Estimating Index Profiles of 1.3- μm Single-Mode Fibers by Near-Field Measurements at Blue Wavelengths

ERNEST M. KIM, DOUGLAS L. FRANZEN, MEMBER, IEEE, MATT YOUNG, AND PEDER M. RODHE

Abstract—Near-field intensity measurements are obtained at the wavelength of 0.45 μm for fibers designed to operate in a single mode at 1.3 μm . At blue wavelengths, the fibers are sufficiently multimode so the near-field scan gives an approximation to the index profile. Near-field scans from six fibers are compared to actual index profiles as determined by the refracted ray method. Experimental near-field scans are also compared to theoretical predictions from a model using numerical solutions to the scalar-wave equation.

SINGLE-MODE FIBERS can be characterized with different parameters and measurement techniques. In quality control, manufacturers frequently measure attenuation, spot size, cutoff wavelength, and minimum dispersion wavelength. The role of fiber index-profile measurements in quality control is not yet clear. The most generally accepted index-profiling technique for single-mode fibers is the refracted ray method sometimes referred to as the refracted near-field (RNF) method [1]–[4]. While RNF yields high resolution with good accuracy, it is susceptible to contamination and requires a sophisticated apparatus with submicrometer positioning accuracy. In the case of 50- μm core diameter multimode fibers, the transmitted near-field (TNF) method gives an acceptable measure of the index profile and is used by many manufacturers to measure core diameter. This paper investigates the feasibility of using TNF methods to determine the index profiles of single-mode fibers designed for 1.3 μm . While usual TNF methods cannot give absolute index values or achieve the resolution of RNF, they could be useful in some applications especially if high-resolution index profiles are not routinely needed. Also, the usual TNF employed here only gives profiles over the core region.

Early work by Sladen *et al.* showed that, for equal mode excitation (Lambertian source) on short lengths of multimode fibers, the TNF closely resembles the refractive-index profile [5]. A large number of fiber modes are required to replicate an index profile with high resolution [6]. This means the

Fig. 1. Model of a typical index profile exhibiting tapered core-clad boundary and a deep on-axis dip.

measurements must be made at a sufficiently high value of the normalized frequency V ¹.

The effect of V -value on near-field profiles was investigated theoretically by numerically solving the scalar-wave equation to give the waveguide modes for commonly encountered index profiles [7]. The near-field intensity is then calculated by summing the intensities of all bound modes allowed for a given value of V . Assumptions in the calculation include equal mode excitation, an unpolarized nearly incoherent source, and a weakly guiding approximation to the scalar-wave equation. Many single-mode fibers have step-like cores with a deep on-axis index depression. A model for this type of profile is given in Fig. 1. Here the on-axis dip goes completely to the cladding and recovers linearly to a step at $0.25 R$, where R is the core radius. Instead of an abrupt core-cladding boundary, the profile starts to taper linearly to the cladding at $0.75 R$. Calculated near-field intensities for this profile are given in Fig. 2(a) and (b) for V -values of 2, 2.79, 8, and 40. When V equals 2, the fiber supports only a single mode, and the near field is Gaussian shaped with significant power propagating in the cladding. Two modes are present when V equals 2.79, and the near-field intensity exhibits an on-axis dip characteristic of the radial variation of the second-order mode. With higher V , the near-field intensity begins to approach the index profile. When V equals 8, there is still significant mode ripple while at a V of 40 the near-field intensity is almost exactly the index profile.

¹The normalized frequency V is given by $2\pi a \sqrt{2n \Delta n} / \lambda$, where a is the core radius, n the fiber refractive index, λ the wavelength, and Δn the index difference between the core and cladding. For large V , the number of bound modes is approximately $V^2/2$.

Manuscript received June 6, 1983; revised August 24, 1983.

E. M. Kim was with the National Bureau of Standards, Electromagnetic Technology Division, Boulder, CO 80303 on leave from New Mexico State University, Las Cruces, NM.

D. L. Franzen and M. Young are with the National Bureau of Standards, Electromagnetic Technology Division, Boulder, CO 80303.

P. M. Rodhe is with the National Bureau of Standards, Electromagnetic Technology Division, Boulder, CO 80303 on leave from Sievert Kabelverk, Sundbyberg, Sweden.

Fig. 2. (a) Near-field radiation pattern for index profile of Fig. 1 at $V = 2$ (top) where there is a single mode, and at $V = 2.79$ (bottom) where there are two modes. Cutoff occurs at $V = 2.76$. (b) Near-field radiation pattern for index profile of Fig. 1 at $V = 8$ (top) and $V = 40$ (bottom). Dotted line is the actual index profile.

Mode ripple can be reduced somewhat by using a broad line-width source which tends to average the fluctuations [6]. Near-field intensities in Fig. 2 were calculated assuming a single frequency source.

Telecommunication fibers that are single mode at $1.3\ \mu\text{m}$ have cutoff wavelengths near $1.2\ \mu\text{m}$ where V is approximately 2.4 (step-index fiber). With blue light ($0.4\text{--}0.45\ \mu\text{m}$), measurements at a V of 7 are possible. It would not be advisable to increase V appreciably by a further decrease in wavelength since germania silicate has absorption bands in the ultraviolet [8]. Near an absorption peak the index exhibits high dispersion, and profile shapes would be expected to change. To investigate the magnitude of this effect, measurements were made on a $50\text{-}\mu\text{m}$ core 0.2-numerical aperture (NA) multimode fibers at wavelengths of 0.45 and $0.85\ \mu\text{m}$. Over this wavelength range, the near-field profiles were similar. As an example, for one fiber, the full widths at half maximum differed by only 3 percent.

Experimental TNF profiles for the $1.3\text{-}\mu\text{m}$ single-mode fibers were obtained using a tungsten halogen source and optics to project a $100\text{-}\mu\text{m}$ -diam spot on the input fiber end. A broad-band interference filter centered at $0.45\ \mu\text{m}$ with a linewidth of $0.07\ \mu\text{m}$ determined the source spectral characteristics. A broad-band filter enhances SNR and reduces coherent effects. The output end of the typical 2-m-long fiber sample was imaged by a $40\times 0.65\text{-NA}$ microscope objective. A silicon detector with a $30\text{-}\mu\text{m}$ -diam pinhole was used to scan the image. Re-

ferred to the fiber end face, the pinhole is equivalent to a $0.75\text{-}\mu\text{m}$ -diam collecting aperture. The pinhole-detector was scanned using a computer-controlled stepper-motor translator to take data points every $0.1\ \mu\text{m}$ as referred to the fiber end face. Dimensional calibration of the scan at $0.45\ \mu\text{m}$ was accomplished using a previously described calibration reticle [9].

Near-field patterns can be influenced by contributions from leaky modes [5]. These contributions cause the near-field intensity to deviate from the actual index profile. In practice, it is not necessary to apply corrections to near-parabolic profile fibers [9],[10], however, for step-index fibers the corrections can be significant. Fortunately for pure step-index fibers, the leaky modes can be eliminated by launching with a NA which is close to that of the fiber. TNF's at $0.45\ \mu\text{m}$ were obtained at launch NA's of 0.36 and 0.14 for the single-mode fibers used in this study, and little difference was observed in the profiles. Moreover, most of the near-field profiles did not exhibit the characteristic leaky mode "ears" observed for step-index fibers. We, therefore, conclude that leaky modes are not a significant problem at least in the fibers tested.

TNF profiles were measured at a wavelength of $0.45\ \mu\text{m}$ for six $1.3\text{-}\mu\text{m}$ single-mode fibers. Figs. 3 and 4 give profiles at wavelengths of 1.0 and $0.45\ \mu\text{m}$ for fibers 1 and 2, respectively. These results are in qualitative agreement with the theoretical trend predicted in Fig. 2. At $1.0\ \mu\text{m}$, there are only a few modes and appreciable power extends into the cladding. The contribution from the second-order mode results in a smooth

Fig. 3. Near-field radiation pattern, fiber 1, at 0.45 and 1.0 μm showing the effect of increased V .

Fig. 4. Near-field radiation pattern, fiber 2, at 0.45 and 1.0 μm showing the effect of increased V .

central depression. At 0.45 μm , there are approximately 25 modes ($V^2/2$), and the near-field power is more confined to the core. In the case of fiber 2 the on-axis dip is narrower and deeper.

The most interesting results are the comparisons of TNF profiles to the actual index profiles as determined by RNF. These comparisons are given for four of the fibers in Figs. 5 through 8 and are representative of the six fibers measured. The height-to-width ratio of a given TNF profile was computer scaled to match the corresponding RNF profile approximately so that comparisons of shape can be more readily made. Actual dimensional information is given in Table I for all six fibers. The RNF measurements were made at 0.6328 μm and have a resolution of 0.75 μm , with a dimensional accuracy of approximately $\pm 0.5 \mu\text{m}$.

Fiber 1 has a shallow index depression and the TNF predicts the same shape and on-axis depth as the RNF. Fiber 3 has a much deeper depression and again the TNF and RNF give about the same on-axis depth. The main differences are the two 5-percent depressions near the peaks of the TNF. Fiber 4 has a funnel-shaped index depression which is also predicted by the TNF, but appears slightly exaggerated. Fiber 5 is nearly a perfect step with a depression going almost to the cladding. The TNF does not completely resolve the dip and 10-percent depressions are apparent in the peaks. Table I compares the core diameters measured by the two methods. The comparisons are made at the 15-percent levels, because there are rip-

Fig. 5. Comparison of 0.45- μm TNF and RNF, fiber 1.

ples and fine structures near the baseline in the RNF's. The RNF's are larger by 0.4 μm on the average. This may not be significant since the RNF calibration accuracy was $\pm 0.5 \mu\text{m}$.

TNF profiles have less resolution than RNF and exhibit ripple in some cases. Index dips for the RNF profiles often appear

Fig. 6. Comparison of 0.45- μm TNF and RNF, fiber 3. Fig. 7. Comparison of 0.45- μm TNF and RNF, fiber 4.

deeper, core-cladding boundaries more perpendicular, and abrupt features more evident. However, the general TNF shapes are correct and relatively insensitive to end preparation, and ripple is less than 10 percent for all fibers tested. This level of ripple is less than theory predicts, probably because of the broad source linewidth. Blue-ultraviolet TNF's on 1.3- μm single-mode fibers could be useful in situations requiring experimental simplicity and two-dimensional information. With sensitive photomultiplier detectors, it would be possible to scan

Fig. 8. Comparison of 0.45- μm TNF and RNF, fiber 5.TABLE I
15-PERCENT CORE DIAMETERS (μm)

Fiber	RNF	TNF	RNF-TNF
1	9.2	8.4	+0.8
2	9.6	9.2	+0.4
3	9.6	9.3	+0.3
4	10.4	9.8	+0.6
5	11.1	11.2	-0.1
6	9.6	9.1	+0.5
average			+0.4

cores in a matter of seconds. Also vidicons with computer image acquisition can rapidly obtain two-dimensional information such as core size, core ovality, and concentricity.

Recently, another more complicated near-field index-profiling technique has been applied to single-mode fibers [11]. The approach uses a modified near-field method with a limited numerical aperture launch and is capable of giving absolute index values over both core and cladding. While detailed comparisons of core profiles to RNF were not reported, it appears resolution could be further improved by using blue wavelengths.

REFERENCES

- [1] W. J. Stewart, "A new technique for measuring the refractive index profiles of graded optical fibers," in *Proc. Conf. Integrated Opt. Opt. Commun.*, Japan, 1977.
- [2] K. I. White, "Practical application of the refracted near-field technique for the measurement of optical fibre refractive index profiles," *Opt. Quantum Electron.*, vol. 11, pp. 185-196, 1979.
- [3] M. Young, "Optical fiber index profiles by the refracted-ray method (refracted near-field scanning)," *Appl. Opt.*, vol. 20, pp. 3415-3422, 1981.
- [4] M. J. Saunders, "Optical fiber profiles using the refracted near-field technique: A comparison with other methods," *Appl. Opt.*, vol. 20, pp. 1645, 1981.
- [5] F.M.E. Sladen, D. N. Payne, and M. J. Adams, "Determination of optical fiber refractive index profiles by a near-field scanning technique," *A.P.L.*, vol. 28, no. 5, pp. 255-258, 1976.
- [6] M. J. Adams, D. N. Payne, F.M.E. Sladen, and A. Hartog, "Resolution limit of the near-field scanning technique," in *Proc. Third European Conf. Opt. Commun.*, Munich, Germany, 1977.
- [7] P. M. Rodhe, "On transmission properties of optical fibres with disturbed geometry." M. S. thesis, Royal Institute of Technology,

Stockholm, Sweden: also, "Calculation of scalar modes of optical fibres with circular symmetric cross section," Institute of Optical Research, Tech. Rep., TR-117-1982-06-29, 1982.

- [8] M. J. Yuen, "Studies of MCVD glass preform by UV spectroscopy: A probe into GeO formation," in *Tech. Dig., Third Int. Conf. IOOC* (Washington, DC), 1981.
- [9] E. M. Kim and D. L. Franzen, "Measurement of the core diameter of graded-index optical fibers: An interlaboratory comparison," *Appl. Opt.*, vol. 21, pp. 3443-3450, 1982.
- [10] K. Petermann, "Uncertainties of the leaky mode correction for near-square-law optical fibres," *Electron. Lett.*, vol. 13, no. 7, pp. 513-514, Aug. 1977.
- [11] D. H. Irving, "Near-field scanning technique for profiling single-mode fibres," *Electron. Lett.*, vol. 19, no. 6, pp. 190-191, Mar. 1983.

*

Ernest M. Kim was born in Tokyo, Japan in February 1956. He received his B.S. degree in electrical engineering from the University of Hawaii, Honolulu, HI in 1977, and the M.S. degree in electrical engineering from New Mexico State University, Las Cruces, in 1980. He is currently completing his Ph.D. degree from New Mexico State University. His thesis research is in optical-fiber geometric measurements.

From 1979, he has been a graduate cooperative education student at the National Bureau of Standards in Boulder, CO, where he has studied various optical-fiber measurement problems. Upon completion of his Ph.D. in January 1984, he will join the Advanced Systems Group of the Burroughs Corporation in Boulder, CO as a Staff Engineer.

*

Douglas L. Franzen (S'64-M'66) was born in Minneapolis, MN, in 1942. He attended the University of Minnesota, Minneapolis, where he received the B.S., M.S.E.E., and Ph.D. degrees in electrical engineering in 1964, 1966, and 1970, respectively, with partial support from an NSF grant.

From 1970 to 1972 he was an NRC/NBS postdoctoral Research Fellow in the Quantum Electronics Division at the National Bureau of Standards, Boulder, CO. There he performed some of the early work on continuous laser sustained plasmas. Since then he has been with NBS where he has developed NBS standard instruments for high-power laser calorimetry and has shared in some original work on sputtered metal vapor ion lasers. His most recent interests include optical-fiber waveguide metrology and associated technologies. Currently he is a project leader in the Optical Electronic Metrology Group, a chairman of an EIA committee on the interlaboratory testing of optical-fiber mea-

surement procedures, and an organizer of the biennial NBS Symposium on Optical Fiber Measurements.

Dr. Franzen is a member of the Optical Society of America and Institute of Electrical and Electronics Engineers.

*

Matt Young confesses that he was born in Brooklyn, NY on January 30, 1941. He received the B.S. Degree and the Ph.D. degree from the University of Rochester's Institute of Optics in 1962 and 1967, respectively.

He has been Research Associate at the Institute of Optics, Assistant Professor of Physics at the University of Waterloo, Assistant Professor of Electrophysics and Electronic Engineering at Rensselaer Polytechnic Institute, and Associate Professor of Natural Science at Verrazzano College. Since 1976, he has been a Physicist with the Electromagnetic Technology Division of the National Bureau of Standards, where he is active in different areas of optics.

Dr. Young is a member of the Optical Society of America, the American Association of Physics Teachers, the American Association for the Advancement of Science, and the Federation of American Scientists. He is past President of the Rocky Mountain Section of the Optical Society of America, former Associate Editor of the Journal of the Optical Society of America, and the author of a book, *Optics and Lasers*.

*

Peder M. Rodhe was born in Stockholm Sweden on May 13, 1945. He received the M.S. degree in Physics from the University of Stockholm in 1973 and the Lic. Techn. Degree in Optics and Wave Propagation Theory from the Royal Institute of Technology, Stockholm in 1982, while studying the light transmission properties of geometrically distorted optical fibers.

From 1975 to 1979 he was involved in the research and development of optical fibers at the Ericsson Telephone Company in Stockholm. From 1979 to 1982 he was an Assistant at the Institute of Optical Research, Stockholm and in 1972 he also joined the Fiber Measurement group at Sieverts Kabelverk AB, Sundbyberg. At present he is a guest worker at the National Bureau of Standards, Electromagnetic Technology Division, Optical Electronic Metrology Group, Boulder, CO, on a fellowship from the Wallenberg Foundation.