Endface index profiling of optical fiber preforms

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A new method of obtaining the refractive-index profile of an optical fiber preform is described. The technique is based on the refraction of light emerging from an endface cut normal to the preform axis. Two forms have been developed. In one, quantitative index data are obtained by a spatial-filtering method. The result is displayed as a 3-D graphic plot. The other uses a new type of spatial modulation which permits a direct display of the 3-D index profile in the form of a visual image.

1. Introduction

The refractive-index profile of an optical fiber preform can be measured by several different techniques, all of which assume a circularly symmetric refractive-index structure in the cross section of both core and cladding. However, in practice many preforms exhibit a slight noncircularity owing to manufacturing imperfections. Furthermore, there is increasing interest in preforms with highly noncircular core or cladding geometries for use in manufacturing polarization-maintaining fibers. In both cases, techniques which rely on transverse illumination of the preform are inaccurate in their reconstruction of the profile.

A solution to the problem is to take several transverse projections and to use a computer-aided tomographic (CAT) technique to reconstruct the 3-D index profile section by section. However, the computer processing time is inconveniently long, and consequently it is hard to envisage the method for routine inspection applications. The alternative is to use thin-slice interferometry. This is tedious and particularly difficult when cutting and polishing delicate cross-sectional slips from highly stressed preforms since the slices tend to shatter.

This paper describes a newly developed method which gives the preform index profile without the need for a mathematical transform. The principle of the technique is based on the recognition that the index profile can be uniquely determined from the refraction of a ray emerging from an endface cut normal to the preform axis. We show that the angle of refraction is accurately proportional to the local refractive index in the endface at the point of ray emergence and, therefore, no lengthy numerical data processing is necessary. The method is direct, rapid, and applicable to noncircular preforms.

Two forms of the endface preform index profiling (EFPI/IP) technique have been developed. The first allows quantitative data to be acquired and displayed in the form of a 3-D graphic plot. Ray refraction angles are measured using either a shadow mask or dynamic spatial filtering as previously developed for transverse preform index profiling (TPIP). The second and perhaps most appealing form uses a new form of spatial filtering to permit a direct visual display of the 3-D index profile in a form not unlike a scanning electron microscope image. Both variants require minimal preparation of the preform and are invaluable for immediate inspection of preform quality.

II. Theory

Figure 1 shows a flat endface, cut normal to the preform axis, immersed in index-matching liquid of index \( n_1 \). The endface is illuminated by a collimated beam of light inclined at angle \( \alpha \) to the plane of the cross section. For simplicity, we consider the preform as a 2-D slab, an approach which is valid for rays which pass through the preform axis, i.e., are incident in a plane which contains the axis.

During its traverse of the preform, a ray experiences refraction (a) at the liquid preform boundary (point \( A \) in Fig. 1), (b) while propagating through the complex index profile of the preform, and (c) on emerging at point \( B \) in the endface. At point \( A \) on the periphery (index \( n_A \)) the refraction angle \( \alpha' \) is given by

\[
\frac{n_1 \sin \alpha}{n_A} = \frac{n_A \sin \alpha'}{1},
\]

If \( n_B \) is the index in the endface at the point \( B \) at which the ray exits and \( \phi \) is the angle through which the ray is deviated from its original course, Snell's law gives
III. Spatial-Filtering Techniques

A. Dynamic Spatial Filtering

The dynamic spatial-filtering technique has been previously successfully used in TP1P.\textsuperscript{3} It has the considerable advantage that ray deflection angles are transposed into a signal in the time domain where accurate measurements can be made more easily. It is a simple matter to adopt the method to the measurement of refraction angles in the preform endface.

The optical arrangement is substantially that used for TP1P and is illustrated in Fig. 2. A lens is arranged to produce an image of the preform endface on a screen in which a small photodetector is situated. The angular distribution of rays emerging from the endface is converted to a spatial distribution in the focal plane of the lens according to

\[ \omega = f/\tan \phi_a, \]

where \( \omega \) is the coordinate in the focal plane perpendicular to the \( u \) axis in the preform endface (Fig. 2), and \( f \) is the lens focal length.

A light chopper rotating at constant angular speed sweeps along the \( \omega \) axis, progressively extinguishing the ray distribution. If \( t \) is the time taken for a blade to rotate from the reference point positioned at angle \( \sigma \) from the axis (Fig. 2) to a position \( \omega \) at which a given ray is interrupted,

\[ \omega = R \tan(\rho t - \sigma), \]

where \( R \) is the distance of the chopper center of rotation to the optical axis. Thus, the ray angle \( \phi_a \) is converted to a time signal given by

\[ \phi_a = \tan^{-1} \left( \frac{R}{f \tan(\rho t - \sigma)} \right). \]

The photodetector in the image plane effectively selects for observation the single ray present at position \( u, v \) in the endface; cessation of the signal indicates that the chopper blade has reached a position along the \( \omega \) axis at which that ray is obstructed. Thus, a measurement of the time to light extinction at position \( u, v \) gives \( \phi_a(u, v) \) from Eq. (9), and hence the local index difference \( \Delta n(u, v) \) from Eq. (6). The complete 2-D profile can be acquired by performing a raster scan of the endface in the \( u, v \) plane, or by moving the photodetector in the image.

In Sec. III we describe two means of associating a ray deflection angle with a position in the endface for the purpose of quantitative measurements. In addition, a method for producing a visual image of the 3-D index profile is outlined.
B. Shadow-Mask Method

As an alternative, a straight knife-edge can be moved in the focal plane to remove rays progressively according to their deflection angle (see inset A, Fig. 3). All areas in the image with an index greater than a value set by the position of the knife-edge will appear dark. The index at the shadow boundary can be found by measuring the position of the edge relative to the optic axis.

If the mask edge is set at right angles to the \( \omega \) axis in the focal plane and is positioned at \( n_c \), areas in the image with index \( n(u,v) > n_c \) will be in shadow. Here \( n_c \) is the index at the shadow edge and is given by

\[
n_c = n_i + \frac{\omega}{2f} \sin \left[ \frac{|2\alpha|}{b} \right].
\]

Thus, a reading of the knife-edge position provides the index of all positions in the endface on a contour represented by the shadow edge.

A variation is to use the knife-edge displaced a distance \( \delta \) from the lens focal plane (inset A, Fig. 3). In this case the shadow boundary is given by

\[
u' = \frac{\omega}{b} + \omega \left( 1 - \frac{l}{b} \right),
\]

\[
\omega = \frac{2f \Delta n}{\sin \left[ \frac{|2\alpha|}{b} \right]}.
\]

Here \( u' \) is the coordinate of the shadow boundary in the image (Fig. 3), \( \omega' \) is the position of the knife-edge measured from the optic axis, and \( l \) is the distance from the lens focal plane to the image plane.

From Eqs. (11) and (12),

\[
u' = \omega' - \frac{\omega}{b} + \frac{2f \cdot \Delta n}{\sin \left[ \frac{|2\alpha|}{b} \right]} \left( 1 - \frac{l}{b} \right).
\]

We see that the shadow boundary coordinate \( u' \) is now directly proportional to the local refractive index \( \Delta n(u,v) \), and, therefore, the shadow edge represents the index profile. This method is useful for directly viewing the profile in the endface image. It is also invaluable when profiling very large (>3-cm diam) preforms, since a small section in the image can be examined independently.

C. Visual Display Using Cylindrical-Lens Modulation

This modification provides a remarkably realistic representation of the 3-D index profile as a 2-D image using the distortion produced by a cylindrical lens placed as shown in Fig. 3 (inset B). The effect of the extra lens is to further refract the rays arriving at the focal plane by an amount in proportion to their distance \( \omega \) from the optic axis, i.e., in proportion to their deflection angle and hence to the local index in the preform endface. For the case where the cylindrical lens (focal length \( f_1 \)) is placed in the focal plane of the primary lens, the secondary angle of refraction \( \beta \) (inset B, Fig. 3) is given by

\[
\tan \beta = \frac{-\omega - \tan \psi (f_1 \tan \psi - \omega)}{f_1 + \tan \psi (f_1 \tan \psi - \omega)},
\]

where \( \psi \) is the angle of the ray to the optical axis with no cylindrical lens present (see inset B, Fig. 3). If \( f_1 \gg \tan \psi (f_1 \tan \psi - \omega) \) as is usually the case, we have

\[
\tan \beta \approx -\omega/f_1.
\]

The effect of this secondary refraction is to displace a ray by a distance \( x \) in or out of the preform endface image, where \( x \) depends on the local refractive index \( n(u,v) \) as follows:

\[
x = l [\tan \beta + \tan \psi] - \tan \psi.
\]

If \( \tan \beta \tan \psi \ll 1 \), we have from Eq. (15) that \( x \approx l \tan \beta \approx -l \omega/f_1 \), and finally,

\[
x = -l f_1 \frac{2 \Delta n(u,v)}{\sin \left[ \frac{|2\alpha|}{b} \right]}.
\]

Thus, the ray displacement \( x \) is proportional to the local index difference \( \Delta n(u,v) \) at the point in the endface where the ray emerged. The displacement distorts the endface image so that the core bow inward with a shape corresponding to the 3-D representation of the index profile.

If the cylindrical lens is displaced by \( \delta \) from the focal plane of the primary lens (Fig. 3, inset B), the ray arrival point in the image plane is given by
Fig. 4. Index profiles for a monomode fiber preform with circular cross section. Direct visual image is shown in (a), and the graphic plot is shown in (b).

INDEX DIFFERENCE

0.01

Fig. 5. Comparison of index profiles for preform of Fig. 4 obtained by endface method (solid line) and transverse-illumination method (dots and fine line).

INDEX DIFFERENCE

0.005

Fig. 6. Index profile for a multimode-fiber preform. The direct visual image is given in (a); the graphic plot is shown in (b) and is sectioned in (c).

INDEX DIFFERENCE

0.01

INDEX DIFFERENCE

0.01

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where the parameter \( p \) is given by

\[
p = \delta r - \delta l + i_{i_2},
\]

and \( u_0 \) is the ray arrival point in the image plane when no cylindrical lens is present. In this case, the appearance of the index-profile image varies with the value of the parameter \( p \). For \( p > 0 \), sections of the index profile with \( \Delta n > 0 \) will appear inside the preform; for \( p = 0 \), the preform image becomes a line with only the index profile displayed; and for \( p < 0 \), the index profile with \( \Delta n > 0 \) will appear to protrude from the preform.

IV. Experiment

A high-quality camera lens \((f = 50 \text{ mm}, f/No. = 1.4)\) was used to project a magnified image of the preform endface onto a screen positioned at \( l = 60 \text{ cm} \) away from the lens focal plane. The endfaces were prepared by diamond sawing, followed in some cases by a brief polishing operation. Total preparation time was typically a few minutes. The endface was then immersed in an index-matching cell and illuminated by a collimated beam of white light from a Hg-arc lamp. A dynamic spatial filtering

A two-bladed chopper driven by a speed-stabilized dc motor was used to obtain the graphic plots of index profile. A small (270-\( \mu \text{m} \) diam) silicon photodiode placed on the optic axis in the image plane detects the chopped light (Fig. 2). The square-wave signal obtained, together with that from the reference detector on the chopper periphery, was fed to a timer/counter which determined their relative delay. Measurements were made in a raster-scan pattern across the endface by moving the preform. After correction according to Eq. (9), the result was displayed as a 3-D profile on a desk-top computer.

B. Shadow-Mask Method

No quantitative measurements were taken; however, for demonstration purposes a knife-edge was placed in the lens focal plane and the image recorded on a photograph for various off-axis distances of the edge. Similar experiments were performed with the edge displaced along the axis a distance \( \delta \).

C. Visual 3-D Images

A secondary cylindrical lens of 10-cm focal length was placed between the primary lens and the screen as shown in Fig. 3. The observed 3-D image of the endface was recorded photographically for various positions of the cylindrical lens along the optical axis.

V. Results

Three preforms made by the MCVD technique have been used to demonstrate the capabilities of the EFPI technique: (1) a monomode preform with a GeO\(_2\)/SiO\(_2\) core, a depressed B\(_2\)O\(_3\)/SiO\(_2\) cladding, and a silica substrate; (2) a graded-index multimode preform with a GeO\(_2\)/P\(_2\)O\(_5\)/SiO\(_2\) core, a depressed B\(_2\)O\(_3\)/SiO\(_2\) buffer layer, and a silica substrate; (3) a highly elliptical monomode preform with a GeO\(_2\)/SiO\(_2\) core, surrounded by an all-silica cladding/substrate.

Figure 4 compares the profile plot obtained by the dynamic spatial-filtering technique for the circular monomode preform [Fig. 4(a)] with its visual 3-D rep-
representation. In this case and for subsequent profiles, only the deposited area is shown and not the complete substrate. The core with its central dip, together with the layer structure in the depressed cladding, can be clearly seen in both displays. The detail in the foreground, and particularly in the background, is not as clearly resolved for a number of possible reasons which are under investigation. In addition, some surface noise is visible, which is attributable to incomplete surface preparation and dust particles.

Figure 5 shows the central section of the profile of Fig. 4 compared with the result obtained using a transverse preform index profiler. The agreement is excellent, even in the detail of the cladding layer structure.

Figures 6(a) and (b) give the visual image and graphic plot, respectively, of the multimode graded-index preform. Details of the layer structure, central dip, and depressed buffer layer are visible, together with an error in profile grading which occurs at the transition from buffer layer to core. This feature may be seen more clearly in the sectional profile of Fig. 6(c), which also allows the extent of the central dip to be observed.

Figures 7(a)–(d) illustrate the effect on the visual image of moving the cylindrical lens to various positions along the optic axis (see Fig. 3) characterized by the parameter 0 of Eq. (19). Starting close to the primary lens (0 < 0), the profile of the multimode graded-index preform appears inside the preform. It then changes at 0 = 0 to display the profile alone with the substrate level visible only as a bright horizontal line marking the

Fig. 8. Visual displays obtained for the preform of Fig. 6 using the shadow-mask method. Shown in (a) is the display for a knife-edge in the focal plane, while (b) illustrates effect of displacing the knife-edge away from the focal plane.

Fig. 9. Index profiles of a highly elliptical monomode fiber preform. The visual image is given in (a) (lower). The whole endface image (upper) of the preform is shadowed by using the mask method, except the core in which the index is higher than the dark area. Graphic display is shown in (b) and that obtained from multiple transverse projections (CAT) in (c) for comparison.
silica datum level. Finally, the profile protrudes from the endface for \( p > 0 \). When the cylindrical lens is close to the image screen, we have the display of Fig. 7(d), which is somewhat flat but is useful for observing the endface geometry.

Figures 8(a) and (b) indicate the appearance of the same preform when the shadow-mask method is applied. Figure 8(a) shows a shadow contour. All areas in the endface with an index greater than a value which depends on the position of the knife-edge in the focal plane are eclipsed. Figure 8(b) shows the effect which occurs when the knife-edge is displaced from the focal plane. The image now displays the index profile in the form of a shadow.

Figure 9 demonstrates the ability of EFPI to determine index profiles in highly elliptical preforms. Figures 9(a) and (b) show the 3-D image and graphic plot, respectively. In this case, the visual image is not as clear as for the other preforms owing to the small size of the core (0.2 \( \times \) 1 mm). Figure 9(c) shows the result reconstructed by CAT from transverse sections obtained by dynamic spatial filtering. It is clear that there is close agreement between the techniques despite the slightly higher noise level on the EFPI profile caused by poor endface finish.

VI. Conclusions

The endface technique provides fast, accurate, and reliable preform refractive-index profiles without the need for a mathematical transform. The method is particularly useful for noncircular geometries where the alternative technique, the transverse-illumination method (TPIP), has difficulties. Visual displays of the index profile can also be obtained in the form of a 3-D image, and we have found this a very considerable advantage.

The new profiling technique may be seen as complementary to the now well-established TPIP method, providing immediate visual evaluation of preform quality as well as rapid profile plots. The technique has advantages over conventional methods, particularly when dealing with difficult preforms, since it provides unambiguous reference data which may be used for calibration purposes. Conversely, profiles are only revealed at the two ends of the preform, and thus the profile evolution along the length cannot be studied.

Appendix

The derivation of Eq. (3) assumed a 2-D slab model. In general, however, a real preform has small components of the refracted ray in a direction normal to the plane of Fig. 1 (the \( u_z \) plane, where \( z \) is the optic axis). We will, therefore, consider two angular components of the ray at the point of entry to the preform and exit from the endface. Taking first the entry point, we have angular components \( \theta_u \) and \( \theta_v \) of the refraction angle in the \( u_z \) and \( v_z \) planes, respectively. We need only consider the \( \theta_u \) component, since the spatial-filtering process is arranged to operate along the \( \omega \) axis, i.e., on \( \theta_u \) components exclusively:

\[
\sin \theta_u = \frac{n_1}{n_A} \sin \alpha \left[ \frac{1}{\cos^2 \gamma - \frac{n_1^2}{n_A^2} \tan^2 \gamma} \right]^{1/2}.
\]  

Here \( \gamma \) is the incident angle of the ray to the preform surface normal; \( \gamma \) varies with the entry point on the preform periphery. Since the preform is in index-matching liquid, \( n_1 \approx n_A \), and Eq. (A1) reduces to [compare Eq. (1)]

\[
\sin \theta_u = \frac{n_1}{n_A} \sin \alpha.
\]

At the point of ray emergence in the endface we have a similar formula:

\[
\cos(\phi_u - \alpha) = \frac{n_B}{n_1} \cos \alpha \left[ \frac{1}{\cos^2 \Phi - \frac{n_B^2}{n_1^2} \tan^2 \Phi} \right]^{1/2},
\]

where \( \phi_u, \alpha_u \) are the angular components of \( \phi \) and \( \alpha \) in the \( u_z \) plane, respectively, and \( \Phi \) is the familiar transverse ray deflection experienced in the TPIP method. Normally \( \Phi \) is small and \( \cos \Phi \approx 1 \). Consequently, we have [compare Eq. (3)]

\[
\cos(\phi_u - \alpha) = \frac{n_B}{n_1} \cos \alpha_u.
\]

We conclude that Eq. (3) is valid anywhere in the endface, and therefore the method is equally applicable to 3-D objects. Note, however, that in the case of preforms with substantial layer structure, \( \Phi \) may be significant. This effect is possibly the reason for the reduced resolution seen for areas in the endface outside the \( u_z \) plane.

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References