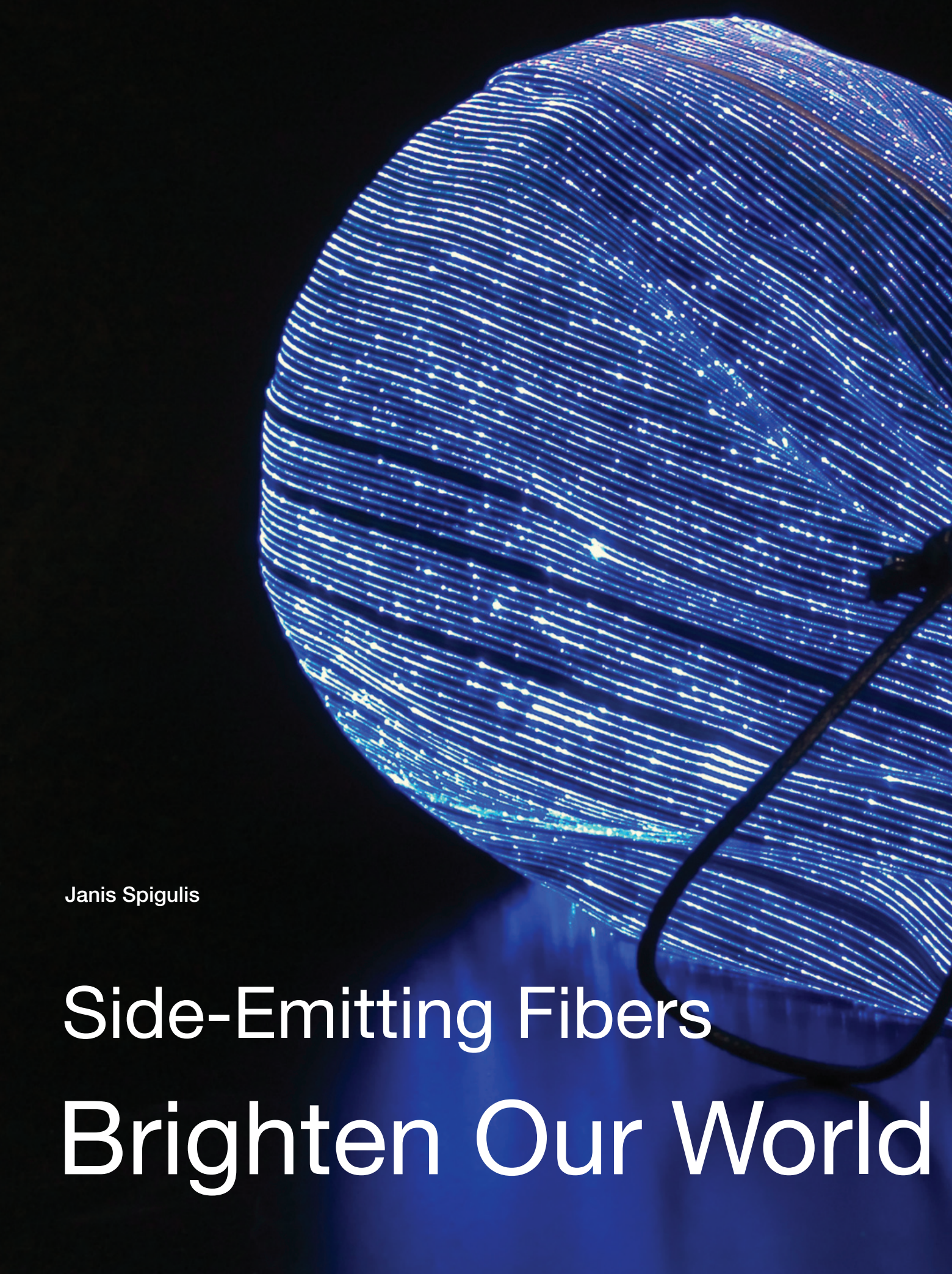




Janis Spigulis

Side-Emitting Fibers Brighten Our World



Optical fibers are usually associated with optical communication, laser power delivery and other applications that carry light from one point to another. Over the past decade, however, these fibers have found a new niche—as photonic non-thermal filaments that can be used for applications ranging from glowing art and fashion to infrared security systems to clinical devices.

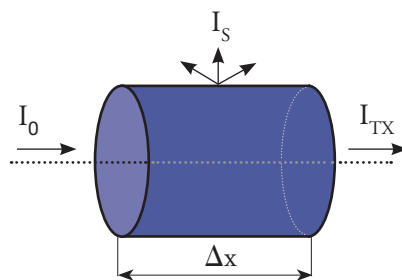
in New Ways

Side-emitting optical fibers are flexible linear illuminators that are designed to promote leakage of the core-transmitted radiation via their side surfaces. The “glowing” effect can be achieved in several ways—by micro-bending the fiber axis, for example, adding specific scatterers or fluorescent additives into the fiber core or cladding material, creating asymmetries in the fiber core/cladding geometry, increasing the refractive index of the fiber cladding material over that of the core material, or leaving diffusive cavities (e.g., air bubbles) inside the fiber core. The fiber’s side emission could be designed to be continuous or interrupted, depending on the fiber design and materials. For instance, an interrupted emission pattern could be used to create a dotted line or irregular bright emitting spots along the fiber’s length.

The fibers have been used to create decorative illumination in air, water and ice; laser shows and displays; glowing textiles for clothes, accessories and interiors; and visible or invisible (UV, IR) framing. They may also have more practical applications in the fields of security surveillance, emergency lighting, fiber-optical sensing and dosimetry and medical phototherapy.

Principles behind the effect

The side-emission effect is created by “leaking” some light from the fiber’s core to its cladding and further via the outer jacket to the surrounding medium, which is usually air. Most often, the



Light propagation in a short fragment of side-scattering optical fiber.

“glowing” fibers exploit the light-scattering phenomenon: Scattering in the fiber is assumed to be much stronger than absorption or any other eventual light-loss mechanisms, so axial transmission and side scattering become two dominant light transport channels.

By representing the fiber as a sequence of numerous very short fragments (see illustration at left), one can conclude that the side-emitted radiation intensity I_S decreases with the distance x from the light input end according to the following equation:

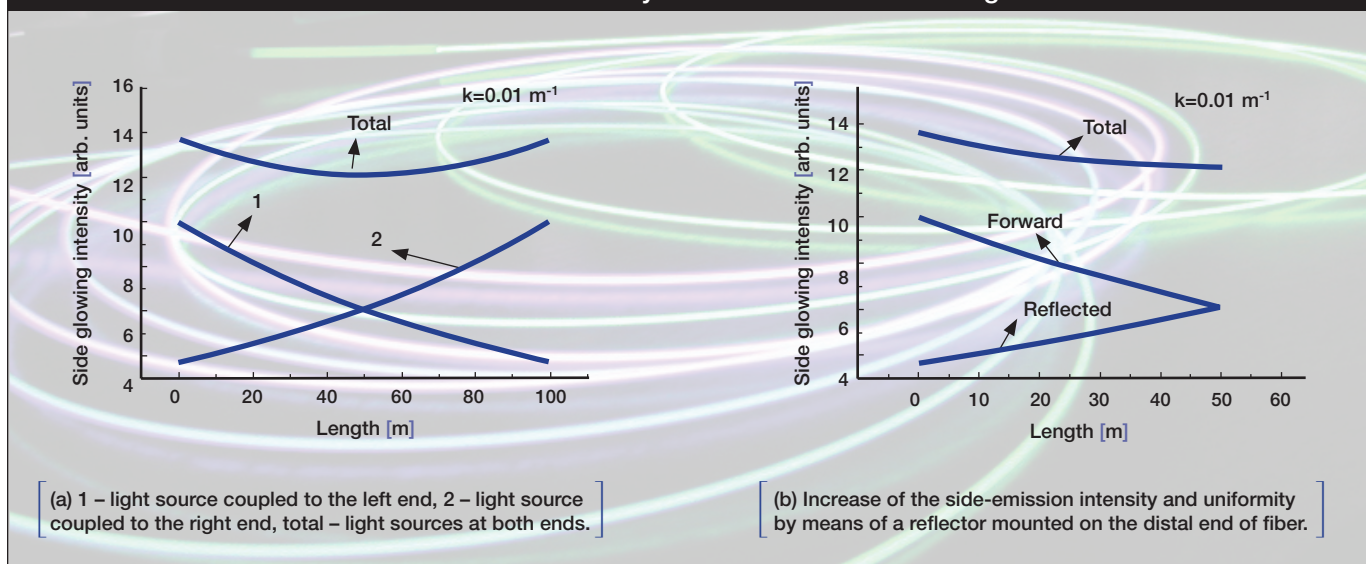
$$I_S(x) = A \exp(-kx) \quad (1),$$

where k is the coefficient of scattering, x is the length of the fiber, and $A = (4\pi)^{-1} I_0 (\exp k - 1)$ —a constant related to the fiber length unit (with I_0 = input intensity). Experimental studies had generally confirmed this simplified physical model. The graph below illustrates this intensity decay graphically [(a), curve 1].

Deciding on the appropriate light management technology is of major importance when it comes to practical use of fiber side-emission. Following are several potential approaches.

- **Coupling one fiber end to the light source** (e.g., laser) is the simplest method of illumination. The other end is left open for the core-transmitted radiation. Although this design version does not provide side-emission uniformity, side-glowing can

Side-Emission Intensity as a Function of Fiber Length



be kept relatively consistent by keeping scattering low; then most of the launched intensity will be transmitted instead of side-emitted and, consequently, the total side-emission efficiency will be low.

- **Coupling light sources to both fiber ends** may appear more complicated technically, but this design approach improves both the intensity and uniformity of the side glowing since the total side-emission at each point summarizes the contributions of both light sources [see graph (a) on p. 36, “Total”].

- **Attaching a reflector to the distal end of the fiber** is a technologically feasible design strategy that may provide sufficient uniformity of side-glow along the fiber length, as well as high conversion efficiency of the input optical power into the fiber side emission [graph (b) on p. 36]. The optimum effect can be achieved if the glowing length x in equation (1) is well harmonized with the scattering efficiency k . In other words, the side-emitting fibers with permanent k values must be manufactured separately for each specific glowing length—not as a universal product for all types of applications.

- **Gradually increasing the scattering efficiency with the fiber length** would be a theoretically ideal solution. Completely uniform side-glowing intensity along the whole fiber could be achieved with the single-end illumination technique. However, implementing this approach would pose serious technological problems. For example, the fiber drawing process would require additional components in order to ensure continuous dosage and control of the scatterers.

- **Exploiting the phenomenon of luminescence** is another way to generate fiber self-emission. This could be done by using radiation propagating along the fiber core to excite luminous molecules or crystals embedded in the fiber core or cladding, or by externally irradiating luminescent fibrous materials by ambient light or UV-radiation.

Applications

Using inexpensive plastic fibers, engineers can reach quasi-uniform side emission lengths of about 30 m; they can create lengths up to half of a kilometer with high-performance silica-core fibers. In addition to these considerable “glowing” lengths, side-emitting fibers are highly flexible, strong, electrically safe, waterproof, resistant to various chemicals, heat-resistant and lightweight.

Silica-core side-scattering optical fibers

Glowing fibers designed with standard SMA input couplers and micro-reflectors at the distal end normally need a



Luminous clothing with woven plastic side-emitting optical fibers.

OPTICS IN THE NEWS

In 2003, *Time* magazine declared the glowing fibers developed by Luminex SpA in Italy to be one of the “coolest inventions” of the year. The fiber contains integrated plastic side-scattering optical fibers that are end-irradiated at various colors by light-emitting diodes. According to the article:

“If only this stuff had been around in the disco era. Luminex is a new kind of fabric that glows—literally. It’s not shiny, it’s not glow in the dark; it actually gives off its own light. Designers took tiny, flexible optical fibers developed for high-energy physics experiments and wove them into ordinary fabric. Power comes from an ordinary battery sewn into the cloth. Luminex is being used in stage costumes, handbags and curtains as well as clothing. The makers are even talking about adding smart chips to the fabric that could make it glow in flashing patterns. Look for a line of silver Luminex pillows from DKNY next year.”

To learn more, please visit www.time.com/time/2003/inventions/invluminex.html and www.luminex.it.



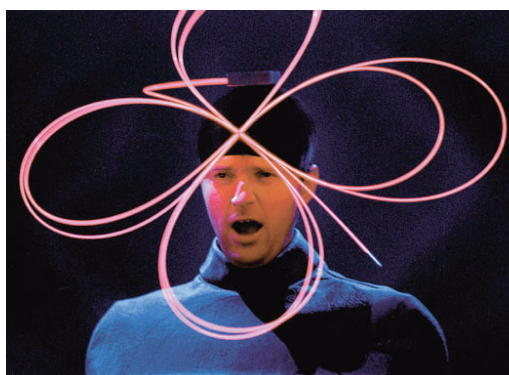
Silica core side-emitting fibers for scenic effects at opera performances. Photographs from the Latvian National Opera's production of Mozart's "The Magic Flute."

well-focused laser beam input. Among the applications for this fiber is so-called laser-fiber artwork, such as the illuminated logo pictured on p. 39 from the annual Photonics West symposium in San Jose, Calif. In this case, copper vapor laser input was used.

Silica-core glowing fibers have also been used to create scenic effects for musical or theatrical performances, such as those seen above and to the right, which were used in the Latvian National Opera's production of Mozart's "The Magic Flute."

By virtue of their side-emitting mechanism of light generation, these fibers will not cause unwanted electrical discharges, ignitions or sparks at the illumination area. This is one reason why they might play an important role for applications in which safety is paramount—such as serving as a luminous lightguide in explosive areas, gas and oil platforms at sea or for military weapons storage.

Quartz, the core material of these fibers, has a broad spectral transmission band—between 0.2 and 2.4 μm —making it possible to use silica-core side-emitting fibers also as invisible guidance that can be seen only using specific convertors such as an infrared photodetector device or as indicators of external interactions such as pressure.



For example, if infrared laser radiation (0.7 to 2.4 μm) is coupled at the input, the side-emitting fibers could be used for security systems, such as creating infrared perimeters and safety barriers for military personnel in extreme battlefield conditions. In addition, fiber side-emitted infrared radiation could be used to mark safe corridors in minefields or the escape route from dusty buildings or dark cave labyrinths.

Ultraviolet side-emission (0.2 to 0.4 μm wavelength range) may be particularly well suited to clinical applications such as the use of UV-C irradiation to induce sterilization. The fibers might also be used to create "smart" textiles for contact skin tanning by means of side-emitted UV-A radiation. Further progress is needed, however, to develop fiber cladding and jacketing materials that are highly transparent in the ultraviolet region of spectrum.

Plastic side-scattering optical fibers

Optical fibers fabricated from plastic materials can be used to create the side-emission effect as well. Plastic fibers absorb more light—and therefore glow darker—than the silica core fibers of identical size; however, a group of them collectively can provide

adequate side-emission at an affordable price. Probably the glowing fiber products that have enjoyed the most commercial success are the so-called “side-glow cables”—finger-diameter bundles of plastic side-scattering optical fibers that are surrounded by a protective transparent tube. Such cables are used for illuminating gardens and swimming pools, framing buildings, illuminating interiors, backlighting and numerous other applications.

These cables, also called “linear flexi-lamps,” are easy to use—the cable-end surface preparation is much simpler than silica-core fiber ends, which require polishing. In addition, conventional white light sources (e.g., metal halide lamps) are well suited for end-irradiation of the relatively large cable input.

Plastic side-emitting fibers are also used in a clinically important product for infants called the “biliblanket”—a soft textile pillow created with woven optical fibers; the luminous blanket is used to treat infant hyperbilirubinemia, which is an abnormal build-up of a blood pigment known as bilirubin. Biliblankets provide uniform planar emission in the blue spectral range (0.4-0.5 μm s) to the infant’s skin—which causes photo-disruption of bilirubin.

Polymethyl-methacrylate side-emitting fibers have even more fascinating applications in fashion. They have been used to develop optical fiber fabric displays on “smart” clothes, which can display various images or animated visual information. (For more information, see “Optical Fiber Fabric Displays,” by Vlado Koncar in the April 2005 *Optics & Photonics News*.)

Luminescent fibers

There have been a number of reports, in the scientific literature and on the Internet, describing fibers that side-emit luminescent light under ultraviolet or visible illumination. Most such fibers are plastic. For example, many are made from polystyrene with specific fluorescent dyes surrounded by a clear acrylic. Lumatec GmbH in Germany has also developed large-core fluorescent liquid light guides. Special scintillating optical fibers are used to detect high-energy radiation and X-ray sensors.

Recently, several companies have manufactured textiles made of “optical” fibers that do not guide the light axially, but become luminous after daylight irradiation. The textiles are made via processes that use strontium oxide chemistry that allow chemical fibers to capture and release that light over a prolonged time period (up to 8 to 12 hours) in the form of a greenish-yellow glow.

Many consumer textile products—carpets, curtains, tablecloths, accessories, clothing, etc.—can obtain an entirely new character when they are given a glowing feature.



Tying it up

Innovative technologies have extended the field of optical fiber applications into unexpected sectors, with applications ranging from everyday consumer products to artwork to clinical equipment and sophisticated security systems. Side-emitting optical fibers are relatively inexpensive, and those based on plastic materials are particularly affordable. The glowing fiber market is still limited mainly by the costs of fiber-adapted miniature light sources with sufficiently high output power. Recent advances in the production of high-performance diode lasers and super bright light-emitting diodes could lead to a breakthrough in this field within the next few years. ▲

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[References and Resources]

Related Reading

- >> J. Spigulis et al., The “glowing” optical fibre designs and parameters, SPIE Proc. **2967** (ed. A. Krumins et al.), Bellingham, WA, 1997, 226-31.
- >> V. Koncar, Optical fiber fabric displays, Opt. Photon. News, **16** (4), 40-44 (April 2005).

On the Web

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