OMF1.pdf

Recent Progress in Optical Fiber Refractive Index Profiling

Andrew D. Yablon
Interfiber Analysis, 26 Ridgewood Drive, Livingston, NJ 07039, USA
andrew_yablon@interfiberanalysis.com

Abstract: Recent optical fiber refractive index profile measurement advances include quantitative phase measurement, multi-wavelength spectroscopy, and computerized tomography. These new techniques, and their application to fiber-based components including tapers, splices, gratings, and couplers, are reviewed and discussed.
OCIS codes: (060.2300) Fiber measurements; (060.2270) Fiber characterization; (290.3030) Scattering : Index Measurements

1. Introduction

Accurate and complete knowledge of a fiber's refractive index profile is critically important for predicting and understanding diverse optical performance characteristics including chromatic dispersion in single-mode fibers, modal dispersion in multimode fibers, macro- and micro-bend behavior, interconnection losses, and nonlinear thresholds. A surprisingly large diversity of optical fiber profiling techniques have been developed since the inception of optical fiber technology decades ago [1-3].

Measurement of a fiber's refractive index profile is inherently challenging, for example compared to an optical fiber preform, because of the microscopic sample dimensions. While preform profiles can be measured relatively accurately, direct measurement of the fiber's index profile is usually preferable since: (1) fiber draw effects are incorporated; (2) some fibers are assembled on the draw tower and therefore cannot be profiled prior to draw; and (3) consumers of optical fiber typically do not have access to the manufacturer's preform profile data.

Although atomic force microscopy has been applied to a chemically etched fiber cleave to quantify a fiber's refractive index profile [4], nearly all techniques are fundamentally optical in nature. Furthermore, nearly all techniques require that any polymer coating be at least temporarily removed from the fiber and that the fiber be immersed in refractive index matching oil. Fiber index profiling methods can be organized according to whether the fiber is interrogated at a cleaved end or transversely through its side. Measurements at a cleaved end are inherently destructive, cannot resolve axial inhomogeneities (as in a fiber grating or at a fusion splice), may obscure residual stress effects [5], and can suffer from measurement artifacts associated with the cleave. On the other hand, while transverse measurements can be non-destructive, they either demand that the fiber's index profile be strictly axisymmetric or require some type of computerized tomography.

The *refracted-ray method* [1,2,6], more often described as *refracted near field* (RNF), scans a focused spot across the end face of a cleaved fiber sample and detects the amplitude of light escaping from this fiber sample. While RNF has previously been the dominant commercial technique, several important advances for optical fiber refractive index profile measurement have been made over the past several years and some have already been commercialized. Generally speaking, the new techniques are phase measurements in contrast to RNF, which requires careful signal amplitude calibration to provide accurate results. Most RNF instruments assume that the refractive index of a fiber's pure silica cladding can be treated as a refractive index reference value but recent research [7] has documented unexpected draw-induced cladding index perturbations that can lead to erroneous RNF measurements. *Transverse interferometry* [1,3] is a longstanding alternative approach for directly measuring the phase of a fiber sample through its side without any cleave. It is worth noting that the accuracy of commercial RNF systems sensitively depends upon periodic calibration against an industry standard fiber, which is itself measured interferometrically [8].

2. Differential Interference Contrast (DIC)

Differential Interference Contrast (DIC) microscopy is a long standing approach for providing image contrast from the phase variation in a transparent object. This phase variation is produced from the variation in path length experienced by rays that are laterally displaced by a distance of a few hundred nm. DIC microscopy was traditionally concerned with providing contrast for biomedical imaging applications, but recently this technique was applied to measure refractive index profiles by relating the contrast in a DIC image of an optical fiber to its internal phase geometry [9,10]. While this is a transverse technique, it is strictly single wavelength. Since the interference is achieved by manipulating the polarization of the beam, there is some concern regarding the influence of birefringence associated with residual stresses and strains in the fiber, particularly in PM fibers. As with most transverse phase imaging techniques, any refraction of the ray by the sample is assumed negligible and ignored.

3. Quantitative Phase Microscopy (QPM)

Quantitative Phase Microscopy (QPM) [11,12] is a relatively new transverse method in which the spatial distribution of phase in a fiber sample is determined from magnified images of the fiber acquired at slightly different focal planes. This technique matches the spatial resolution of RNF and is applicable to a wide variety of optical fibers. Like other transverse techniques, QPM has been used to map the refractive index of axially heterogeneous structures such as fusion splices [13] and gratings [14] but requires tomography when applied to non-axisymmetric fiber samples. QPM has been applied to non-axisymmetric fiber samples without tomography [15], but this required polishing fiber samples into very thin axial disks and is therefore not very practical.

4. Multi-Wavelength Optical Fiber Index Profiling

Recently, a new technique capable of directly measuring a fiber's refractive index profile across a broad band of wavelengths using a combination of transverse interferometry and Fourier Transform Spectroscopy (FTS) was described [16]. In this technique, the fiber is placed in one arm of a Mach-Zehnder interferometer illuminated by a broad band source that is both temporally and spatially incoherent. A computer controlled phase shifter imposes a known continuous phase shift and the detected image of the fiber sample is processed via Fourier analysis to reveal the fiber's index profile across the entire band of illumination. Like all types of spatially-resolved FTS, continuous improvements in computer processing speed, memory, and detector technology (specifically CCD resolution and interface speed) have been important enablers of this new technology. In principal this technique can directly reveal the material dispersion of the fiber in a spatially resolved manner, which is an important advance since before the advent of multi-wavelength fiber profiling, material dispersion could only be estimated from knowledge of the fiber doping profile. Another advantage of this technique is the incorporation of high numerical aperture oil-immersion objectives that provide diffraction-limited spatial resolution that is finer than the measurement wavelength [16].

5. Computerized Tomography

RNF can be used to map the 2-dimensional variation in refractive index of a fiber's cross section by raster scanning the spot [6]. In addition to the inherent limitations associated with measuring a cleaved end noted earlier, this approach is understandably time consuming. An alternative approach combines a phase sensitive measurement technique such as transverse interferometry [17-20] or QPM [13] with a computerized tomographic approach in which the phase delay of the fiber sample is measured at a multiplicity of angles and the resulting dataset is combined into a complete 2-dimensional representation of the index profile. As with multi-wavelength fiber index profiling technology, advances in computer processing speed, available memory, and detector technology are critical to the practicality of this approach. Computerized tomography can also be combined with a multi-wavelength fiber index profile measurement. Tomography can reveal unexpected azimuthal refractive index non-uniformities in fibers that are mistakenly assumed to be axisymmetric, such as graded-index multimode fibers (GIF or GI-MMF). Computerized tomography is essential when using a transverse approach to measure non-axisymmetric fibers such as PM fibers or cladding-pumped rare-earth-doped fibers with a non-circular cladding. A sequence of 2-dimensional tomographic fiber index profile scans can be acquired along the axial length of a non-homogeneous fiber sample thereby revealing the entire 3-dimensional refractive index variation [13].

6. Novel Applications

Traditionally, refractive index profiling was only applied to as-drawn fiber samples either for predicting or diagnosing their optical performance. Although it is not widely appreciated, fiber index profiling technologies can also be applied to analyze fiber components such as fusion splices [13,20-23], fiber couplers, physical tapers, long-period gratings [24], and even short-period Bragg fiber gratings [14,25,26]. When combined with suitable numerical modeling, refractive index profile data acquired on a fusion splice can be particularly useful for diagnosing the source of splice loss and providing critical insights towards splice optimization [21]. In addition, refractive index profile data acquired at specific polarizations can directly quantify the fiber's birefringence and residual elastic stress in an optical fiber sample [7]. Finally, the refractive index of fluids or inclusions such as microspheres inside an optical fiber can also be measured by some of the new techniques [14].

7. Outlook

Fiber profiling technology naturally follows optical fiber design trends. At this point, most fiber profiling technologies are extremely effective for measuring traditional telecom fibers. However, certain types of microstructured optical fibers are difficult to measure with any current fiber index profiling technology and therefore opportunities for important improvements remain. For example, air holes must usually be infused with refractive index matching oil to avoid catastrophic refraction and reflection at their boundaries, and even in this case ray refraction may require a diffraction approximation [20,27]. A reflection-based approach for measuring microstructured fiber was developed [28], but this technique requires excellent cleaves which are particularly difficult to achieve with many microstructured fibers. Recent growth in the field of large-cladding-diameter high-power fibers has elevated the importance of profiling the refractive index of such fibers. Finally, it is worth noting that many of the technologies employed for optical fiber refractive index profiling are also effective for characterizing optical waveguides [6], and the ongoing development of (non-fiber) photonic crystal structures may also provide important applications for these technologies.

8. References

[1] D. Marcuse, *Principles of Optical Fiber Measurements* (Academic, 1981), Chap. 4.
[2] K. W. Raine *et al*, "Refractive Index Profiling – State of the Art," J Lightwave Technol **7,** 1162-1169 (1989).
[3] F. El-Diasty, "Characterization of optical fibers by two- and multiple-beam interferometry," Opt Lasers Eng **46**, 291-305 (2008).
[4] P. Pace *et al*, "Refractive index profiles of Ge-doped optical fibers with nanometer spatial resolution using atomic force microscopy," Opt Express 1**2,** 1452-1457 (2004).
[5] M. R. Hutsel *et al*, "Accurate cross-sectional stress profiling of optical fibers," Appl Opt **48**, 4985-4994 (2009).
[6] N.H. Fontaine *et al*, "Two-dimensional index profiling of fibers and waveguides," Appl Opt 38, 6836-6844 (1999).
[7] A.D. Yablon, "Optical and Mechanical Effects of Frozen-in Stresses and Strains in Optical Fibers," IEEE J Sel Topics Quant Elect **10**, 300-311 (2004).
[8] National Physics Laboratory, Middlesex, UK, see [Online]. Available: http://www.npl.co.uk/optical-radiation-photonics/optical-comms-and-data/products-and-services/optical-fibre-refractive-index. Also discussed in references [16] and [25].
[9] B. Kouskousis *et al*, "Quantitative phase and refractive index analysis of optical fibers using differential interference contrast microscopy," Appl Opt **47,** 5182-5189 (2008).
[10] N.M. Dragomir *et al*, "Refractive Index Profiling of Optical Fibers Using Differential Interference Contrast Microscopy," IEEE Photon Technol Lett 1**7,** 2149-2151 (2005).
[11] A. Roberts *et al*, "Refractive-index profiling of optical fibers with axial symmetry by use of quantitative phase microscopy," Opt Lett **27**, 2061-2063 (2002).
[12] E. Ampem-Lassen *et al*, "Refractive index profiling of axially symmetric optical fibers: a new technique," Opt Express **13**, 3277-3282 (2005).
[13] N.M. Dragomir et al, "Three-Dimensional Refractive Index Reconstruction With Quantitative Phase Tomography," Microsc Res Tech **71**, 5-10 (2008).
[14] N.M. Dragomir et al, "Three-Dimensional Quantitative Phase Imaging: Current and Future Perspectives," appearing in *Three-Dimensional and Multidimensional Microscopy: Image Acquisition and Processing XV*, Proceedings of the SPIE vol. 6861 (2008).
[15] E. Ampem-Lassen *et al*, "Index mapping for fibers with symmetric and asymmetric refractive index profiles," Opt Express **16**, 10912-10917.
[16] A.D.Yablon, "Multi-Wavelength Optical Fiber Refractive Index Profiling by Spatially Resolved Fourier Transform Spectroscopy," J Lightwave Technol 28, 360-364 (2010).
[17] P.L. Chu et al, "Nondestructive determination of refractive index profile of an optical fiber: fast Fourier transform method," Appl Opt **18**, 1117-1122.
[18] B.L. Bachim *et al*, "Refractive-index profiling of azimuthally asymmetric optical fibers by microinterferometric optical phase tomography," Opt Lett **30**, 1126-1128 (2005).
[19] B.L. Bachim *et al*, "Microinterferometric optical phase tomography for measuring small, asymmetric refractive-index differences in the profiles of optical fibers and fiber devices," Appl Opt **44**, 316-327 (2005).
[20] P. Kniazewski *et al*, "Microinterferometric tomography of photonics phase elements," appearing in *Microsystems Engineering: Metrology and Inspection III*, Proceedings of the SPIE vol. 5145 (2003).
[21] A.D. Yablon, Optical Fiber Fusion Splicing (Springer 2005), Sect. 7.3.
[22] N.M. Dragomir *et al*, "Phase-sensitive imaging techniques applied to optical fibre characterisation," IEE Proceedings in Optoelectronics **153**, 217-221 (2006).
[23] N.M. Dragomir *et al*, "Analysis of Changes in Optical Fibers During Arc-Fusion Splicing by Use of Quantitative Phase Imaging," Microsc Res Tech **69**, 847-851 (2006).
[24] D.D. Davis *et al*, "Long-period fibre grating fabrication with focused CO_2 laser pulses," Electron Lett **34**, 302-303 (1998).
[25] B. P. Kouskousis *et al*, "Quantitative investigation of the refractive-index modulation within the core of a fiber Bragg grating," Opt Express **14**, 10332-10338 (2006).
[26] N.M. Dragomir *et al*, "Nondestructive imaging of a type I optical fiber Bragg grating," Opt Lett **28**, 789-791 (2003).
[27] W. Gorski *et al*, "Tomographic imaging of photonic crystal fibers," Opt Lett **32**, 1977-1979 (2007).
[28] Y. Youk et al, "Refractive Index Profiling of a Core-Doped Photonics Crystal Fiber," IEEE Photon Technol Lett **19**, 810-812 (2007).