Nondestructive measurement of refractive index profile for holey fiber preforms

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Abstract: A non-destructive technique is presented to determine the refractive index profile of holey fiber preforms. The holes are filled with index matching oil and the holey preform deflection data is measured. An improved optical path-length formula and back projection method is used to reconstruct the two-dimensional filled holey fiber preform refractive index distribution.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2300) Fiber measurements; (160.5470) Polymers; (230.4000) Microstructure fabrication

References and links

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1. Introduction

Holey fibre is a new class of optical fibre that has recently attracted considerable attention due to its unique guiding properties [1]. Greatly modified cladding refractive indices with flexible air hole structure designs makes it unique for various applications, which are not possible in conventional optical fibres. Holey fibres are typically made from single material such as undoped silica or polymers [2]. To produce high-quality holey fibres, two scale reduction stages are required for small-scale feature holey fibres. The presence of air holes makes it difficult to non-destructively determine perform profiles, especially for a second stage preform, which is crucial for predicting optical properties of the holey fibres. Chu first proposed a non-destructive method to measure circularly symmetric conventional optical fibre preforms [3]. Marcuse proposed an experimentally more convenient method by using Abel's inversion [4]. With *a priori* knowledge of near circular or elliptical preforms, several methods were proposed for non-circularly symmetric conventional preform measurements [5-9]. A nondestructive measurement of the two-dimensional refractive index profile for arbitrary preform index distributions without *a priori* knowledge of the preform was proposed by using the tomography method [10]. A non-destructive method for measuring the profile of a Holey Fibre Preform (HFP) has not been reported before. The purpose of this paper is to demonstrate such a method. The method involves filling the air holes with index matching oil to form a Filled Holey Fibre Preform (FHFP), which is treated as a preform with an arbitrary index distribution. The deflection function is used to calculate the optical path length in an improved manner. The back projection method is performed to convert the path length measurements into a refractive index profile. The HFP profiles are inferred by replacing the filling oil by air.

2. Theory

The holes of the HFP are filled with index matching oil to reduce the index difference between the holes and preform material so that the preform together with the filled holes can be treated as a preform with arbitrary index distribution $n(\rho,\theta)$. Figure 1 shows the geometry of the launching arrangement for an FHFP of radius R, which is surrounded by a medium of index matching oil n_0. A ray is shown to enter the FHFP at a distance ρ from the origin O and at an angle θ with respect to the x-axis, and the deflection function $\phi(\rho,\theta)$ is measured. There is no simple expression for $\phi(\rho,\theta)$ that can be inverted to give the refractive index as a function of position. However, under the assumption of small numerical aperture, the deflection function can be related to the optical path length difference.

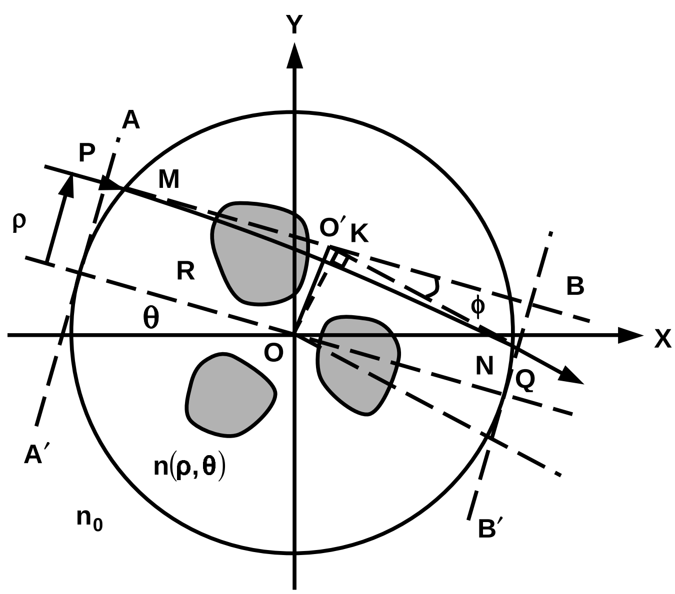

Fig. 1. Ray trajectory in a Filled Holey Fiber preform (FHFP) cross section

In a polar coordinate system, the arbitrary index distribution can be expressed as

$$n(\rho,\theta) = n_0 + \Delta n(\rho) + \delta n(\rho,\theta) \tag{1}$$

The accumulated optical path length difference $\Psi(\rho,\theta)$ through the FHFP from the launching plane AA' to the output observation plane BB', is given by

$$\Psi(\rho,\theta) \approx n_0 \int_0^{\rho} \phi(\xi,\theta) d\xi + \frac{n_0 \rho}{12} \phi(\rho,\theta)^3 + C_0 \tag{2}$$

where

$$C_0 = 2\int_0^{R} \Delta n(r) dr \tag{3}$$

is a constant. The main hypothesis is that the FHFP may be regarded as a phase object, so that the actual ray trajectory can be approximated by a straight line between the launching and observation planes. This assumption does not introduce any significant error provided one uses a very small index difference between the oil and the single material HFP refractive index.

In the Cartesian coordinate system, if the optical path differences are known for all θ between zero and π, the normalized index profile can be reconstructed by the discrete integral [11]

$$f(x,y) \approx \frac{\pi}{N} \sum_{l=1}^{N} g_{\theta_l}(x\cos\theta_l + y\sin\theta_l) \tag{4}$$

where the angles θ_l with l=1,2,…N are those for which the optical path length differences are known. Values $g_\theta(\rho)$ are calculated by inverse Fourier transforms

$$g_\theta(\rho) = \int_{-\infty}^{\infty} S_\theta(k)|k| \exp(i2\pi k\rho) dk \tag{5}$$

where k is the spatial frequency and $S_\theta(k)$ is the Fourier transform of path length difference function of $\Psi_\theta(\rho)$, which is given by

$$S_\theta(k) = \int_{-\infty}^{\infty} \Psi_\theta(\rho) \exp(-i2\pi k\rho) d\rho \tag{6}$$

$S_\theta(k)$ and $g_\theta(\rho)$ can be obtained efficiently by applying a fast Fourier transform and an inverse fast Fourier transform, respectively.

To obtain the index profile of the holey fiber preforms, the first step is to use the laser-scanning method to measure the deflection function $\phi(\rho,\theta)$ of FHFP for N_θ orientations. For each orientation, the whole preform is scanned transversely with an increment $\delta\rho$. Then the optical path length differences $\Psi_\theta(\rho)$ are calculated by using Eq. (2) and the FFT is applied to the optical path length difference function to obtain $S_\theta(k)$. The back-projecting filtered function $g_\theta(\rho)$ is obtained by using the inverse FFT in Eq. (5). For each point (x,y), the normalized index profile of the FHFP is obtained by numerical integration over the rotation angle θ by using Eq. (4). To minimize the influence of measurement noise, which is generally of higher frequencies, $S_\theta(k)$ is multiplied with a Hamming window function $H(k)$ before taking the inverse FFT. Superior reconstructions are usually obtained by applying such a window to filter the projection.

3. Experiments and results

To demonstrate the technique for reconstructing the holey fiber preform profiles, three different HFPs are measured using a NetTest PK2600 preform refractive index analyser. The measurements are performed at a wavelength of 632.8 nm, and the raw data from the detector are used for the index reconstruction. We used 4000×180 arrays data with $5\mu m$ radial step and

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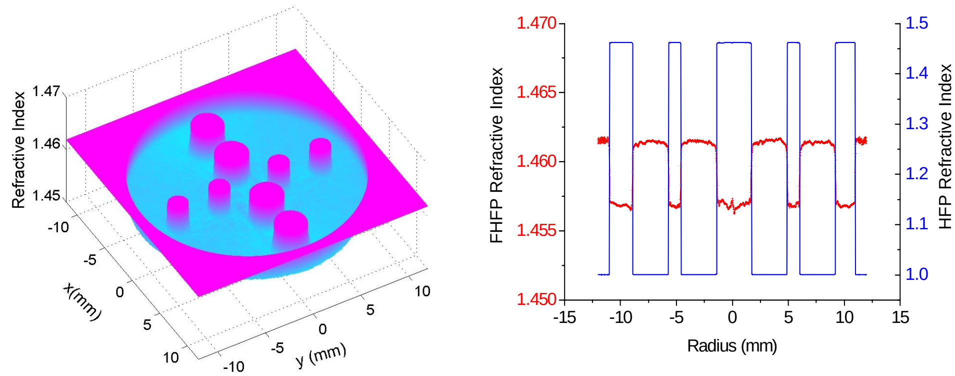
1° angle step to reconstruct the index profile. Preform A is a silica preform with eight air holes. Preform B, which was produced by scale reduction, is a polymer HFP with three air holes. Preform C is a more complex polymer preform with a structure of 48 holes, prepared in the same way.

In the first case (the silica preform), the HFP was immersed in index matching oil, with the holes filled with the same oil. The three dimensional display of FHFP profile reconstructed from the deflection function is shown in Fig. 2(a). Based on the two dimensional FHFP index tomography result, the single material preform structure can be obtained as shown in Fig. 2.(b) [blue curve], the corresponding cross-sectional profile of the FHFP is shown in Fig. 2(b) [red curve]. The tomographic measurement of the hole dimension and position agrees with the milling data and measurements from the end of the preform. For a silica preform, the oil can be cleaned with acetone. A test has been conducted to draw a cleaned tube to capillaries and no additional attenuation and strength problems were noticed. Recent research shows that the roughness and contamination of the hole may contribute to the high loss of holey fiber [12]. However, if the polishing and etching processes have been done after the RIP measurement, the contamination effects on optical fiber loss will be minimized.



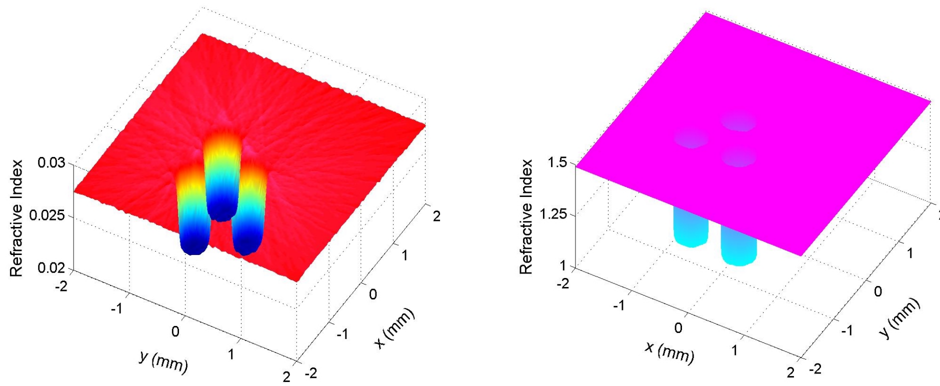
(a) (b)

Fig. 2. Eight-hole silica HFP tomography plots: (a) Refractive index distribution of three-dimensional display of FHFP; (b) Cross-section display of HFP.

The second preform measurement was performed on a PMMA (polymethylmethacrylate) polymer preform with a refractive index of n_{PMMA} = 1.4897 at 632.8 nm. Due to polymer's high index contrast to silica, two types of index matching oil were used to minimize the mismatch influence. The holes of the polymer HFP were filled with matching oil whose index is close to the polymer index, (n = 1.4822), the preform was placed in a silica tube filled with the same oil, and the silica tube was then immersed into another oil whose index (n = 1.4609)is close to that of silica. This layered arrangement is required in order not to contaminate the oil bath of the PK2600, and maintain the capacity to measure both silica and polymer preforms without a complete changeover of the oil in the instrument.

The reconstructed three-dimensional index profile of the polymer FHFP is shown in Fig. 3(a), and the refractive index profile of the polymer HFP is shown in Fig. 3(b). Again, a comparison with optical microscope images of the perform structure shows excellent agreement.

To demonstrate that this method can be used to measure complex holey preform structures, a third preform, with three concentric rings of 8, 16, and 24 holes respectively was measured. The reconstructed two-dimensional index profile of the polymer FHFP is shown in Fig.4. The layered index matching scheme is visible, with the red area corresponding to the silica index matching oil, the yellow corresponding to the silica tube, the blue corresponding



(a) (b)

Fig. 3. Three-hole Polymer HFP tomography plots (a)Three dimensional display of the measured refractive index profile of a polymer filled holey fibre preform (bottom view) (b) Three dimensional display of the refractive index profile of the polymer HFP.

to the polymer index matching oil and the turquoise area being the polymer preform. The 0.5 mm diameter holes are clearly resolved, and variations in hole diameter across the preform are revealed.

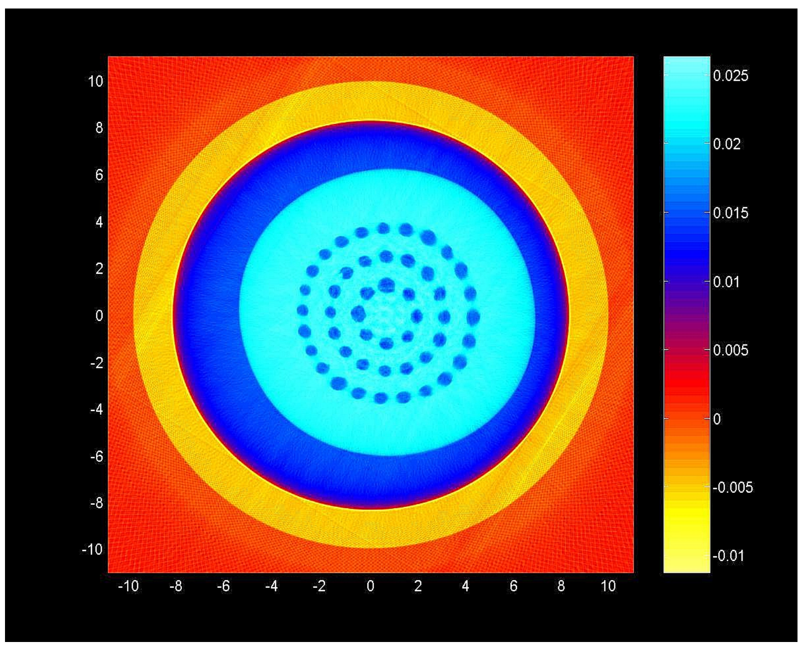


Fig. 4. Two-dimensional display of the refractive index profile of the three-ring 48 holes polymer FHFP.

When measuring complex preforms such as shown in Fig. 4 it is essential to use index matching oil of the appropriate index. In an earlier attempt to measure this three-ring structure preform we used the matching oil as commonly used for silica preform profiling (with index n =1.4609). However, this led to significant distortions in the central region of the reconstructed preform due to the index contrast being too large (~0.03). By using the layered arrangement of a polymer preform in index matched oil inside a silica tube that is mounted in silica index matching oil, this problem is overcome. The recognizable refractive index distortion is due to the Gibbs phenomenon caused by index mismatch between silica and polymer matching oil. If the numerical aperture is less than 0.2, the index distortion will be negligible.

Since only a finite amount of discrete data is available to reconstruct the refractive index, the resolution is limited by the accuracy of the deflection measurement. Currently our tomography can achieve $5\mu m$ spatial resolution. The accuracy of the tomography results have been compared with SEM measurement, the rsm index error is less than 0.001.

4. Conclusion

A nondestructive technique for determining the refractive-index profile of holey fibre preforms has been demonstrated based on a two-dimensional tomographic method. The complete tomographic method makes it possible to reconstruct HFP profiles accurately without *a priori* knowledge of the preform. This method is very valuable for determining the refractive index profile and structural integrity of new structured holey fibre preforms in a non-destructive manner.

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