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A New Optical Fiber

By P. KAISER, E. A. J. MARCATILI, and S. E. MILLER

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Currently there is strong interest in optical fibers for use as a transmission medium, analogous to the use of coaxial or wire pairs in the low-frequency region. Most work is devoted to a fiber structure consisting of a central glass core surrounded by a cylindrical glass cladding having a slightly lower index of refraction. This in turn requires that the chemical composition of the core glass differs from that of the cladding glass, leading to undesired effects at the core-cladding interface and perhaps limiting the minimum fiber losses achievable.

The Nippon Sheet Glass Company and the Nippon Electric Company together have developed a fiber (which they call SELFOC) with an index of refraction decreasing parabolically from the fiber axis to its outer boundary. This fiber requires a continuous variation in chemical composition from the fiber axis outward, with attendant complications in the fabrication process. A related guide requiring a film very thin compared to the wavelength has just been reported.[1]

The unique property of the new fiber is that a viable, handleable transmission medium is created by a structural form that uses only a single low-loss material.

The conception was stimulated by the findings of P. Kaiser, et al., who fabricated unclad round fibers and measured their spectral losses in up to 32-meter unsupported lengths.[2] Recently he found total losses as low as 2.5 dB/km at wavelengths near 1.1 μm using selected samples of low OH content fused silica. Similarly low losses have been measured at 1.06 μm in bulk fused silica by T. C. Rich, et al.[3] It appeared attractive to use material of this kind without the need for modifying the composition to alter the refractive index as is necessary with conventional core-cladding fibers or with graded-index fibers.

Figure 1 shows section views of two possible forms of the single-material (SM) fiber. The usefully guided energy is concentrated pri-

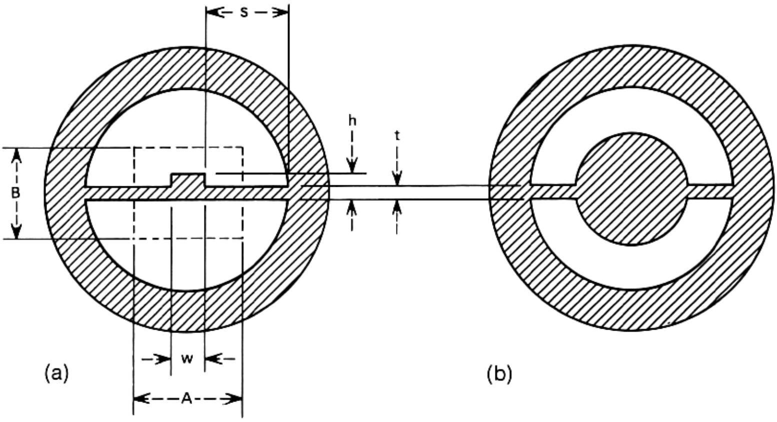

FIG. 1—Cross section of an SM fiber with (a) rectangular and (b) cylindrical core.

marily in the central enlargement, shown rectangular in Fig. 1a and round in Fig. 1b. In Fig. 1a, the central body has dimensions w and h for single-mode operation or dimensions A and B for multimode operation. There is an exponentially decaying field extending outward from the central member in the slab of thickness t; with appropriate spacing between the central enlargement and outer cylinder the guided-wave field at the outside surface can be made negligibly small and the fiber can be handled exactly as can the conventional core-cladding type fiber. Slab modes are possible on the supporting structure, but these are strongly coupled to the outer shell and are readily lost to the surrounding medium. Not shown in the figure is the possibility of adding an absorbing coating on the outer surface for avoidance of crosstalk in a multifiber cable.

The SM fiber structure can have a single propagating mode for any supporting slab thickness t and for any shape of the central enlargement, provided the size of the central enlargement is properly chosen. Practically, though, t must be limited in order to keep the slab dimension s, and consequently the overall size of the guide, reasonably small and still have the exponentially decaying slab field at the outer supporting cylinder small enough.

Analysis has been carried out for both single- and multimode SM fibers of several geometries. A few of the results are abstracted here. For the rectangular-guide case, Fig. 1a, and $t \gg \lambda$, there will be a single propagating mode provided

$$\frac{1}{h^2} + \frac{1}{w^2} \geqq \frac{1}{t^2}. \tag{1}$$

Note that wavelength does not appear in this expression, correct to first order. More exact analysis shows that for $t = 4.89\ \mu\text{m}$ and $h = 7.0\ \mu\text{m}$, the limiting width w for single-mode operation is $7.07\ \mu\text{m}$ at $\lambda = 1.0\ \mu\text{m}$ and $6.94\ \mu\text{m}$ at $\lambda = 0.6\ \mu\text{m}$. In these structures the slab field decays by $1/e$ in 2.80 and $2.75\ \mu\text{m}$ at λ equal to 1.0 and $0.6\ \mu\text{m}$, respectively.

The wave propagation effects of the slab support can be represented by a uniform-index side support having the same height as the core and an equivalent index $n_e = n_c(1 - \Delta_s)$, where n_c is the index of the w-by-h core. Then, from the equality condition of eq. (1), it can be shown that

$$\Delta_s = \frac{1}{8}\left[\frac{\lambda}{wn_c}\right]^2. \tag{2}$$

Arbitrarily small values of Δ_s can be achieved by making w [and according to (1), also h and t] appropriately large.

For the multimode rectangular guide the number of guided modes may be shown to be

$$N = \frac{\pi}{2}\frac{AB}{t^2}\left\{\frac{1}{1 + \left(\frac{\pi}{2v}\right)^2}\right\} \tag{3}$$

where

$$v = \frac{\pi t}{\lambda}\sqrt{n_c^2 - n^2}, \tag{4}$$

and n is the index of the unshaded region outside the dotted region of Fig. 1a, and A and B are defined in the figure. Note that the number of modes, eq. (3), is (to first order) independent of wavelength–a unique property. For all modes the field decays exponentially along the slab as noted above; for the highest-order mode the field penetration is the largest and decays by $1/e$ in a length l, where

$$l = \frac{\sqrt{2}t}{\pi}\sqrt{1 + \left(\frac{\pi}{2v}\right)^2}. \tag{5}$$

For the multimode SM fiber the equivalent full-height support has an equivalent refractive index $n_c(1 - \Delta_m)$ where

$$\Delta_m = \frac{1}{8}\left(\frac{\lambda}{tn_c}\right)^2. \tag{6}$$

The value of Δ_m can be used to calculate numerical aperture, the tol-

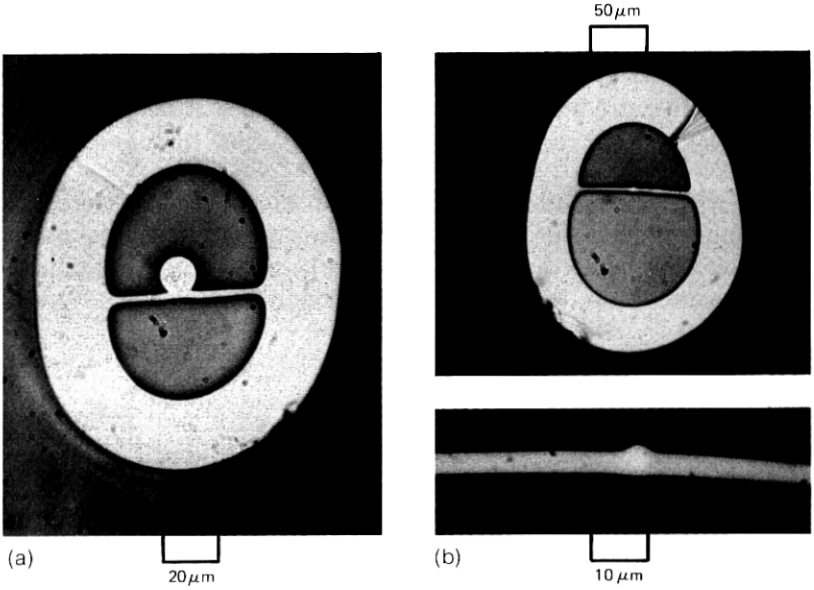

Fig. 2—Photographs of an experimental (a) multimode SM fiber and (b) single-mode SM fiber (top), with magnified core region (bottom).

erable radius of curvature, and modal dispersion. We give here only the numerical aperture,

$$\text{N.A.} = n_c\sqrt{2\Delta_m} = \frac{\lambda}{2t}. \tag{7}$$

SM fibers intended to approximate the geometries shown in Fig. 1 were drawn in an oxygen-hydrogen torch from 6.5 mm i.d., 10 mm o.d. fused quartz tubes containing thin, polished plates and small-diameter rods supported in the center of the tubes. Plates of about 0.2 mm thickness, and core rods of approximately 0.2 mm and 1 mm diameters, resulted in single- and multimode fibers, respectively, whose cross sections are shown in Figs. 2a and b.

For 15-μm-core multimode fibers, a slab thickness t varying between 3 and 4 μm resulted in numerical apertures ranging between 0.11 and 0.08 ($\lambda = 0.6328$ μm), which agree excellently with the predicted values of 0.106 and 0.079, respectively [see eq. (7)]. The h/t ratio of the single-mode guide was about 6.5 μm/4 μm, or 1.625, with the width w amounting to 5 μm.

The spectral losses of the SM fibers were expected to closely approximate those of the unclad fibers drawn from the same material. Whereas this was true for the general shape of the spectral loss curve which was determined between 0.5 and 1.15 μm, the minimum losses were generally higher. For a 300-m-long, Suprasil 2 multimode fiber they amounted to 39, 50, and 28 dB/km at 0.66, 0.80, and 1.06 μm, respectively. Lowest losses of a single-mode fiber having a slightly different geometry than that shown in Fig. 2b were 55 dB/km at 1.06 μm. We believe that residual contamination of the preform elements is the source of the excess losses.

Total scattering losses in the order of 7.5 dB/km at 0.6328 μm demonstrate that the approximately 30 modes (3) of the multimode fiber are well guided and do not lose power into the surrounding cladding to any significant degree.

Other applications of the SM-fiber principle appear promising. Active fiber guides can be created by putting the active material in the central core or by putting it in a liquid surrounding the central member. Integrated optical circuits can utilize the same structure. For example, for a core and slab of index 1.472, slab thickness $t = 0.98\ \mu m$, and a surround index 1 percent less than 1.472, we find the single-mode limit at $h = 1.10\ \mu m$ and $w = 6.75\ \mu m$ at $\lambda = 0.6328\ \mu m$; the field decays transversely in the slab by $1/e$ in 2.67 μm. Thicker slabs allow larger w and h with single-mode guidance. In early research on optical integrated circuits, J. E. Goell observed wave propagation in a curved guide of the above general form, now understood as another verification of the principle of the SM fibers.

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