Measuring the refractive-index profile of optical fibers by the cladding-mode near-field technique

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A new measurement system has been developed that simply determines the refractive-index profile of any optical fiber by analyzing the propagation of cladding modes. Measurement accuracy was verified by a comparison with the refractive near-field method, and a sufficient resolution level was achieved to produce the fine structural details in single-mode fibers.

The optical characteristics of any optical fiber are determined primarily by the refractive-index profile. Current advances in fiber manufacturing technology have permitted production of numerous fiber structures, including dispersion-modified and polarization-maintaining designs, having intricate refractive-index profiles with fine structural details. To characterize accurately the various fiber types in either a laboratory or a manufacturing environment, a high-resolution refractive-index profiling system is necessary.

A number of techniques are available for the measurement of refractive-index profiles, but most present some application difficulties. Interference techniques require extensive sample preparation and extremely complex and time-consuming mathematical routines. On the other hand, simplified techniques such as the transmitted near-field technique require correction factors for leaky mode propagation and have inherent problems when single-mode fibers are examined. The refractive near-field (RNF) technique was developed to resolve the above problems; however, the requirement of sophisticated optical and mechanical equipment confines this method to a laboratory environment.

Recently we proposed a novel method, the cladding-mode near-field (CNF) technique. The CNF technique directly determines the index profile, similarly to the RNF technique, but overall system complexity is greatly reduced. In this Letter we present the theory of the CNF measurement as well as resolution and accuracy limits of a practical measurement system.

When the refractive index of the fiber cladding is greater than the surrounding medium, light can propagate through the cladding as well as through the core. The propagation of a ray in the cladding, Fig. 1, is described using Snell’s law by

\[ N^2(\mathbf{r}) - N_0^2 = -N_0^2 \sin^2 \theta_1 + \sin^2 \theta_3, \]

where \( \theta_1 \) and \( \theta_3 \) are the cladding and exit ray angles, respectively, \( N_0 \) is the constant cladding index, and \( N(r) \) is the local refractive index at the exit plane of the fiber. Under proper launch conditions, the intensity distribution across the fiber endface will be constant.

The total power radiating from each point then will be independent of location, but the angular distribution of \( \theta_3 \) will be a direct function of \( N(r) \). If the detection system’s numerical aperture is suitably limited at \( \theta_{3\text{max}} \), then the maximum detected propagation angle \( \theta_{1\text{max}} \) is a function of the localized refractive index only. The intensity at the image plane consists of all power radiating from modes with propagation angles less than or equal to \( \theta_{1\text{max}} \); thus, as the refractive index changes, \( \theta_{1\text{max}} \) and the detected intensity must also change. The function

\[ I(r) = I(\theta_{1\text{max}}) \]

must first be determined empirically by analyzing the intensity level in the constant-index cladding as the detector’s numerical aperture is varied. Generally this function can be approximated by

\[ I(r) = A \theta_{1\text{max}}^2, \]

where \( A \) is a constant of the test fiber and launch conditions. By combining Eqs. (1) and (3), the variation in refractive index can be directly computed from the measured intensity:

\[ N(r) - N_0 = \frac{\sin^2 \theta_{3\text{max}} \left[ 1 - I(r)/I_0 \right]}{2N_0}, \]

where \( I_0 \) is the cladding intensity level at the measurement’s numerical aperture.

Sensitivity of the measurement to refractive-index changes is dependent on system design. The intensity

Fig. 1. Ray diagram describing cladding-mode propagation.
Fig. 2. Theoretical relationship among spatial resolution, system numerical aperture, and S/N ratio required to detect a 0.0001 refractive-index change.

Fig. 3. Schematic diagram of experimental measurement system.

distribution that leaves the test fiber is in actuality a composite of many point sources. To detect small changes of refractive index, the measurement system must have the capability to resolve these closely spaced sources. Classically the spatial resolution $b$ is a function of the detector's numerical aperture ($\sin \theta_{\text{max}}$) and of the center wavelength of the light source $\lambda$:

$$b = 0.610 \frac{\lambda}{\sin \theta_{\text{max}}}.$$  \hspace{1cm} (5)

Obviously, the spatial resolution improves with increasing numerical aperture; however, from Eq. (4) there is a trade-off between dynamic range and spatial resolution:

$$\Delta I/I_0 = \frac{2N_0 \Delta n}{\sin^2 \theta_{\text{max}}}.$$  \hspace{1cm} (6)

To record a 0.0001 change in refractive index at 650 nm, the required detector signal-to-noise (S/N) ratio and the resultant spatial resolution as a function of the system's numerical aperture are plotted in Fig. 2.

The experimental arrangement is shown schematically in Fig. 3. A test fiber is prepared utilizing standard cleaving techniques and is placed onto an x–y–z stage (no matching liquid is required). Filtered light ($\lambda = 650$ nm) from a quartz-halogen lamp is focused at the bare fiber–coating-material interface of the test fiber. A fraction of the scattered intensity couples into the cladding region where primarily cladding-mode excitation occurs. The probability of launching propagation modes exists. However, experimental results confirm that the level of propagation modes is significantly less than the dynamic range of the detector.

The numerical aperture of the detection system is controlled by a variable aperture (A1) placed directly behind lens L2. This position was chosen for convenience and is mathematically equivalent to placing the aperture in front of the lens. A1 is adjusted during the system calibration i.e., formulation of Eq. (2), and otherwise is fixed at the optimal size determined by the relationship shown in Fig. 2. The near-field pat-

Fig. 4. Comparison between RNF and CNF techniques. Top, 100–140-μm step-index multimode MCVD fiber. Bottom, 50–125-μm graded-index multimode VAD fiber. Solid curves, CNF technique; dashed curves, RNF technique.

Fig. 5. CNF results for a dispersion-shifted VAD single-mode fiber.
tern leaving the aperture is projected onto the camera head of a vidicon detection system (Hamamatsu C-1000), where a desktop computer is used to analyze the intensity profile and determine the corresponding refractive-index profile.

Profiles of a 100–140-μm step-index multimode modified chemical-vapor deposition (MCVD) fiber and a 50–125-μm graded-index multimode vapor axial deposition (VAD) fiber obtained by the RNF and CNF techniques are shown in Fig. 4. The existence of propagation and leaky modes in CNF measurements would drastically deform the resultant index profiles. However, the above results verify the absence of such modes since the two methods produced similar profiles.

The experimental system was designed to detect a 0.0001 change in refractive index, which permitted single-mode fiber measurements. Figure 5 shows results for a VAD dispersion shifted single-mode fiber exhibiting a graded-index inner core and a pure SiO$_2$ outer core. Resolution limits were sufficient to permit this intricate structure to be reproduced accurately. Two-dimensional index profiles can be produced simply by conducting a raster scan of the detected near-field pattern. Figure 6 shows an example for a polarization-maintaining single-mode fiber. The small-diameter core (6.5 μm) and lower-index stress-induced areas are clearly displayed.

The cladding-mode near-field technique has been shown directly to produce accurate refractive-index profiles for any optical fiber design. Fiber end degradation does not affect results; thus standard cleaving techniques can be used. System setup and operation are effortless, making this technique applicable to both manufacturing and laboratory environments. Spatial resolution is sufficient to produce fine structural details and can be increased by utilizing either a more elaborate detection system or a shorter-wavelength light source.

References