LINEARITY AND RESOLUTION OF REFRACTED NEAR-FIELD SCANNING TECHNIQUE

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Refracted near-field scanning is an attractive method for precisely determining the index profile of an optical waveguide. This method was first proposed and demonstrated by Stewart[1] and later refined by White.[2] In an earlier paper, I analyzed the linearity and precision of the method; this paper additionally discusses resolution and related areas.

Lambertian and non-Lambertian sources

Refracted near-field scanning depends upon measurement of the power that is refracted through the cladding of the fiber and beyond an opaque stop. If the source is Lambertian, then, in principle, the power transmitted around the stop is a precisely linear function of $(n^2 - n_L^2)$, where n is the index of the fiber (core or cladding) at any point and n_L is the index of the fluid that surrounds the fiber.[4] If n and n_L are approximately equal, the transmitted power is very nearly a linear function of $(n - n_L)$.

Many non-Lambertian radiances may be approximated by a function proportional to $\cos^m \theta$. If the radiation pattern is circularly symmetric, the power transmitted around the stop is proportional to $1 - \cos^{m+2} \theta$; the system is not linear in index to the extent that this function is not proportional to $\sin^2 \theta$. (The power that a Lambertian source radiates into a cone is proportional to $\sin^2 \theta$.[5]) Figure (1) shows the function $1 - \cos^{m+2} \theta$ vs $\sin^2 \theta$ for several values of m. $m = 0$ is a Lambertian source, $m = -1$ is a uniform point source, and $m = 4$ and 8 are rough approximations to sources like edge-emitting LEDs and lasers. The function is linear over almost any small range; a Lambertian source is not strictly required for refracted near-field scanning. However, calculations based on the radiometry of Lambertian sources may be in error by a large factor.[4]

Linearity and calibration

To calibrate the system and determine the linearity of the output power as a function of refractive-index difference, I use a quartz fiber with each of several index-matching fluids and plot transmitted power vs index difference. Figure (2), which is taken from Reference (3), shows such a plot. Each of three quartz-fiber samples was tested with each of four oils to produce the twelve points in the figure. Figure (2) also shows a line of best fit and estimates of the random and systematic errors of the system. I have shown further in Reference (3) that relative values of index (such as core-cladding difference) may be measured to $\pm$ 0.0005 if the temperature of the fluids is held sufficiently constant.

Resolution limit

White has argued that the spatial resolution limit of the system is that of a diffraction-limited lens with an opaque central stop.[2] The work presented here does not entirely support this argument; rather, the resolution limit of the system is more nearly equal to that of the lens without the stop. This is so because the condensing lens associated with the stop is not an imaging system but merely a collector of light.

The solid line of Figure (3) shows an exact calculation of the edge-response width (10 - 90% points) of a diffraction-limited annular lens as a function of the fraction ε of the diameter that is obscured by the stop.[6] The resolution limit RL is taken to be equal to the edge-response width; the vertical axis is normalized to the Rayleigh limit, 0.61 λ/NA. The discrete points are data obtained by scanning across the edge of a cleaved quartz fiber immersed in mineral oil. Figure (4) shows a typical set of scans. The value of ε varies by about 10% depending upon whether the light is focused into the fiber or the oil; the numbers in Figure (4) are the averages of the two values.

Data derived from scans like those in Figure (4) are shown in Figure (3). Whereas there is some effect resulting from increasing ε, the data do not agree well with the theory and show that the resolution is diffraction limited as long as ε is less than about 0.7. When ε exceeds 0.7, resolution suffers, probably because of diffraction of the light outside the narrow conical shell by the sharp edge of the fiber.

Comparisons with other methods

At the time of this writing, we are just beginning comparisons. Figure (5) shows measurements on a step fiber by the refracted near-field method and by near-field scans of the exit faces of meter- and kilometer lengths using over-filled launch conditions. The former method resolves the central index dip and shows structure in it, and also shows the presence of a complicated barrier layer. Core-diameter measurements agree to about 10%. Comparisons with at least one other laboratory are still at an early stage.

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. and Quantum Elect., 11, 185-196 (1979). See also references 3-16 therein for a bibliography of other measurement techniques.
3. M. Young, Appl. Opt. (accepted for publication 1 Aug. 1980).
4. M. Young, NBS Technical Note, in preparation.
5. M. Young, Optics and Lasers, Springer, New York, Heidelberg, Berlin (1977), Chap. 3.
6. Eric Johnson very kindly performed the edge-response calculations; Ernest Kim supplied the near-field scans.

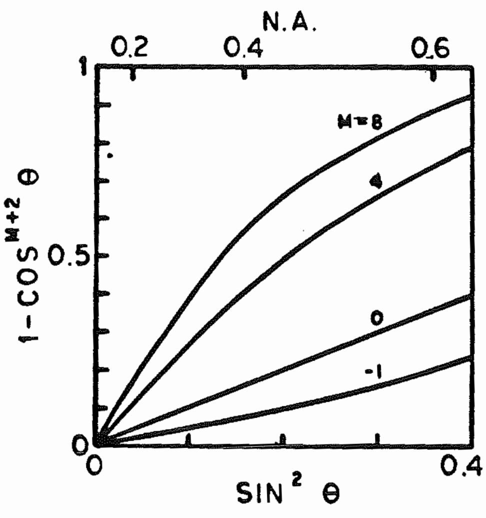

Figure 1. A function useful for describing non-Lambertian sources.

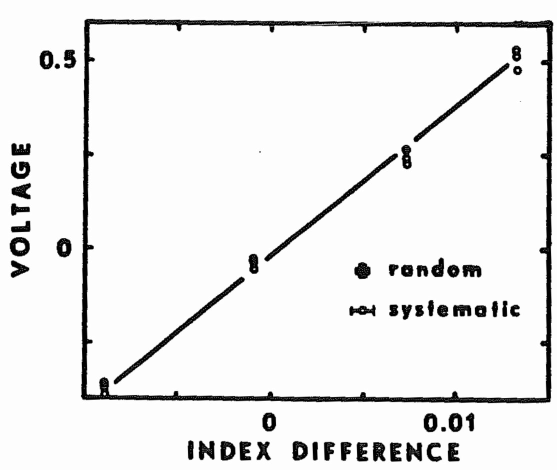

Figure 2. Normalized recorder voltage vs. difference of refractive index between the quartz fiber and each of four immersion fluids.

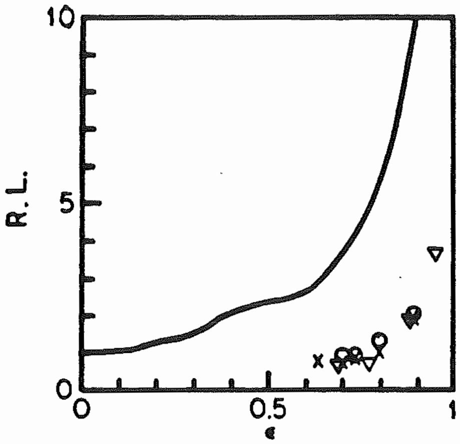

Figure 3. Normalized resolution limit as a function of relative diameter. RL = 1 corresponds to the Rayleigh limit.

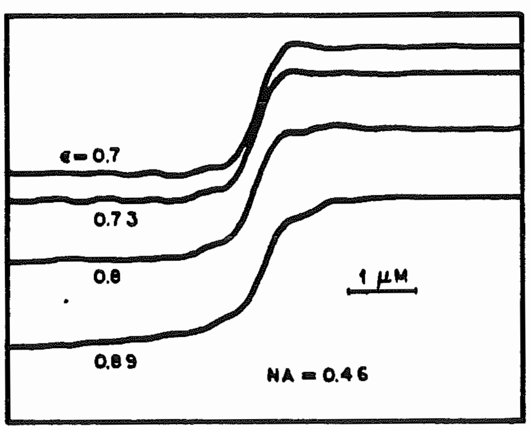

Figure 4. Scans across the edge of a cleaved quartz fiber. The fiber is to the right of the step.

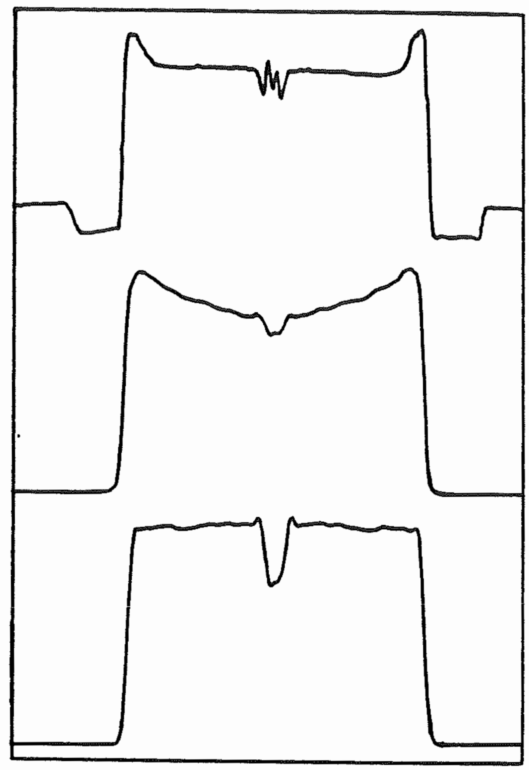

Figure 5. Scans of the core of a step fiber.
Top: refracted near field scan.
Center: scan of exit face of 1-m length.
Bottom: scan of exit face of 1-km length.