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Applicability of the Focusing Method to Measure the Refractive Index Profile of Polymer Optical Fibers*

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Abstract The possibility of applying the focusing method to measure the refractive index profile of polymer optical fibers is studied through combination of the theoretical analysis and experimental verification. The result shows that the focusing method is an easy and feasible way to determine the refractive index of graded-index POFs; however, as the light rays cross each other near the POF boundary, the focusing method is not an appropriate way to decide accurately the refractive index profile of step-index POFs.

Keywords Polymer optical fiber; Refractive index profile; Focusing method; Fiber measurement

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0 Introduction

Polymer optical fibers (POFs) are considered as high-performance fiber links at short distance because of their low cost, robustness and easy of preparation and termination[1~3]. Determination of their refractive index profiles is of great importance in both the evaluation of performance and design, manufacture of the fibers[4,5]. Some techniques have appeared to measure the refractive index profile of graded-index POFs (GI-POFs), such as the transverse interferometric method[6] and the refracted near-field method[7]. Unfortunately, the former needs an expensive interference microscopy[8], and the latter requires a complicated equipment to scan the end of the fiber and to measure the intensity of refracted light escaping from the fiber[9]. The focusing method is a simple and effective method to measure the refractive index of glass optical fibers (GOFs) and performs as well[10]. This paper studied the applicability of this simple method to determine the refractive index of POFs.

1 Principle

The principle of the focusing method is shown schematically in Fig. 1. The POF is immersed in an index - matching liquid to eliminate light refractions at the outer boundary of its cladding. A collimated light passes through the fiber core, which functions as an ideal cylindrical lens to focus the light. The light power distribution of the focused rays is measured at an arbitrary distance L from the fiber core. The focusing reaction is in close relation to the light ray trajectory, which is dependent of the core refractive index distribution. Therefore, from the measured power distribution at the observation plane $P(y)$, the refractive index of the core can be decided.

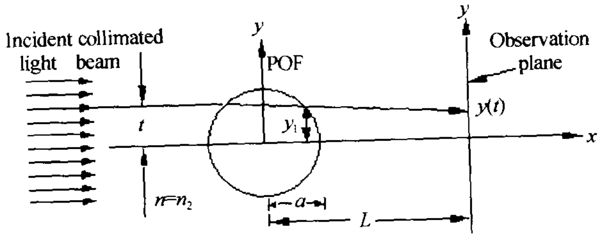

Fig. 1 Schematic figure of the principle for the focusing method

The amount of light power carried by the two adjacent incident rays is coherent with the one at the observation plane. The vertical distance of the two refraction rays can be simplified to dy according to the paraxial ray theory[11]. When the collimated uniform rays are used, the power of the incident rays $P(t)$ is a constant, namely, P_i. Then there is

$$P_i \cdot dt = P(y) \cdot dy \tag{1}$$

where dt is the distance between the two adjacent rays from the optical axis measured at the input plane, and dy is the corresponding distance of the above two rays at the observation plane.

Once the power distribution at the observation plane is measured, the function of $t(y)$ can be obtained from Eq. (1) as follows

$$t(y) = \frac{1}{P_i}\int_0^y P(y')dy' \tag{2}$$

According to the reference[11], the refractive index distribution, $n(r)$, can be obtained

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$$n(r)-n_2=\frac{n_2}{\pi L}\int_r^a \frac{t-y(t)}{(t^2-r^2)^{1/2}}\mathrm{d}t \qquad (3)$$

2 Experiment

A high-stable non-interferential light source was employed to avoid interference. The emitting light passed through a 50 μm pinhole and a parallel pipe, one by one and became to be an uniformly collimated light beam. A microscopy was reinstalled so that the magnification can match the measured POF. This uniformly collimated beam went directly to the POF, which was laid transversely in a matching liquid in a special sample box. The light intensity distribution at the observation plane was recorded by a CCD camera connected to a computer. The observation plane was set to be $L=a$.

The standard SI-POF samples (Agilent Co. Ltd.) with $n_1=1.492$, $n_2=1.472$ and $a=0.5$ mm were used in the experiments. We choose castor oil with $n_c=1.477$ as the matching liquid.

The samples from the Institute of Chemistry, Chinese Academy of Science, which were assumed to have a Graded-Index distribution by diffusion with some dopants, were measured by our experiment system.

3 Results and discussion

3.1 SI-POF

Using the Snell's law, the theoretical t-y relation of the standard SI-POF sample was calculated and shown in Fig. 2 ($L=0.5$ mm). It is

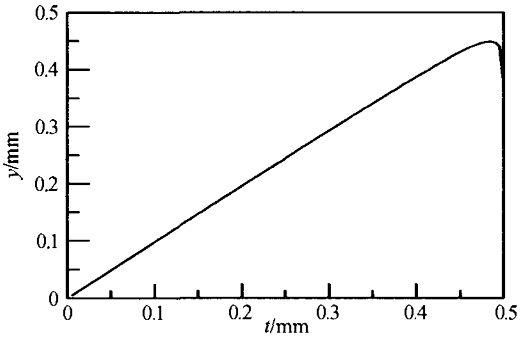

Fig. 2 The theoretical relationship between t and y for the SI-POF

clear that, after passing through the fiber core, the incident light rays near the boundary cross each other even at $L=a$. That is to say, in the experiment, the recorded light density distribution near the boundary (in the region of $y=0.375$ to $y=0.45$) will correspond to two different t positions of rays. For the focusing method, the relationship between the t and y is determined by the measured light intensity. If we cannot distinguish the two incident rays' contributions to the light intensity, we cannot obtain the exact relationship between t and y in the light crossover region, thus fail to obtain the accurate refractive index profile.

Fig. 3 shows the measured and theoretical refractive index distribution of the standard SI-POF. The solid curve is the measured refractive index distribution obtained by Eq. (3). Here we assume that no incident rays crossed at the observation plane after passing through the fiber core, *i. e.*, t corresponds to y one by one. The relationship between t and y is obtained by the measured power intensity using Eq. (2). The dashed curve is the theoretical refractive index distribution obtained also by Eq. (3) based on the relationship between t and y in Fig. 2. It is clear that our measured data failed to coincide well with the theoretical curve. The most significant difference is that the refractive index values near the boundary cannot be reached. The reason is that the rays crossed when passing through the boundary of the fiber. Thus when a much higher accuracy is required in measuring the refractive index distribution of SI-POFs, the focusing method is not an appropriate way owing to the crossover of rays at the boundary of the fibers.

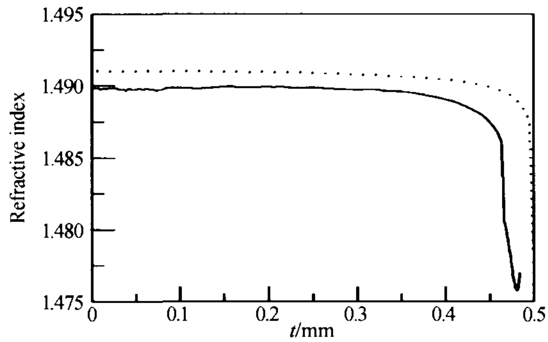

Fig. 3 The experimental refractive index distribution (solid line) and the theoretical one (dashed line) for the SI-GOF

3.2 GI-POF

The feasibility of the focusing method to measure the refractive index of GI-POF was verified using computer simulation. We estimated the deflection of rays inside the core by assuming a parabolic index distribution

$$n(r)=n_1\left[1-2\Delta\left(\frac{r}{a}\right)^2\right]^{1/2},\Delta=\frac{n_1^2-n_2^2}{2n_1^2} \qquad (4)$$

According to the paraxial ray equation, the relation of the deflection ray at the point of exit y_1 and the incident point t can be decided approximately[11]

$$y_1=t[1-4(1-t^2/a^2)\Delta] \qquad (5)$$

where, y_1 is the vertical distance at the exit point of the deflection ray. From the geometrical relation shown in Fig. 1, the deflection ray at the observation plane y is

$$y = y_1 + \left(\frac{dy}{dx}\right)_{x=(a^2-t^2)^{1/2}} [L - (a^2 - t^2)^{1/2}] \quad (6)$$

Starting with a parabolic index distribution with $n_1 = 1.492$ and $n_2 = 1.472$, the relationship between t and y was obtained using Eq. (6), and then power distribution at the observation plane was calculated by Eq. (1). With the help of Eq. (3), the refractive index distribution was obtained and shown in Fig. 4 as the solid curve. For comparison, the refractive index profile decided by Eq. (4) is also presented with the dashed curve.

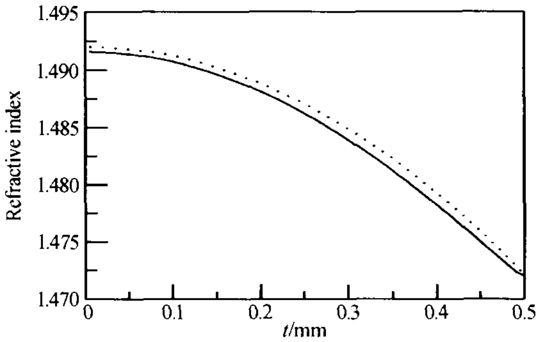

Fig. 4 Computer simulation for the refractive index profile of GI-POF using the focusing method

Fig. 4 indicates that the focusing method applied to the GI-POF is self-consistent. The maximum deviation between the computed refractive index profile and the assumed ideal one is less than 0.03%. Detailed simulation shows that the power density fluctuation has little influence on the refractive index profile. These results show that the focusing method is not very sensitive to the measurement inaccuracy of the light power density, that is, it does not amplify measurement errors greatly.

From Eq. (6), we should emphasize an important point here that the incident rays will not cross at the observation plane. Thus the experiment system can loyally record the power intensity distribution by which we can obtain an accurate relationship between t and y. Therefore, compared with SI-POF, the focusing method is an appropriate way to measure the refractive index profile of GI-POFs.

To verify the above theoretical analysis with experiments, the samples from the Institute of Chemistry, Chinese Academy of Science, were measured by our experiment system. The obtained refractive index is shown in Fig. 5, which gives successfully a parabolic distribution of the refractive index. In addition, the bandwidth derived from the data in Fig. 5, 0.15 GHz, agrees well with the one measured by impulse response method in time domain[12].

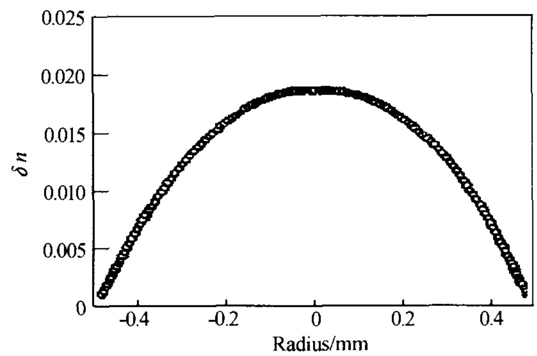

Fig. 5 The measured refractive index of the GI-POF

4 Conclusion

Applicability of the focusing method, which requires relatively simple equipments, to measure the refractive index profile of both SI-POF and GI-POF were discussed. Both the computer simulation and the experimental results show that the focusing method is a feasible way to measure the refractive index profile of GI-POFs. However, as the incident rays crossed at the boundary of SI-POF owing to its larger difference between the core refractive index and the boundary index compare to the SI-GOF, it is difficult to obtain a relatively accurate result of the index profile for SI-POFs.

References

1 Ishigure T, Sato M, Kondo A, *et al*. High-bandwidth graded-index polymer optical fiber with high-temperature stability. *J Lightwave Technol*, 2002, **20**(8): 1443～1448

2 Giaretta G, White W, Wegmuller M. High-speed (11 Gbit/s) data transmission using perfluorinated graded-index polyer optical fibers for short interconnexts (>100). *IEEE Photon Technol Lett*, 2000, **12**(3): 347～349

3 Zheng S L, Zhang X M, Chen K S. Far field pattern and differential mode attenuation of POF. *Acta Photonica Sinica*, 2003, **32**(12): 1434～1437

4 Song N, Yin Z M, Ge W P. Theoretical calculation of the propagation characters of optical fibers. *Acta Photonica Sinica*, 2002, **31**(5): 566～569

5 Liu K, Yu R J. Analysis of bandwidth of multimode GI-POF. *Acta Photonica Sinica*, 2002, **31**(7): 819～823

6 Koike Y, Ishigure T, Nihel E. High-bandwidth graded-index polymer optical fiber. *J Light wave Technol*, 1995, **13**(7): 1475～1489

7 Canfield B K, Vigil S R, Kuzyk M G. Refractive and dispersive measurement of polymer optical fibers and fiber performs. *Proc of SPIE*, 1998, **3473**: 34～42

8 Iga K, Kokubun Y, Yamamoto N. Refractive index profile measurement of the focusing fibers by using transverse differential interferometry. *Trans IECE Jpn*, 1976, **60**(76): 1176～1179

9 White K J. Practical application of the refracted near-field technique for measurement of optical fiber refractive index profile. *Optical Quantum Electronics*, 1979, **11**(2): 185～196

10 Marcuse D, Presb Y H M. Focusing method for nondestructive measurement of optical fiber index profiles. *Appl Opt*, 1979, **18**(1): 14～22
11 Marcuse D. Refractive determination by the focusing method. *Appl Opt*, 1979, **18**(1): 9～13
12 Dai X H, Ai X C, Liu Z M, *et al*. Characterization of the refractive index distribution of polymer optical fiber. *Chin Sci Bull*, 2002, **47**(12): 982～985

聚焦法测量塑料光纤折射率分布的可行性研究

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摘 要 结合理论分析和实验验证,探讨了聚焦法测量塑料光纤纤芯的折射率分布的可行性。结果表明,对GI-POF而言,聚焦法是一种简单可行的技术. 但是对SI-POF,由于入射光线在光纤边界处发生交叉,聚焦法不能精确测量其折射率分布.
关键词 塑料光纤;折射率分布;聚焦法;光纤测量

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