Nondestructive measurement of refractive index profile of optical fiber preforms using moiré technique and phase shift method

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ABSTRACT

The refractive index profile of optical fiber preform is measured by a nondestructive technique based on Talbot interferometry. In this technique the preform is placed between two ronchi ruling gratings of 10 lines/mm and the system is illuminated by an expanded and collimated beam of He-Ne laser. In this arrangement the 2nd grating is positioned in the Talbot image of the 1st grating and the preform axis is parallel to the gratings planes. To eliminate the effect of clad on the light beam deflection during the measurements, the preform is immersed in an index matching liquid. The phase front of the laser light over the 2nd grating can be monitored by analysis of the moiré pattern which is formed over there. The analysis is done by means of 4-step phase shift technique. In this technique the second grating is moved in four steps of 1/4 of the grating vector and in each step the intensity profile of the moiré pattern is recorded. The phasefront can be specified by using the recorded intensities. The refractive index profile of the preform can be calculated from the changes on phasefront while the preform is placed between the gratings respect to the case when it is absent. The whole procedure is automated and computer controlled by using a CCD camera to record the moiré fringes, a stepper motor for linear translation of the 2nd grating and a code in MATLAB to control the system and measurements.

Keywords: optical fiber preform, refractive index profile, Talbot interferometry, moiré technique, phase shift method

1. INTRODUCTION

Refractive index profile of optical fiber preforms has a crucial role in optical properties of optical fibers. Since the optical fiber is produced from a preform, nondestructive measurements on the preform are preferred, even though destructive techniques[1] also have been used on measuring the refractive index profile. Among the usual measurements techniques, interferometry[2-4], focusing[5-6] and ray tracing[7] methods are mostly used for this purpose. Between them, interferometry is one of the most precise and reliable methods but it needs also a precise optical set up and it is very sensitive to vibrations.

In this work we are introducing a new nondestructive technique for the mentioned measurement, which is based on moiré technique[7] and Talbot interferometry[8]. The optical set up in this technique is very stable and it is possible to mount it in a rugged case for industrial applications. In this technique the preform is immersed in an index-matched liquid and is placed between two Ronchi ruling gratings when the grating vectors and the preform axis are in three parallel planes. A collimated and expanded coherent laser beam illuminates the set up when the gratings are in Talbot images of each other. Analysis of the produced moiré pattern over the second grating, determines the maps of deflected beams by the preform and so the refractive index of the preform can be obtained.

2. THEORETICAL APPROACH

2.1. Determination of the Index profile

In this technique the ray traverses the perform core at right angle to its axis. The refractive index profile, of the perform, *n(r)* is considered to be axially symmetric and can be written as,

$$n(r) = n_0 + \Delta n(r)\,. \tag{1}$$

When n_0 is the refractive index of the clad and $\Delta n(r)$, is the difference between the core and the clad refractive index profiles and it can be expressed as[4]:

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$$\Delta n(r) = \frac{1}{\pi}\int_r^a \frac{\psi(y)dy}{\sqrt{y^2 - r^2}} \tag{2}$$

When the preform is along the *x* axis and the laser beam propagates in *z* direction. a and $\psi(y)$ respectively are the radius of the core and the ray deflection angle due to the changes in refractive index of the perform. A parallel beam, passing through such a medium of varying index of refraction (here the preform) locally is deflected by the medium. The deflection angel is a direct map of refractive index profile of the mediums as shown in Eq. (2). Talbot interferometry is used in here to measure the deflection angle, $\psi(y)$.

2.2. Deflection angle measurement using the moiré methods and Talbot interferometry

When a grating of pitch *q,* is illuminated by a collimated and monochromatic coherent light of wavelength λ, its Talbot images will be formed at distances[10], $l = mq^2 / \lambda$, when $m = 0,1,2,\cdots$. If another similar grating is placed at one of these locations, the Moiré pattern will be appeared over it[10]. The Talbot image and so the Moiré pattern will be distorted when, a phase object is placed between the gratings. Analysis of the distorted pattern provides the changes in the phase front of the light due to existence of the phase object and so the refractive index profile of the object.

Different methods exist for measuring the phase distribution over a fringe pattern. Phase shifting technique is used in this work because of its precision and also the stability of its results respect to the appeared noises over the Moiré fringes. This technique requires that the phase shifting to be done at least in three steps [11]. The Moiré fringe distribution in the absence and presence of preform may be described by Eq. (3):

$$I(x, y) = A(x, y)[1 + \gamma(x, y)\cos(\phi_i(x, y))], \quad i = 1,2 \tag{3}$$

Where $A(x, y)$, $\gamma(x, y)$ and $\phi_i(x, y)$ respectively are the mean intensity, the normalized fringe visibility and the phase of the wave front over the second grating. In Eq. (3), *i*=1 (*i*=2) corresponds to the case when the preform isn't (is) between the gratings. To find $\phi_i(x, y)$, it can be shifted in steps of Δ, where,

$$\Delta = 2\pi / N, \quad N \geq 3. \tag{4}$$

The intensity distribution over the moiré fringes at the *j*th step of the shift is,

$$I_j(x, y) = A(x, y)[1 + \gamma(x, y)\cos(\phi_i(x, y) + j\Delta)], \quad 1 \leq j \leq N \tag{5}$$

In this work we have set *N*=4 i.e., the second grating is moved in a way to generate $\Delta = 0, \pi/2, \pi$ and $3\pi/2$. Using this algorithm, $\phi(x, y)$ is calculated as Eq. (6):

$$\phi_i(x, y) = \tan^{-1}\left(\frac{I_2 - I_4}{I_1 - I_3}\right), \;. \quad i = 1,2 \tag{6}$$

The unwrapped form of $\phi(x, y)$ can be written as,:

$$\phi_{wi}(x, y) = \phi_i(x, y) \pm 2\pi k, \quad \mathrm{i} = 1,2 \;, \; 0 \leq k \leq m. \tag{7}$$

Where *k* is an integer number and *m* is the total number of detected discontinuities.

To calculate the deflection angle of the beams, $\psi(y)$, due to existence of the perform, it is necessary to obtain the changes in the phase distribution over the moiré pattern, while the preform is placed between the gratings respect to the case when it is absent.

$$\Delta\phi(x,y) = \phi_2(x,y) - \phi_1(x,y) \tag{8}$$

For small deflections, the deflection angle can be written as

$$\psi(y) \approx \tan\psi(y) = \frac{y}{L} = \frac{q}{2\pi L}\,\Delta\phi(x,y)\,. \tag{9}$$

Where L is the distance between perform axis and the second grating (Fig. 1).

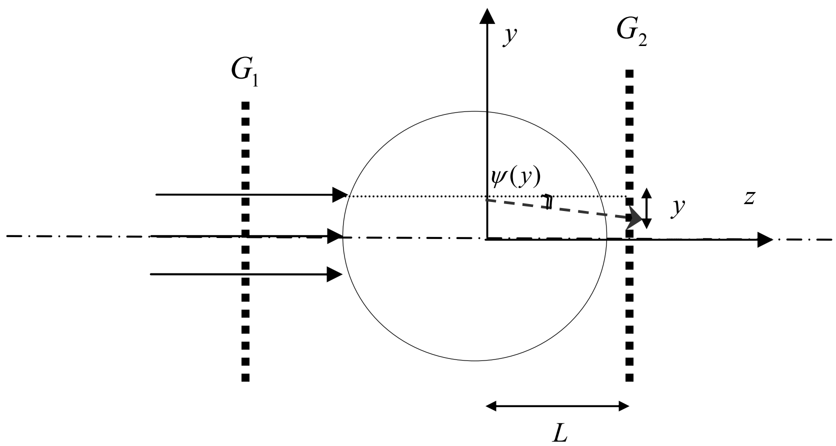


Figure 1. Each rays deflects by an angle of $\psi(y)$ as it passes trough the perform.

3. EXPERIMENT AND RESULTS

Fig. 2 shows the experiments setup. In this set up two similar Ronchi ruling gratings of 10 lines/mm, G_1 and G_2, are illuminated by an expanded and collimated beam of a 10 mW He-Ne laser when G_2 is placed in the Talbot image of G_1. The preform, P, is immersed in an index matched liquid and is positioned between G_1 and G_2 in a way that its axis is normal to the propagation direction of the laser light. We measure the refractive index profile of a preform which is manufactured in Optical Fiber factory in Poonak-Tehran. Table 1 and 2 respectively show the composition of the index-match liquid[12] in w% and**.** characterizes of the preform.

Table 1 The index-match liquid composition

Component	W%	Refractive index
Decahydronaphthalin	82	1.4742
n-Heptan	18	1.3487

Table 2. characterizes of the preform

Refractive index of clad	1.46
Core radius	4.1 mm
preform radius	8.2 mm

Figs 3a, 3b and 3c respectively show the moiré pattern when the preform is absent, when the preform is betweenthe gratings but its refractive index is not matched with its surrounding liquid and when the preform is immersed in an index-matched liquid.

A computer controlled stepper motor through a gear box moves G_2 in direction of the grating vector, to generate the required phase shift over the moiré pattern. The lens, L_2, CCD camera, image grabber, PC and a code in MATLAB forms the image recorder and analyzer part of the set up.

Figs 4a and 4b respectively show the wrapped and unwrapped phase-maps which are calculated on the basis of Eqs. (6) and (7), in the absence of the preform. Figs. 5a and 5b are the similar phase maps when the preform is in the set up.

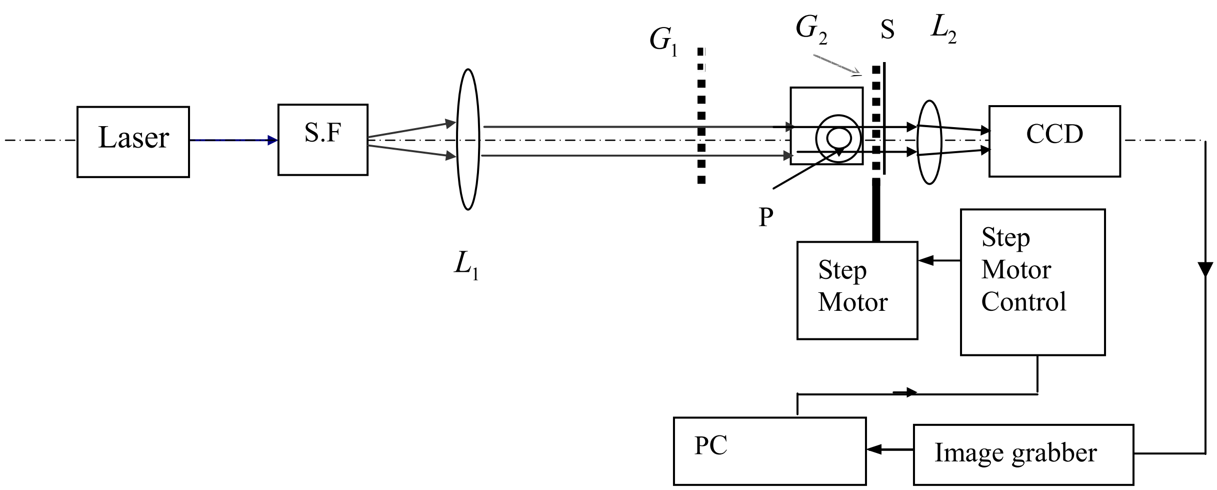
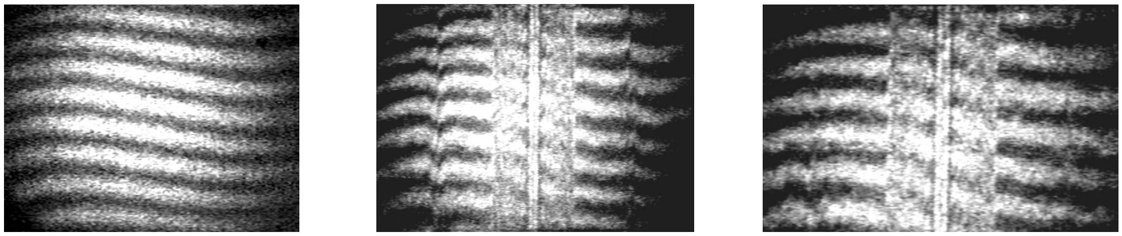


Figure 2. Schematic diagram of moiré deflectometer for determining refractive index profile of optical fiber performs. S.F, L_1 $G1$, P, SM, $G2$, S and L_2, respectively stand for spatial filter, first lens, first gratings, perform, stepper motor, second grating, diffuser and secondary imaging lens.



(a) (b) (c)

Figure 3 the moiré pattern a)when the preform is absent, b) when the preform is between the gratings but its refractive index is not matched with its surrounding liquid c) when the preform is immersed in an index-matched liquid.

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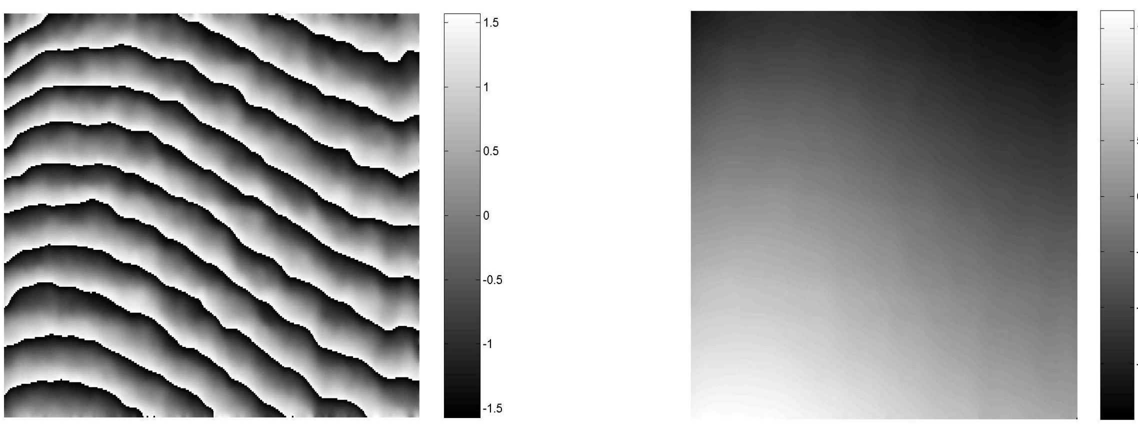
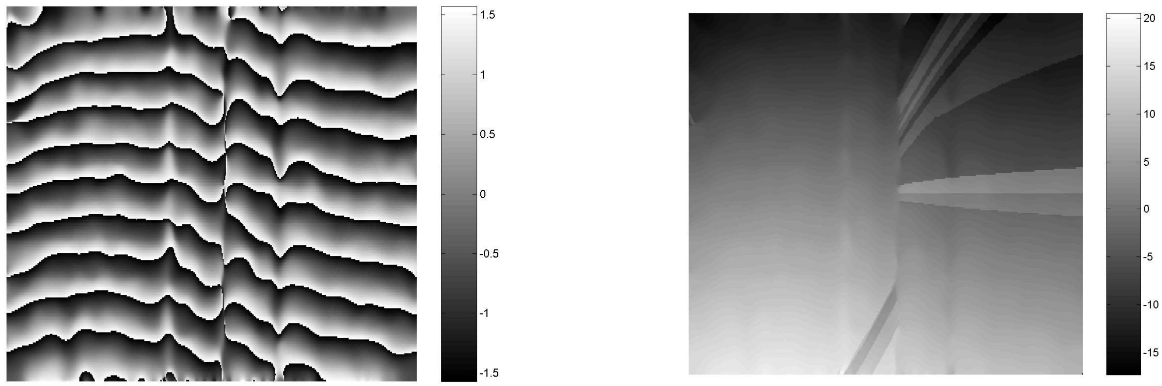


(a) (b)

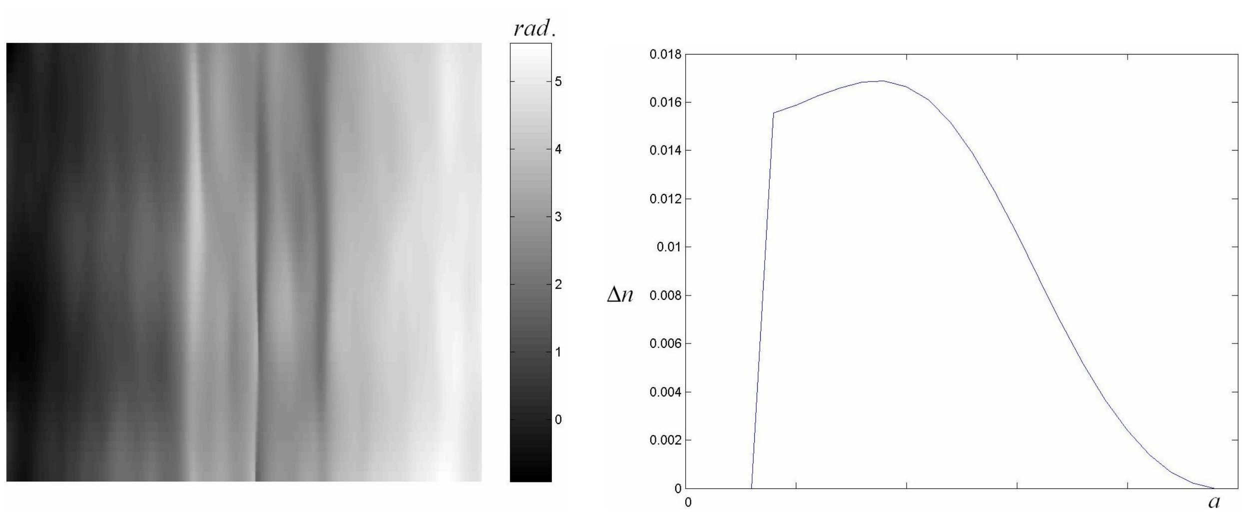
Figure 4. a) The wrapped phase-map, and b) the corresponding unwrapped phase-map, of the testing field in the absence of the preform.



(a) (b)

Figure 5. a) The wrapped phase-map, and the corresponding unwrapped phase-map, of the testing field when the preform had been in the setup.

The phase changes which are imposed on the wave front over G_2 when the preform is in the set up, can be calculated on the basis of Eq. (8). This means that Fig. 4b should be subtracted from Fig. 5b. Fig 6a shows the result of this calculation and Fig 6b is the calculated refractive index profile for the core of the preform by using Eqs. (9) and (2).



(a) (b)

Figure 6. (a) Phase distribution caused by sample, (b) refractive index profile measured from the phase distribution shown in (a), in the core regain of the preform, vertical axis shows the refractive index difference between core and clad, and horizontal axis shows the distance from the center of core.

4. CONCLUSION AND REMARKS

In this work we have presented a new method for nondestructive measurement of refractive index profile of optical fiber preform which is based on moiré technique and Talbot interferometry. We have used this method to measure the refractive index profile of a preform which is manufactured in Optical Fiber factory in Poonak-Tehran and have obtained the profile shown in fig. 6. By this technique the refractive index profile can be measured by an accuracy of 0.002.

In this technique, the optical set up is ragged and is not sensitive to vibrations. We have also made the whole measurement procedure computer controlled.

The arrangement of the experiment which is shown in Fig. 2 also helps us to eliminate the effects of light diffraction which are caused by the layered structure of the preform.

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