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# Determination of the refractive index profile of polymer optical fiber preform by the transverse ray tracing method

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**Abstract**

In graded-index polymer optical fiber (GI-POF), the refractive index profile is an important parameter in defining its bandwidth. However, direct determination of the refractive index profile of GI-POF is difficult due to its extreme thinness. In this study, the refractive index distribution of the GI-POF is indirectly determined by measuring the refractive index distribution of the GI-POF perform by applying the transverse ray tracing method to a simplified measurement system that we developed.

In this system, a parallel tabular ray is irradiated transversely to a GI-POF preform. The transverse ray from the preform is then projected on a screen, and its digital image is processed to calculate the refractive index distribution. The calculation is based on a transverse ray simulation, a computer program that we developed in which the refractive index distribution of the preform is determined by comparing the displacement of the transverse ray projected on the screen with the actual measurement.

The accuracy of this new measurement method is validated by comparing the refractive index distribution of a GI-POF preform with the refractive index distribution measured by the conventional method using an interferometer. We find that the refractive index distribution measured by this novel method agrees well with that measured by the conventional method.


*Keywords:* Refractive index measurement; Ray tracing; Graded-index optical fiber preform; Refractive index profile

## 1. Introduction

Polymer optical fibers (POF) attract attention as an optimal transmission medium for optical networks in homes and offices [1]. POF have large diameters that allow easy connection with other optical devices. In addition, high bandwidth of GI-POF allows realization of high speed information transmission.

The refractive index profile is an important parameter in defining the bandwidth of a GI-POF. GI-POF, however, are extremely thin, and direct determination of its refractive index profile is difficult [2]. It is also known that the refractive index distribution of GI-POF is almost equivalent to that of its perform [3]. Therefore, the determination of the refractive index distribution of the GI-POF preform will indirectly determine the refractive index distribution of the GI-POF. In this study, the refractive index distribution of a GI-POF preform is easily measured by applying the transverse ray tracing method to a simplified measurement system that we developed.

Several methods for determining the refractive index profile of optical fiber preform have been developed over recent years, and comparative studies of these measurement methods have been made [4,5]. There are mainly two types of measuring refractive index distribution, the destructive [6,7] and non-destructive [8] method. In the destructive method, the measurement sample must be fabricated precisely to accurately measure the refractive index distribution. Light focusing method, optical interference method, and method measuring the bending of transverse ray are few examples of the non-destructive method, all of which require the construction of a highly accurate

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measurement system in order to precisely define the refractive index distribution. Moreover, the measurement sample must be a perfect circle or an ellipse [9].

In this study, we propose a simple and inexpensive measuring technique that does not require preparing of the measurement sample. This novel non-destructive method measures the refractive index distribution by precisely tracing the transverse ray traversing through the GI-POF perform. In addition, its results are highly accurate, the calculation time is short, and can be applied not only to perfectly circular fibers but also to elliptical fibers.

## 2. Fabrication of graded-index polymer optical fiber preform

### 2.1. Interfacial gel polymerization technique

The GI-POF preform rods are fabricated using the interfacial gel polymerization technique [10]. In this technique, a monomer mixture is injected in a poly(methyl methacrylate) (PMMA) tube, and then heated by an external heat source. The inner wall of the tube starts to swell and forms a gel phase between the interface of the methyl methacrylate (MMA) monomer mixture and PMMA. Although the PMMA tube is homogeneously heated, polymerization occurs from the gel phase due to the gel-effect. The MMA monomer diffuses more easily into the formed gel phase than the dopant molecule because its molecular volume is smaller. Hence, a concentration distribution of the dopant molecule is formed from the center to the periphery of the PMMA tube as polymerization proceeds.

### 2.2. Materials

The MMA monomer (KURARAY Co. Ltd.) is purified by the usual procedure. Benzyl *n*-butyl phthalate (BBP, Wako Pure Chemical Industries, Ltd.), benzoyl peroxide (BPO, Nacalai Tesque, Inc.) and *n*-butyl mercaptan (nBM, Wako Pure Chemical Industries, Ltd.) are used without further purification. The function and properties of each material is summarized in Table 1.

### 2.3. Fabrication method

A monomer mixture is first injected in a glass tube and nitrogen substituted. The glass tube is rotated on its axis at approximately 2000 rpm in a 70 °C oven for 24 h. The MMA monomer starts to polymerize along the inner wall of the tube due to centrifugal force. The obtained PMMA tube becomes the cladding layer. The size of the polymer tube depends upon the size of the glass tube used. In this experiment, two different sized glass tubes which resulted with PMMA tubes with diameters of 9.45 and 5.95 mm are used. A MMA monomer mixture with BBP (15 wt%), BPO (1.5 wt%), and nBM (0.2 wt%) is injected in the PMMA tube and polymerized by interfacial gel polymerization technique in a 70 °C oven for 24 h. The obtained GI-POF preform is highly transparent and bubble-free.

## 3. Measurement theory

### 3.1. The ray tracing method

Several methods that trace transverse rays propagating in GI-POF preforms have been proposed. The ray tracing method introduced by Sharma et al. [11] which applies variable transformed ray equation to the Runge–Kutta integration equation is superior for its high accuracy and short calculation time. In this study, we developed a computer program that traces transverse rays using this method.

The transverse ray tracing method is based on the matrix form of the ray equation, shown as follows:

$$d^2R/dt^2 = D(R) \tag{1}$$

Here, $dt = ds/n$, $R = (x,y,z)$ is an array defining the position of a point on the ray, and

$$D = n(R)(\partial n/\partial x, \partial n/\partial y, \partial n/\partial z) \tag{2}$$

Eq. (1) is solved using a specially shortened version of the Runge–Kutta method [12].

### 3.2. Ray trajectory inside the graded-index region

First, we consider a cross-sectional diagram of a GI-POF preform as shown in Fig. 1. The peripheral region of the perform known as the cladding has a constant refractive index ($n_R$), and gradually changes within the central region of the preform known as the core.

There are mainly two types of light rays propagating within the preform. Most light rays incoming the preform at the interface of the core and cladding, as shown as ray A in Fig. 1, propagate in straight lines. The other type of ray incoming the preform near the center axis, as shown as ray B in Fig. 1, are bent in the direction of the center axis due to the refractive index distribution in the core region, and is projected on the screen.

Table 1
Materials used and their physical properties

| Material | Chemical formula | Molecular weight (g/mol) | Refractive index | Function |
|---|---|---|---|---|
| Methyl Methacrylate (MMA) | $H_2C{=}C(CH_3)COOCH_3$ | 100.12 | 1.492 (Polymer) | Monomer |
| Benzyl *n*-butyl phthalate (BBP) | $C_6H_4(COOCH_2C_6H_5)COO(CH_2)_3CH_3$ | 312.36 | 1.538 | Dopant |
| *n*-Butyl mercaptan (nBM) | $CH_3(CH_2)_3SH$ | 90.19 | – | Chain transfer |
| Benzyl peroxide (BPO) | $C_{14}H_{10}O_4$ | 242.23 | – | Initiator |