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Fabrication and Properties of Single-Mode Optical Fiber Exhibiting Low Dispersion, Low Loss, and Tight Mode Confinement Simultaneously

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Single-mode fiber with a new index profile design has been fabricated. The design allows the decoupling of bandwidth related factors from considerations which affect curvature-induced losses.

I. INTRODUCTION

In a previous publication, Lazay et al.[1] reported a single-mode fiber design with a new refractive index profile that allows the wavelength of zero total dispersion to be positioned in the vicinity of 1.31 μm, while simultaneously providing low loss and tight mode confinement. This report will describe the fabrication and properties of fibers of this new design.

The design uses a heavily fluorine-doped phosphosilicate cladding and a germania-doped silica core. The core and cladding compositions were chosen to provide a reduced material dispersion that cancels the waveguide dispersion near 1.3 μm. At the same time, the total core-to-clad index difference was chosen to give a delta of 0.5 percent, sufficient to produce a small modal size and excellent resistance to curvature-induced losses. We anticipate that the losses ultimately achievable with this new design will be lower than those of step-index GeO_2–SiO_2 core fibers of the same core diameter, largely because of the reduced contribution from Ge scattering. Ainslie et al.[2] have pointed out the loss advantage to be gained by the use of a low refractive index cladding and moderately doped core.

Previous single-mode fiber designs which we have studied were based on either a low Δ (~0.20 percent) and large core diameter (~10 μm) or a high Δ (~0.5 percent) and a small core diameter (~7.5 μm). The first class of fibers is capable of having zero dispersion wavelengths near 1.3 μm but has exhibited sensitivity to cabling induced loss because of mode confinement problems. The second class of fiber has exhibited no cabling induced loss but has a zero dispersion wavelength near 1.35 μm and, consequently, the dispersion near 1.3 μm is too large for high data rate (274 mb/s and above) undersea systems having repeater spacings of 30 to 50 km.[3,4]

II. DESIGN

The basic goal is to make a fiber with a lightly GeO_2 doped SiO_2 core such that the material dispersion contribution will cancel the waveguide dispersion at or very near to the system operating wavelength, which is expected to be around 1.3 μm.[4] At the same time, it is imperative to retain the relatively small core (e.g., 7.5 to 8 μm) and large Δ in order to have low bending-induced loss. This is accomplished by providing a phosphosilicate cladding heavily doped with fluorine. The negative Δ^- of the cladding, combined with the positive Δ^+ of the core, both relative to silica, gives the required total Δ value of about 0.5 percent. With a core diameter of 7.5 to 8 μm, this design provides excellent resistance to bending-induced loss, and cutoff wavelengths of around 1.2 μm. Most importantly, since the core and cladding doping levels can be varied independently, the core composition can be adjusted to make the wavelength of zero total dispersion fall at or very close to the projected system operating wavelength.

Phosphorous doping of the cladding was necessary to provide reasonable processing temperatures. Although the P_2O_5 raises the refractive index slightly, the F doping depresses it much more, without substantially affecting the processing temperature. The reduction in refractive index of silicate glasses when fluorine replaces oxygen was discovered by Schott and Abbe in the late nineteenth century,[5] and the use of fluorine doping to reduce the refractive index of silicate compositions in optical fibers has been reported previously.[6,7,8,9]

III. FIBER FABRICATION

The preform was made by Modified Chemical Vapor Deposition (MCVD) in a 19- by 25-mm Heraeus T08-WG silica tube. The delivery rates of the reactants for the cladding ($SiCl_4$, $POCl_3$, and CF_2Cl_2) were chosen to give a glass deposition rate of about 0.35 g/min and a Δ^- of

−0.185 percent. The cladding was deposited in 16 passes without pressurization. The core was deposited in two passes using $SiCl_4$ and $GeCl_4$ with a Δ^+ of +0.315 percent. A compensated collapse procedure was used, but no other chemical drying agents were used. After drawing, the fiber dimensions were OD 114 μm, core diameter 7.5 μm, deposited cladding diameter 44 μm, and length 1 km.

IV. CHARACTERIZATION OF FIBER

Cutoff was determined, using the method described by Lazay,[10] as the location of the rapid drop in power transmitted through a 3-meter length of fiber as the wavelength of the incident light was increased. A well-defined cutoff was located at $\lambda_c = 1.192 \pm .005$ μm.

The loss spectrum was measured from 1.0 to 1.7 μm using the far-end/near-end technique with a 3-meter near-end length. The loss was measured with and without a single 40-mm radius loop in the near-end length. Figure 1 shows the loss curve measured with the loop. Quite surprisingly, the loss curve without the loop was essentially identical, even in the vicinity of cutoff at 1.19 μm. It has been our experience that this is a signature of very good mode confinement. The loss has a local minimum at 1.30 μm of 0.57 ± .03 dB/km, and a minimum loss of 0.40 dB/km at 1.50 μm. Beyond 1.5 μm, the loss rises rapidly and all evidence indicates that the loss is unbounded. This loss "edge" occurs when the effective mode index (the propogation constant divided by $2\pi/\lambda$) falls below the index of the substrate tube. When this happens, the mode becomes cut off because the power can leak through the cladding and be lost by the process of radiation.[11] The wavelength at which the loss rises can be moved to longer wavelengths by increasing the thickness of the deposited cladding. In any case, the loss at 1.3 μm is not adversely affected.

The total chromatic dispersion in the single-mode regime was calculated from the derivative of group delay versus wavelength data.[12] These data were obtained using narrow pulses generated by stimulated Raman scattering in a single-mode fiber pumped with 1.06-μm pulses from a mode-locked *Q*-switched Nd:YAG laser. The wavelength of the pulses emerging from the Raman fiber was selected with a grating monochromator. Figure 2 shows the spectral dependence of the dispersion. The zero dispersion wavelength, λ_0, is located at 1.312 μm.

V. CONCLUSIONS

We have made a fiber that implements a new design. This design allows dispersion optimization through the manipulation of core and cladding glass compositions, while providing low curvature-induced losses through proper choice of core diameter and Δ. The ability to

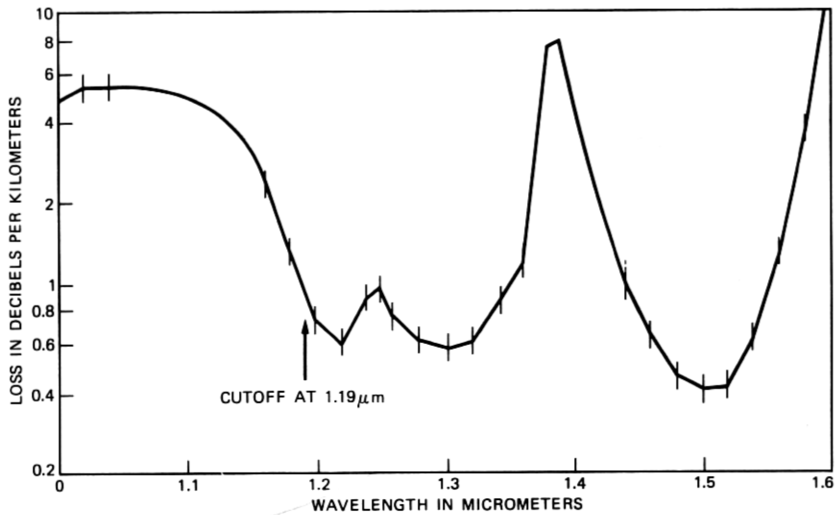

Fig. 1—Loss versus wavelength for depressed index single-mode fiber. The error bars represent 3σ.

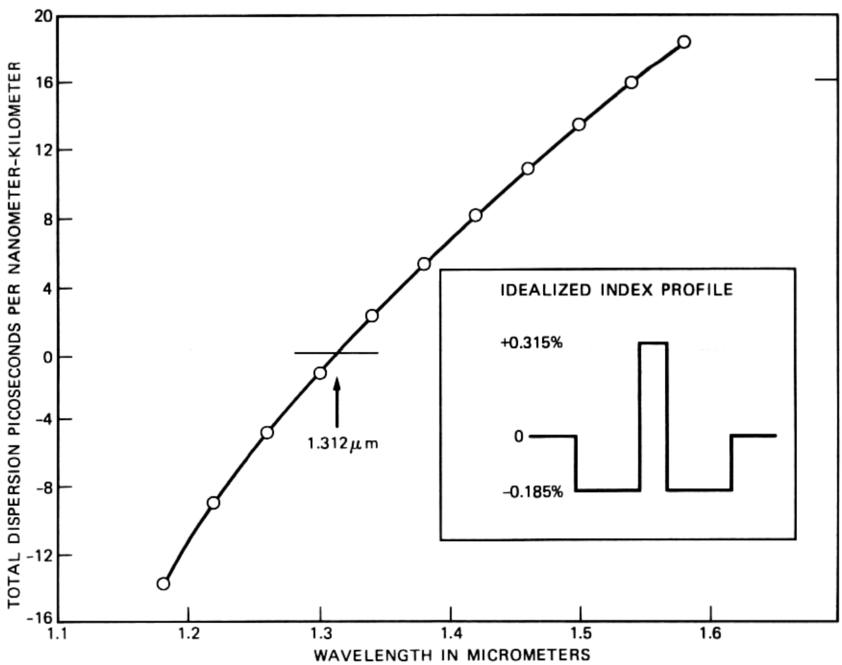

Fig. 2—Total dispersion versus wavelength for depressed index single-mode fiber. The inset shows the idealized refractive index profile.

largely decouple bandwidth design from loss related requirements is a new and unique feature of this design.

It is anticipated that further reduction in loss will be possible. A more complete study of the curvature-induced loss sensitivity of this fiber is underway.

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