# Refractive-index profiling of azimuthally asymmetric optical fibers by microinterferometric optical phase tomography

**Brent L. Bachim, Thomas K. Gaylord, and Stephen C. Mettler**

*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0250*

Received December 13, 2004

Accurate nondestructive refractive-index profiling is needed in the modeling, design, and manufacturing of optical fibers and fiber devices. Most profile measurement techniques cannot correctly characterize fibers with small or irregular refractive-index variations over their cross sections. Microinterferometric optical phase tomography (MIOPT) is a technique that allows measurement of fiber refractive-index profiles exhibiting such variations. We present the first demonstration, to our knowledge, of MIOPT. The profile of a polarization-maintaining fiber is measured by MIOPT and shown to be in agreement with (destructive) fiber end-face measurements. MIOPT is also applied to the limiting case of a symmetric single-mode fiber. © 2005 Optical Society of America

*OCIS codes:* 060.2270, 060.2400.

Accurate nondestructive refractive-index profiling is needed in the modeling, design, and manufacturing of optical fibers and fiber devices.[1–3] Small and asymmetric refractive-index variations present over a cross section pose a particular problem when attempting to characterize fiber index profiles: Most profiling techniques are not capable of detecting small index variations or require an assumption of azimuthal symmetry.[4] Other techniques, such as etching combined with topographical profiling, can detect small index variations but require calibration and are destructive.[5]

Microinterferometric optical phase tomography (MIOPT) is a nondestructive refractive-index profiling technique that offers the ability to characterize small and asymmetric refractive-index variations over an optical fiber cross section.[4] The technique combines microscopy-based fringe-field interferometry with parallel projection-based computed tomography to allow cross-sectional measurements of relatively small objects such as optical fibers. Profiling is accomplished by collecting a set of fringe-field interference images of a sample and at a sequence of angles around the sample. The interference images are then analyzed to produce a set of projections required to implement tomographic reconstruction of the sample cross section.

In this Letter we present the first demonstration, to our knowledge, of MIOPT. Measured refractive-index profiles are given for two different optical fiber samples. One sample has an azimuthally asymmetric cross-sectional profile, whereas the other has a symmetric profile. The measured experimental results demonstrate the ability of MIOPT to profile both azimuthally asymmetric and symmetric optical fibers. Before details of the results are presented, the measurement apparatus and procedure are discussed.

The measurement apparatus used for acquiring the necessary interference images resembles that described in Ref. 4. A Mach–Zehnder two-objective transmitted-light interference microscope with a bandpass-filtered mercury lamp source provides an appropriate interferometer arrangement for generating fringe-field interference images of a small sample object. A high-resolution scientific-grade digital camera is used to acquire the resulting interference images, which are then transmitted to a computer for storage. A motorized rotation stage, under the control of a motion controller, rotates an optical fiber sample around its longitudinal axis to allow acquisition of interference images at a sequence of angles around the sample. The computer, running a custom LabVIEW program, controls sample rotation and image acquisition during measurement through a single program.

An optical fiber sample is prepared for profiling by first removing any buffer or coating layers. The sample is then inserted into a small-bore needle and attached to the needle with a small amount of adhesive. After attachment, the sample is cleaned, positioned in the sample arm of the interference microscope, and brought into focus. Index-matching oil with an index value close to that of the sample cladding surrounds the fiber sample and allows focusing with reduced diffraction effects. The interferometer is then adjusted to produce a suitable fringe field as observed with the camera.

After initial sample preparation, an interference image is acquired at the current projection angle and stored for subsequent processing, and the sample is rotated to the next measurement angle. Periodically, acquisition is temporarily halted and the microscope focus is adjusted to ensure that the sample remains correctly focused. The image acquisition, storage, and sample rotation process is repeated until interference images are collected over 360° around the sample.

After a full set of interference images for the fiber sample is collected, image processing techniques are used to identify the fringe minima locations in each image. The index projections required for reconstructing the cross-sectional refractive-index profile of the sample are derived from the identified minima locations.[4]

In Figs. 1–4 we present measured refractive-index profiles for a bow-tie-type polarization-maintaining fiber (PMF) and a single-mode fiber (SMF) obtained

0146-9592/05/101126-3/$15.00 

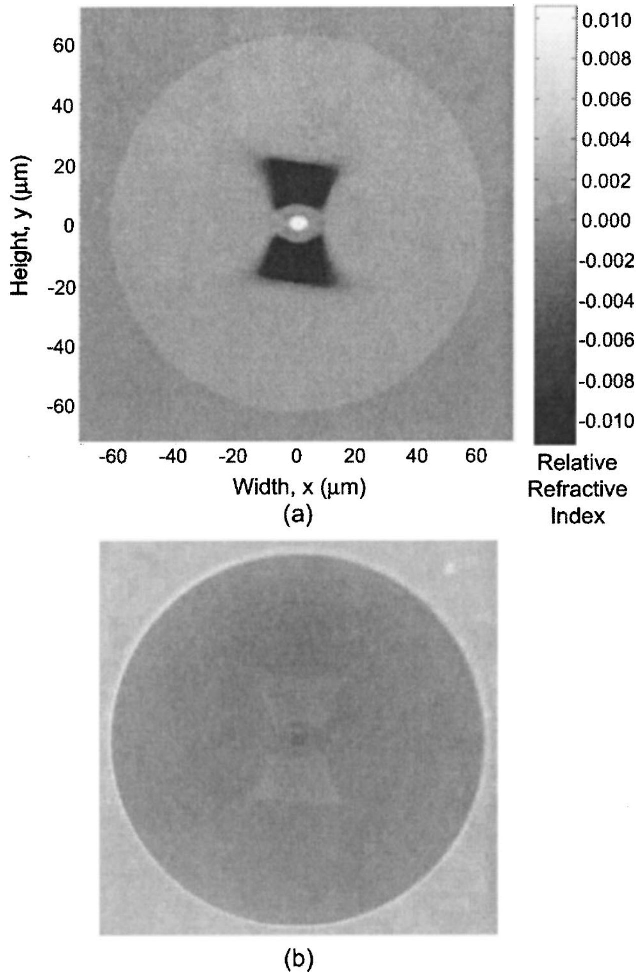


Fig. 1. (a) Reconstructed relative refractive-index profile of a bow-tie-type PMF. (b) Dark-field reflected-light image of the PMF end face. Structural features present in both the reconstructed profile and the end-face image agree closely.

with MIOPT. PMF has an azimuthally asymmetric refractive-index profile, whereas SMF has a symmetric profile. Both profiles are reconstructed from 360 interference images taken every 1° around the samples and processed with a modified reconstruction filter.[4,6] After processing the SMF interference images, it is necessary to correct for a slight ambient temperature variation that occurs during measurement (additive shift). The reconstructed profiles are shown relative to the surrounding refractive index of the matching oil used during measurement $[n(x,y) - n_{\text{oil}}]$.

The reconstructed cross-sectional refractive-index profile of the bow-tie-type PMF is shown in Fig. 1(a). The bow-tie shape of the stress-producing region is evident in the profile. Noise in the profile is relatively low, and the typical tomographic starring effect, though present, is minor; the low levels of both result from practices implemented in MIOPT during measurement and reconstruction.[4] The cladding diameter in the reconstructed profile closely matches the PMF's specified value (125 $\mu$m). Also, the portion of the cladding away from the bow-tie region is uniform. The quantitative features present in the reconstructed profile agree well with the qualitative features observed in the dark-field reflected-light image of a polished end face of the PMF shown in Fig. 1(b) (taken with a microscope at 50× magnification). Particularly evident in both the profile and the image are the slant of the outer edges of the bow-tie region and the distortion at the corners. Although a birefringence profile is not measured for the PMF, such a profile can be obtained with MIOPT by subtracting two profile measurements taken with an aligned polarizer–analyzer pair, with one profile obtained with the pair aligned along the fiber longitudinal axis and the other obtained with the pair aligned perpendicular to the longitudinal axis.

Figure 2(a) shows the vertical line profile taken through the center of the reconstructed profile, and Fig. 2(b) shows the equivalent horizontal line profile. Detailed features of the core region are evident, including the center dip and overall ellipticity. The variations present in the lower-index stress-

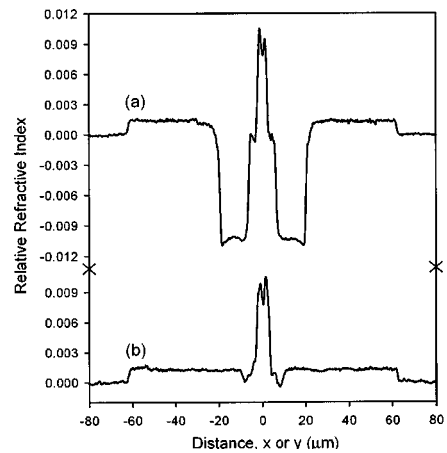


Fig. 2. (a) Vertical line profile taken through the center of the reconstructed profile of the PMF $[n(0,y)-n_{\text{oil}}]$. (b) Horizontal line profile taken through the center of the reconstructed profile of the PMF $[n(x,0)-n_{\text{oil}}]$.

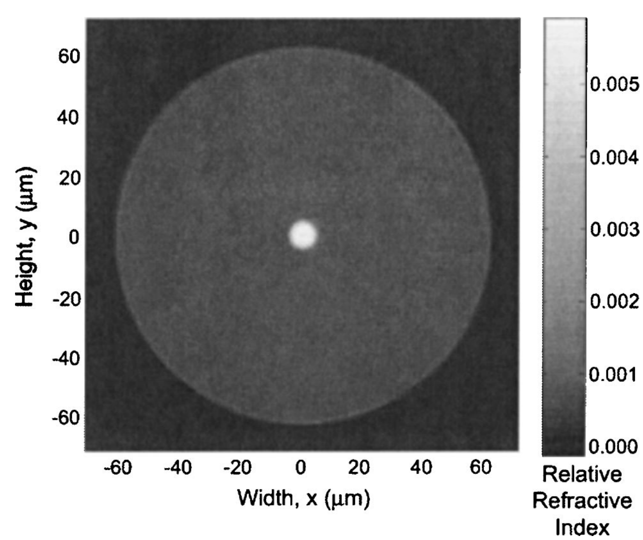


Fig. 3. Reconstructed relative refractive-index profile of a SMF.

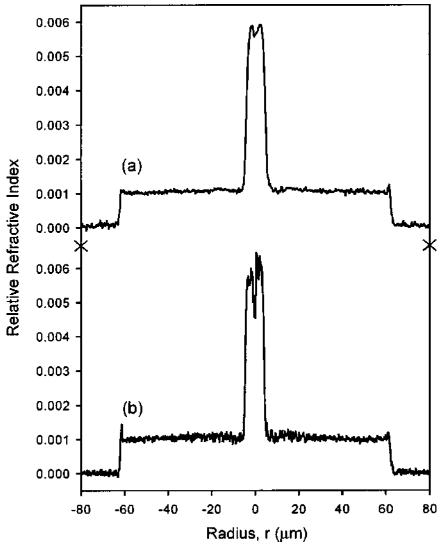


Fig. 4. (a) Vertical line profile taken through the center of the reconstructed profile of the SMF $[n(0,y)-n_{\text{oil}}]$. (b) One-dimensional profile calculated with transverse interferometry, which assumes azimuthal symmetry.[3]

producing region are apparent in the vertical line profile.

MIOPT can also be used to profile optical fibers with azimuthally symmetric cross-sectional refractive-index profiles. Although tomography is not required for profiling symmetric objects, its application can lower overall noise levels and potentially reveal index irregularities and other unintended nonuniformities. As an example, a measurement of a standard telecommunication single-mode optical fiber is conducted, with the resulting reconstructed index profile shown in Fig. 3. The cladding and core diameters in the reconstructed profile closely match the SMF's specified values (125 and 8.2 $\mu$m, respectively). As expected of typical SMF, the profile is azimuthally symmetric.

Figure 4(a) shows the vertical line profile of the relative refractive index through the center of the reconstructed profile. As a comparison with a common one-dimensional profiling technique, transverse interferometric profiling,[3,7] the profile shown in Fig. 4(b) was calculated from the last interference image of the set used in the MIOPT reconstruction. The two profiles are similar, though the line profile taken from the MIOPT reconstruction does have lower noise levels. On the basis of the two index profiles measured by MIOPT, the estimated spatial resolution is 0.5 $\mu$m, and the index resolution is estimated to be below (better than) $1\times10^{-4}$. The resolution values of the technique are estimated and depend on many factors (CCD array size, resolving power, beam deflection, source wavelength, etc.).[8,9]

In summary, we have presented the first, to our knowledge, nondestructive measurements of optical fiber refractive-index profiles obtained with MIOPT. The example measured profiles demonstrate experimentally the ability of MIOPT to profile both azimuthally asymmetric and symmetric optical fibers or fiber devices. Thus the technique is suitable for characterizing samples such as optical fiber exposed to laser light and fluid-filled microstructure and photonic crystal fiber. The advantages of using MIOPT for profiling include lower noise levels and higher resolution, both of which are important for accurate characterization of intentional or unintentional small or irregular index variations. Refinement of the experimental apparatus and implementation of more-sophisticated processing algorithms can improve accuracy and reduce starring (or other) artifacts. Three-dimensional refractive-index profiles $[n(x,y,z)]$ of optical fiber can be obtained by stacking two-dimensional cross-sectional profiles.

This research was performed as part of the Interconnect Focus Center research program supported by the Semiconductor Research Corporation, the Microelectronics Advanced Research Corporation, and the Defense Advanced Research Projects Agency. The authors thank Andrew F. Ingles for his help with the interference microscope system. T. K. Gaylord's e-mail address is tgaylord@ece.gatech.edu.

## References

1. K. Dossou, S. LaRochelle, and M. Fontaine, J. Lightwave Technol. **20**, 1463 (2002).
2. E. Anemogiannis, E. N. Glytsis, and T. K. Gaylord, J. Lightwave Technol. **21**, 218 (2003).
3. L. M. Boggs, H. M. Presby, and D. Marcuse, Bell Syst. Tech. J. **58**, 867 (1979).
4. B. L. Bachim and T. K. Gaylord, Appl. Opt. **44**, 316 (2005).
5. S. T. Huntington, P. Mulvaney, A. Roberts, K. A. Nugent, and M. Bazylenko, J. Appl. Phys. **82**, 2730 (1997).
6. D. A. Viskoe and G. W. Donohoe, IEEE Trans. Instrum. Meas. **45**, 70 (1996).
7. H. M. Presby, D. Marcuse, H. W. Astle, and L. M. Boggs, Bell Syst. Tech. J. **58**, 883 (1979).
8. Y. Park, S. Choi, U.-C. Paek, K. Oh, and D. Y. Kim, Appl. Opt. **42**, 1182 (2003).
9. W. Górski, Opt. Lasers Eng. **41**, 563 (2004).