Characterization of Polarization Maintaining Photonic Crystal Fiber from Far Field Measurements

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Abstract

The development of theoretical and experimental method for the characterization of Polarization Maintaining Photonic Crystal Fiber (PM PCF) from far filed intensity measurements has been reported. To maintain the polarization in PCF different air hole diameter along orthogonal axes adjacent to the core region has been introduced. This helps in creating an effective index difference between the two orthogonal polarization modes. It is shown that air hole spacing (Λ), air hole diameter (d) and effective cladding index differences of PM-PCF can also be obtained from its far field measurements.

Key-words: Polarization-Maintaining PCF, Far-field, Characterization

1. Introduction

Polarization maintaining fibers (PMFs) are found to have extensive applications in coherent optical communication systems and in optical fiber based polarization sensitive experiments including design and development of optical sensors. PMFs are also required for high bit rate transmission systems as they can eliminate polarization mode dispersion (PMD) and also stabilize the functional performance of optical devices. The modal birefringence of conventional PMFs, for example PANDA, Elliptical Core and Bow tie fibers etc. are found in the order of $5x10^{-4}$ [1]. This birefringence can be further tailored and enhanced in case of photonic crystal fiber (PCFs) [2-5].

PCFs have generated great amount of interest in optical communication as they exhibit many superior transmission characteristics and have high degree of design flexibilities [6]. It is possible to design highly birefringent fiber with photonic crystal structure. Recently polarization maintaining (PM) PCFs have been fabricated and their transmission characteristics have been reported [1] using two different air hole diameters along two orthogonal axis near the core region, which provides and effective index difference between two orthogonal polarization modes[2-4]. The birefringence of such PM PCFs can be further enhanced by tuning the size of air hole diameters near the core region. It is shown that birefringence of PM PCF can have one order higher magnitude than that of conventional PMFs and is reported to be in the order of 10^{-3} [1]. Accordingly, it is expected that PM PCFs exhibit better PM characteristics. Extensive numerical calculation for birefringence and other transmission characteristics of PM PCFs have been reported in the recent past [7]. Efforts have also been taken to fabricate low loss PM-PCF exhibiting extremely low PMD and very high birefringence. However, the transmission characteristics of such PM PCF depend on the waveguiding (e.g., MFD, V-values along major and minor axis, Birefringence etc.) and geometrical (Core radius of major and minor axis of PM PCFs, air hole diameters, etc.) parameters of PM-PCFs. Therefore the knowledge of these waveguiding and geometrical parameters are required to assess the performance and transmission characteristics of PM-PCFs.

In this paper, we report the development of theoretical and experimental method for the characterization of Polarization Maintaining Photonic Crystal Fiber (PM PCF) from far filed intensity measurements has been reported. To maintain the polarization in PCF different air hole diameter along orthogonal axes adjacent to the core region has been introduced. This helps in creating an effective index difference between the two orthogonal polarization modes. It is shown that air

Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications III, edited by Shizhuo Yin, Ruyan Guo, Proc. of SPIE Vol. 7420, 742015 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.826167

hole spacing (Λ), air hole diameter (d) and effective cladding index differences of PM-PCF can also be obtained from its far field measurements.

2. Theory

Far field intensity pattern have been already used to characterize Photonic Crystal Fiber and encouraging results have been reported in the recent past [8-9]. In this paper we use the same technique with certain modification to develop a method to characterize PM PCF from its far field intensity patterns.

PM-PCF yields an elliptical core spot size in its near and far field regime and hence it is considered as elliptical core fiber. The propagation characteristics of elliptical core optical fiber had been obtained accurately by its equivalent Rectangular Core Waveguide (RCW), having the same aspect ratio, core areas and core-cladding refractive index difference. The elliptical cross section of PM PCF is approximated to be rectangular shape for obtaining the far field intensity expression in our analysis.
In this paper, the transverse cross-section of the PM PCF is elliptical in shape which is approximated as equivalent rectangular core waveguides. We derived the propagation characteristics of the elliptical-core waveguide from the equivalent rectangular core waveguide having the same aspect ratio, core areas and core-cladding refractive indices as mentioned in [12] and which is briefly described as follows:

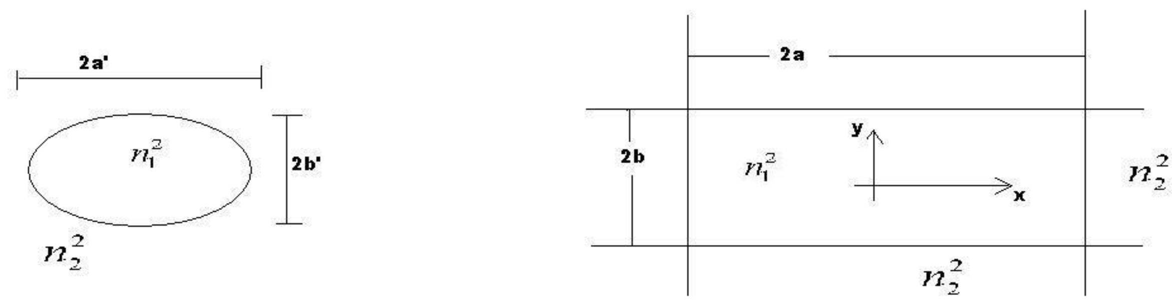

Fig. 1: Transverse cross section of elliptical core described by refractive index profile with its equivalent pseudo rectangular core waveguide described by refractive index profile

Refractive Index Profile of elliptical core can be given by

$$n^2(x,y) = n_1^2, for(\frac{x^2}{a'^2} + \frac{y^2}{b'^2})\langle 1.0$$

$$n^2(x,y) = n_2^2, for(\frac{x^2}{a'^2} + \frac{y^2}{b'^2})\rangle 1.0$$

Which is approximated by the pseudo rectangular core waveguide having following refractive index distribution:

$$n^2\left(x,y\right) = n'^2(x) + n''^2(y) - n^2$$

Where

$$n'(x) = n_1 \qquad |x| \langle a$$
$$= n_2 \qquad |x| \rangle a$$

and

$$n''(y) = n_1 \qquad |y| < b$$
$$= n_2 \qquad |y| > b$$

Finally, it's shown that a/a'=b/b'=$\sqrt{\pi}/2$, as Area of rectangle (4ab) =Area of ellipse (πa'b')

Thus, the elliptical cross section of PM PCF can be considered as two crossed planar waveguides namely X-polarized and Y-polarized cross section. These X-polarized and Y-polarized planar waveguide acts like two slab waveguides. Hence far field intensity expression of the slab waveguide for TE mode is obtained. We use only TE modes as the TE modes don't depend on refractive indices directly like TM modes [10]. The far-field radiation pattern $\Psi(r, \theta, \Phi)$ is the inverse Fourier transform of the aperture or near fields. The normalized (wrt θ=0) far-field intensity distribution for the fundamental TE mode [10] of symmetric slab waveguide is given as

$$|\Psi|^2 = \left[\frac{U^2W^2}{(U^2-\alpha^2)(W^2+\alpha^2)}\left\{\cos\alpha - \alpha\sin\alpha\frac{\cos U}{U\sin U}\right\}\right]^2 \quad \text{for} \quad U \neq \alpha$$

$$|\Psi|^2 = \left[\frac{U^2W^2}{(2V^2)(U\sin U)}\left\{\cos^2\alpha - \sin^2\alpha + \frac{\sin 2\alpha}{2\alpha}\right\}\right]^2 \quad \text{for} \quad U = \alpha$$

where $V^2 = U^2 + W^2$, α = ka sinθ, k = $2\pi/\lambda_0$, λ_0 is the free-space wavelength and 'a' is the half-thickness of the core along the respective axes.

The universal curve (fig. 3) for far field intensity pattern of the planar waveguides is obtained from the above equations and is used for estimating the core dimensions and hence aspect ratio of PM PCF. It is noted that α_{10} and α_{50} are the value of α (=ka sinθ) at the θ_{10} & θ_{50} respectively which correspond to angles in the far field intensity pattern at which the intensity has dropped to 10% and 50% of its maximum value (at θ=0). The intensities are measured at θ_{10} because it is practically very difficult to measure the first minimum intensity position accurately in far field intensity pattern [11].

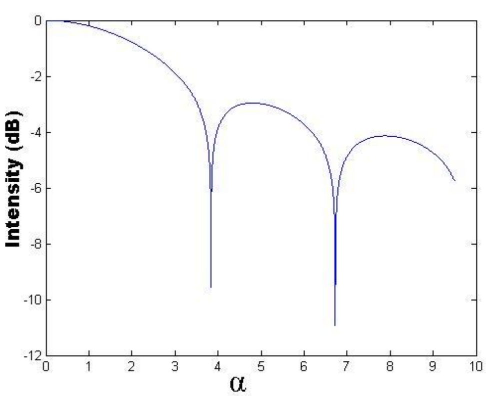

Fig. 2: Far- Field intensity pattern for Slab-wave guide

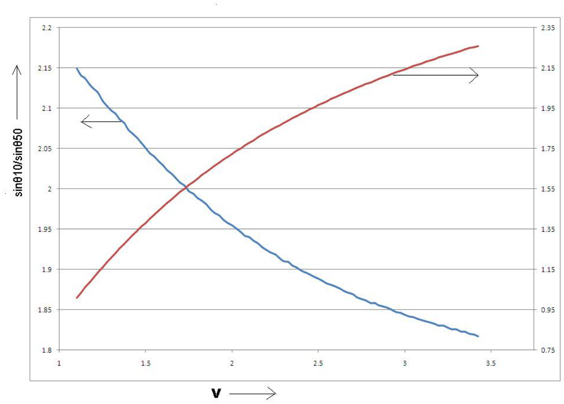

Fig. 3: Variation of the ratio α_{10}/α_{50} (blue) and α_{10} (red) with the V parameter

2.1 Mode field Diameter of PM PCF

Mode field Diameter (MFD) is a measure of the diameter of the area in which an optical signal propagates through a Single mode fiber (SMF). Although most of the signal is confined to the core, some of the signal travels in the cladding, so the MFD is of greater significance than the core diameter. [13].

Far-field intensity distribution of the slab waveguide is assumed to be Gaussian and hence its MFD has been calculated from the far field intensity measurement with the following formula [14].

$$MFD = (2\lambda_0) / (\pi \sin\theta_e),$$

Where, θ_e is the angle where the far-field intensity falls to $1/e^2$ of the maximum intensity.

3. Experimental setup & Characterization method

3.1 Experimental setup

This setup consists of a laser with wavelength 633nm, microscopic lens, fiber chuck and holders, Polarizer sheet (to find the polarization axes of laser and the fiber), detector with digital display and 20 meter long PM PCF. Fiber ends are prepared carefully. Laser is kept in straight and horizontal position so that the maximum input light is coupled in the fiber. Fiber out put end is mounted on a calibrated circular mount fitted with detector such that the fiber end is at the center of the circle and when we rotate the circular mount only detector moves at the circumference of the circle. The output of the detector is read in the digital display attached with it.

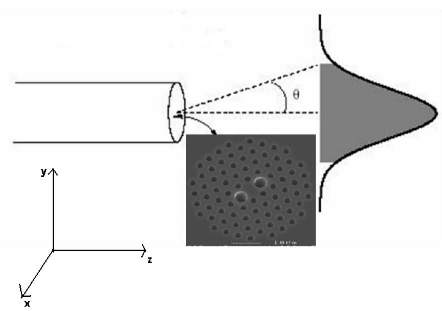

Fig. 4: line sketch of far- field intensity pattern

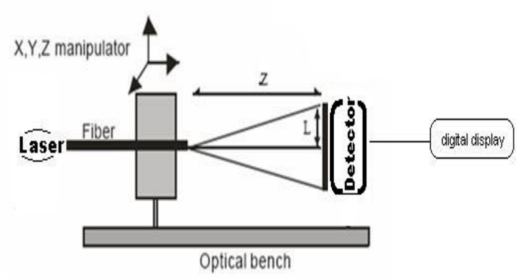

Fig. 5: sketch for Far field measurement arrangement

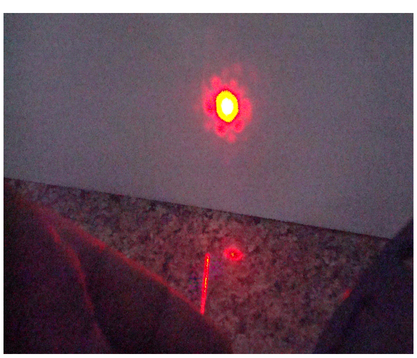

Fig. 6: Far field pattern of PM-PCF

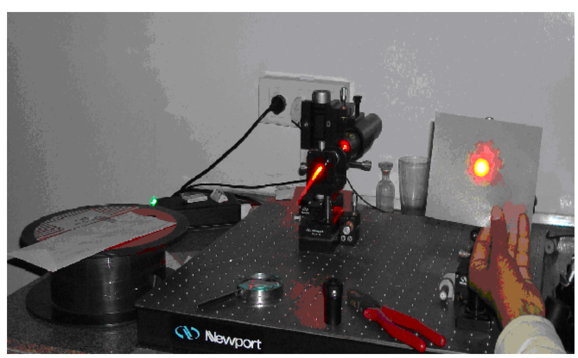

Fig. 7: Experimental arrangement for far field measurement

3.2 Characterization methods

First the fiber ends has been stripped and cleaved properly. The polarization axis of laser and fiber both has been found. The y-polarized mode is coupled and its far field intensity pattern along x-direction is measured. The measured far-field intensity variation is corresponding to the far-field intensity of fundamental TE mode of the PM-PCF along one axis.

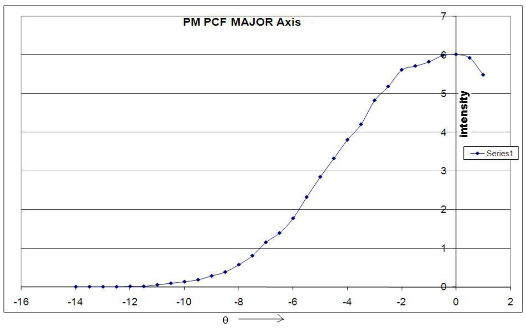

Fig. 8: Measured far field intensity distribution along major axis

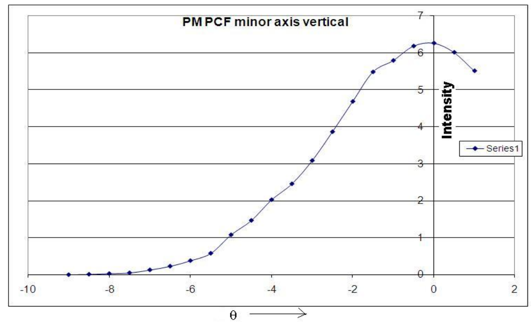

Fig. 9: Measured far field intensity distribution along minor axis

Similarly, the x-polarized mode has been coupled and its far-field intensity pattern along y-direction is measured. This measured far-field intensity variation is corresponding to the far-field radiation pattern of fundamental TE mode of the PM-PCF along another axis.
The angles θ_{10} and θ_{50} which correspond to angles in the far field intensity pattern at which the intensity has dropped to 10% and 50% of its maximum value (at $\theta=0$) is measured experimentally from the graph for both the axes and thereby ratio $\sin\theta_{10}/\sin\theta_{50}$ is calculated.
From the standard graph (Figure 3) for the slab waveguide, the V value for the corresponding value of $\sin\theta_{10}/\sin\theta_{50}$ is obtained. For the respective V numbers the corresponding α_{10} (= k_0 a $\sin\theta_{10}$) is calculated from the right hand ordinate of the standard graph. Since θ_{10} was already known, the core radius along the respective axes is calculated, since the wavelength of operation is known.
As we had already calculated the V parameter so we can also calculate the numerical aperture ($\sqrt{(n_1^2-n_2^2)}$) along the both axes; where n_1=1.45 (refractive-index of core) and the n_2 (calculated effective refractive index of cladding).

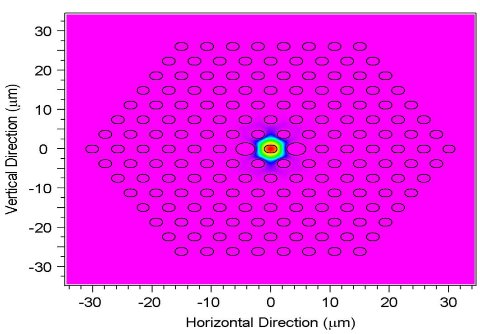

Fig. 10: Schematic view of far field as seen by R-Soft

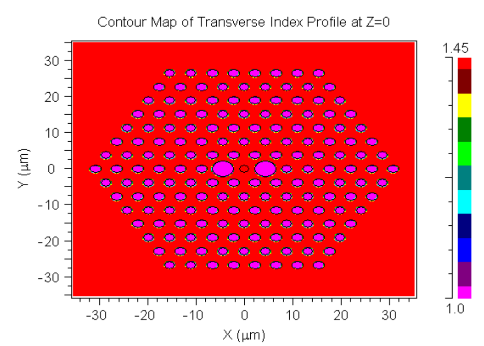

Fig. 11: Cross-sectional view of PM-PCF by R-Soft

Thus, by measuring far field intensity angles at which the intensity has dropped to 10% and 50% of its maximum value, the parameters for the pseudo rectangular waveguide are calculated. From this data the elliptical core of PM PCF has been characterized in terms of core dimension, and also the core cladding refractive index difference and V parameters along the two axes.

Further, we find the experimental value of θ_e, the angle where the far-field intensity falls to $1/e^2$ of the maximum intensity from the measured far-field intensity curve. Then with the help of the formula of MFD (= $(2\lambda_0)/(\pi \sin\theta_e)$,) MFD of propagating light wave is obtained for both the axes.

4. Results and Discussions

Experimental results were calculated and matched with manufacturer data as well as the data calculated by Plane wave expansion method using the R-Soft Band solver, which have been compared and tabulated in table 1.As in the case of far field the axis interchanges, thus major axis in the near field becomes minor axis in far field and vice versa. Near-field axis along big air holes act as minor axis termed as 'axis-1' and hence yield lower effective refractive index in cladding along big air holes, similarly axis along regular air holes act as major axis termed as 'axis-2' and yield larger value of effective refractive index in the cladding. These interpretations have been verified experimentally and tabulated in the table given below.

Table 1: Comparison between Manufacturer's/ Calculated data and Experimental/ Measured data

	Manufacturer's/ Calculated data		Experimental/ Measured Data
MFD	Axis-1	3.1 micron	3.08 micron
	Axis-2	3.6 micron	3.79 micron
Core Radius (micron)	Axis-1		b'=1.28754, b=1.45284
	Axis-2		a'=2.0454, a=2.308
Refractive index(Cladding)	Axis-1	1.43298	1.43860
	Axis-2	1.44086	1.44335
Birefringence		0.00788	0.00475
V-parameter	Axis-1	2.8295	2.65
	Axis-2	3.2985	3.175
Numerical Aperture	Axis-1	0.22151	0.18146
	Axis-2	0.16254	0.13871

5. Conclusions

Far-Field method is applied to characterize PM PCF. Assuming the elliptical core of PM PCF as an equivalent rectangular waveguide we first find the parameters for the equivalent rectangular/slab waveguides. Then with the suitable approximation we calculated and characterized the PM PCF. The result so obtained matches with the manufacturer's/calculated data with the measured values within the experimental limit. Thus, this method provides us a useful tool for online characterization of PM PCF. It is expected that this method will serve as standard technique to characterize PM PCF in future and will also be useful to design and develop application specific PMPCF both in optical communication and in sensor systems.

6. Acknowledgements

The authors gratefully acknowledge the financial support provided by (i) Major research project grant entitled "Characterization of Photonic Crystal Fibers for telecom and sensing applications" supported by University Grants Commission (UGC), Govt. of India and (ii) "TIFAC-Center of Relevance and Excellence in Fiber Optics and Optical Communications at Delhi College of Engineering, Delhi" through "Mission Reach" program of Technology Vision-2020, Government of India.

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