical fiber is immersed into a biological chamber (e.g., a flask) containing biological material (e.g., algae, bacteria, etc.) possibly in a support medium like water. The LDF(s) provide light for biological material growth.



Fluorescent or phosphorescent material can be added to the LDF coating that serves to modify the scattered light. Suitable up or down converter molecules may also be included in the coating to produce light of different wavelengths from that of the input light source. For example, Figure 11 shows white light emanating from an LDF fiber powered with a blue 445 nm laser diode. The color conversion of blue light to white light is done using a Ce-YAG phosphor doped into the coating of the fiber. The fiber diameter is 500 μ m and length is 1.5 m. The brightness of the fiber can exceed 10,000 lux.



Figure 11. White light emanating from an LDF fiber powered with a blue 445 nm laser diode. The color conversion of blue light to white light is done using a Ce-YAG phosphor doped into the coating of the fiber.

Due to the small size of LDF fiber, the scattered light can be coupled into flat glass to make a very low level illumination fixture similar to a back light unit (BLU) used for LCD displays. A single LDF fiber is attached around the perimeter of a sheet of glass. The glass has a coating on it that scatters light coupled to the waveguide glass sheet. The picture on the left in Figure 12 shows the 4"x 4" glass plate with no power to the LDF and the picture on the right shows what happens when the LDF is powered with 455nm 1W diode laser.

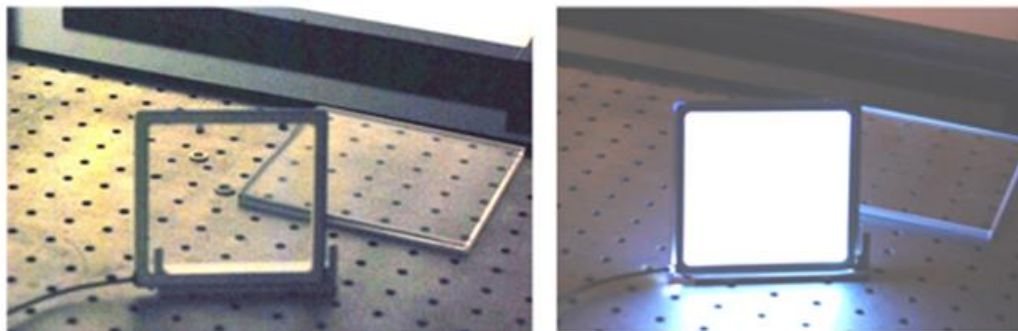


Figure 12. A 4"x 4" glass plate with a single LDF fiber attached around its perimeter. The glass plate has a coating on it containing a light scattering agent. The picture on the left is with no power to the LDF and the picture on the right shows what happens when the LDF is powered.

Figure 13 shows a much larger diameter (~2mm) LDF fiber called a Light Diffusing Cane. This is simply a large diameter core with no cladding. The large diameter gives it a very high numerical aperture making it very easy to couple to a LED with 90% coupling efficiency. Surface scattering or phosphor layer(s) can be added as well as a polymer jacket to facilitate handling. The cane can have a length from 5cm to 1m and can be powered with 1 or 2 LED sources up to 1000 lm brightness. The cane is not flexible but can be shaped by heating.



Conclusions

We describe a light diffusing optical fiber (LDF) with a silica glass core containing scattering centers that effectively scatter light through walls of the fiber along its length. The LDF's light transmission is wavelength independent across the UV, visible light, and near IR spectral range. The LDF's high flexibility due to its small diameter, scattering uniformity, and low absorption loss make it an interesting illumination product for a variety of light source applications including UV curing. In fact, we have shown that LDF's can be used to perform photocuring or photochemistry in areas where it is difficult, if not impossible to get actinic radiation by normal, conventional means.

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