

Calibration technique for refracted near-field scanning of optical fibers

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The refracted near-field scanning method for determining the refractive-index profile of an optical waveguide was first suggested by Stewart and reduced to practice by him and White.^{1,2} The method is attractive because it can be applied to a fiber with any length and no special end preparation. No correction for leaky modes is required, as with (transmitted) near-field scanning; no extensive computations are required, as with techniques that illuminate the fiber at right angles to the axis; and (apart from a clean end that is normal to the fiber axis) no specially prepared sample is required, as with many interference techniques.² In addition, refracted near-field scanning, unlike direct-reflection methods, is relatively insensitive to the presence of a layer of contamination on the surface. The resolution of refracted near-field scanning is nearly comparable to that of conventional optical microscopy.

The principle of the method is comparatively simple. A radially symmetric fiber is placed in a transparent movable cell containing liquid whose index of refraction is comparable to (and preferably slightly higher than) that of the fiber cladding. The fiber end face is held parallel to the faces of the cell and is illuminated with a focused beam whose numerical aperture greatly exceeds the acceptance angle of the fiber.

The most extreme rays of the incident cone are refracted and emerge from the exit face of the cell. If the index of the fiber at the point of illumination is changed, as by translating across the face of a graded-index fiber, then the vertex angle of the emerging cone will change slightly. We introduce a small opaque stop behind the fiber, so that a hollow cone of rays is transmitted beyond the stop. As the fiber is scanned, the outer radius of the cone varies with the index, whereas the inner radius, being a function of the stop size and position only, remains constant.

If the source is Lambertian, the power radiated into a cone is proportional to $\sin^2\theta$ (where θ is the vertex angle of the cone)³; in this case, White's Eq. (2) shows that the power transmitted around the stop should vary linearly with the index of the fiber at the point of illumination; if the source is not Lambertian, the transmitted power may still be sufficiently linear over a small enough range of angles and indices.⁴

To calibrate his system, White translated the stop in the direction parallel to the fiber axis; he calculated the power transmitted around the stop as a function of position and thereby related transmitted power to index. However, I

sought a method that was more direct and more amenable to analysis as a measurement system.

Because a calibrated set of fibers is not readily available, I use a single quartz fiber and several index-matching fluids and plot transmitted power as a function of the refractive-index difference. The experimental arrangement is similar to White's and uses a He-Ne laser with a quarterwave plate as a source, a 40X, 0.55-N.A. microscope objective to illuminate the fiber, and a specially constructed, high-aperture condensing lens to focus the emergent cone of rays onto a uniform, large-area silicon detector. Data are taken on an x-y recorder; the linearity of the electronics has been verified with a set of neutral-density filters calibrated at 633 nm with a spectrophotometer.

For calibration, I used four oils sequentially with each of three quartz-fiber samples. The indices of the oils were supplied by the manufacturer, who claimed an uncertainty of ± 0.0005 .⁵ The index of the quartz may be calculated from data provided by Malitson for fused quartz or from that provided by Fleming for rapidly quenched quartz^{6,7}; the calculated values differ by 0.00014. I settled on their average of 1.45726 and assigned an error of ± 0.0001 .

Figure 1 shows the results of the calibration runs. The horizontal axis is the difference between the index of the fluid and that of the quartz at 633 nm; the vertical axis is the output of the system when a fiber is in place, normalized to the value in the absence of the fiber. A calculation showed linearity at the 90% confidence level.⁸ However I did not calculate a least squares line of best fit because the points have uncertainty along the horizontal axis as well as the vertical. Rather, I used a method similar to that suggested by Natrella.⁸ The center of mass of all the points as well as the means of each of the four sets are calculated. Three line segments join the four means,

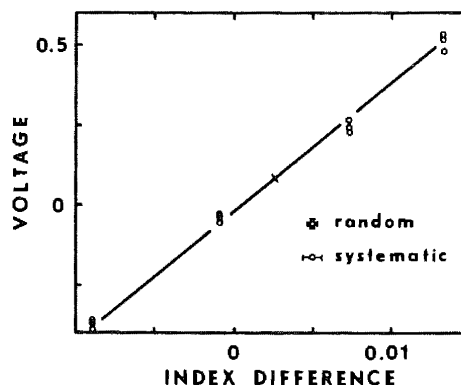


Fig. 1. Normalized recorder voltage vs difference of refractive index between the quartz fiber and each of four immersion fluids. An estimate of random and overall systematic errors is also indicated. The slash shows the center of mass of the points from which the line of best fit was calculated (see text).

and their slopes are calculated. The best-fit line is that which passes through the center of mass and whose slope is the average of the slopes of the three line segments.

The vertical error bar in Fig. 1 is an estimate of the instrumental limit of error (or resolution) of the x - y recorder; the actual vertical errors are also of this order. The horizontal error is the sum of the index uncertainties just mentioned, as well as an additional ± 0.0004 owing to the effect on the oils of the ± 1 -K temperature variation in the laboratory. Because the large horizontal error bar is not reflected in large vertical scatter, I conclude that most, if not all of the horizontal error (except the temperature component) is a systematic error that is common to each oil and has approximately constant magnitude and sign; the two horizontal error bars show the random and systematic errors separately.

If we project the vertical error onto the horizontal axis, we find that the actual value of the index at a point may be known to ± 0.0015 or thereabouts; however, the more important relative values (such as the difference between core and cladding) can be measured to ± 0.0009 if the temperature is uncontrolled or ± 0.0005 if the temperature remains constant during the measurement process. When running an unknown sample, I choose one of the oils and determine the scale each time by making an initial run with a quartz fiber. When the system is undisturbed, repeatability is at least equal to the width of the line drawn by the x - y recorder.

References

1. W. J. Stewart, in *International Conference on Integrated Optics and Optical Fiber Communication* (IOOC, Tokyo, 1977), pp. 395-398.
2. K. I. White, *Opt. Quantum Electron.* **11**, 185 (1979). See also Refs. 3-16 therein for a bibliography of other measurement techniques.
3. M. Young, *Optics and Lasers* (Springer, New York, 1977), Chap. 3.
4. M. Young, NBS Technical Note, in preparation.
5. I am indebted to Michael Liva and William Sacher of Cargille Laboratories for providing the liquids, their indices, and their Sellmeier coefficients.
6. I. H. Malitson, *J. Opt. Soc. Am.* **55**, 1205 (1965).
7. J. W. Fleming, *Electron. Lett.* **14**, 326 (1978).
8. M. G. Natrella, *Experimental Statistics*, NBS Handbook 91 (1963), pp. 5-22, 5-23, and 5-27.