Measurement 90 (2016) 542–548

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Measurement of the focusing constant of gradient-index fiber lens and its application in developing GRIN fiber probes

Chi Wang [a,b,c], Ting-ting Xu [b], Shu-bo Bi [b], Xi Mao [c,*], Jun Zhu [a], Zhi-wen Yuan [a]

[a] Science and Technology on Near-surface Detection Laboratory, Wuxi 214035, China
[b] Dept. of Precision Mechanical Engineering, Shanghai University, Shanghai 200072, China
[c] School of Mechatronics Engineering, Henan University of Science & Technology, Luoyang 471003, China

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 19 February 2016
Accepted 27 April 2016
Available online 7 May 2016

Keywords:
Gradient-index (GRIN) lens
GRIN fiber probe
Curve fitting
Focusing constant

ABSTRACT

The curve-fitting algorithm is adopted to measure the focusing constant of a gradient-index (GRIN) fiber lens, which is used to further design ultra-small GRIN fiber probes. Firstly, the refractive index profile of a GRIN fiber lens is acquired by using the Optical Fiber Refractive Index Profile tester. And the focusing constant of the GRIN fiber lens is obtained by means of the curve-fitting algorithm of quadratic polynomial. Secondly, the measured focusing constant is used to design ultra-small GRIN fiber probes with different focusing properties. Thirdly, according to the designed optical probe models, GRIN fiber probe samples have been fabricated and tested. Finally, comparative analysis is conducted between the theoretical focusing performance parameters and the experimentally measured values. The results show that, in the given condition, the fitted value of the focusing constant of GRIN fiber lens and the theoretical focusing performance parameters of GRIN fiber probes, respectively agree well with the nominal value provided by the manufacturer and the experimentally measured data. Therefore, the proposed methods of measuring the focusing constant of GRIN fiber lens and its application in designing GRIN fiber probes are validated and feasible to further developing ultra-small GRIN fiber probes requiring specific optical focusing performance.

1. Introduction

Self-focusing lens is also known as the gradient-index (GRIN) lens, with the optical properties of plane surface, small diameter, and large numerical aperture, etc. It is widely used in optical fiber communication, optical fiber sensing, and medical endoscope [1–4]. In recent years, the ultra-small self-focusing optical fiber lens (GRIN fiber lens) has broad application prospects in research of ultra-small GRIN fiber probes for the imaging detection in cardiovascular and other small organizations [5–8]. The refractive index profile of a GRIN fiber lens is a key factor that influences its optical performance. Its refractive index profile coefficient can be expressed by focusing constant *g*. During the development of GRIN fiber lens probes, the focusing performance of the probes can be controlled in a certain extent by changing the constant *g*. Therefore, the measurement of the constant *g* is an important research issue in design and production of GRIN fiber probes, which can be used to further evaluate and control the related equipment performance.

The traditional measurement methods of refractive index profile include near-field scanning, refraction, focusing, interfering, etc. [9–11]. In recent years, with the development of detecting technology, there were some newly-published technical literature about the measurement of the refractive index profile of GRIN lens and focusing constant *g*. Sun et al. [12] used CCD imaging method to measure the center of refractive index and focusing constant of GRIN lens, through the linear relationship between the objective distance and the reciprocal of magnifying rate in different imaging locations. Liu et al. [13] utilized a transmitted-light differential interference contrast to measure the refractive-index profile in an optical fiber. Youk and Kim [14] studied a reflection-type confocal scanning optical microscope system for measuring the refractive index profile of an optical fiber. Lv et al. [15] applied a non-destructive method to obtain the refractive index profile of GRIN lens by means of optical coherence tomography to measure the optical path of the light traveling through GRIN lens. El-Din and Wahba [16] used a digital holographic phase shifting interferometric method to improve the investigation precision of optical parameters. The methods investigated by the above researchers are typically limited to optical performance test of gradient refractive index materials, which mainly focuses on the acquisition of

* Corresponding author.
E-mail address: maoxi_2015@126.com (X. Mao).

http://dx.doi.org/10.1016/j.measurement.2016.04.079
0263-2241/

refractive index profile. There is a lack of further test of the focusing constant g, which is a key technology in the process of developing GRIN fiber probes.

The authors preliminarily researched the curve fitting testing methods for the measuring of focusing constant g in Ref. [17]. However, there is a lack of its further analysis or application in the development of GRIN fiber probes. Based on the previous published study results, the curve-fitting algorithm of quadratic polynomial is adopted to measure the focusing constant g of a GRIN fiber lens. Then, the measured focusing constant is used to design ultra-small GRIN fiber probes with different focusing properties. According to the designed optical probe models, some samples of ultra-small GRIN fiber probes are developed with high precision manufacturing and detecting devices. And comparative analysis is conducted between the theoretically designed focusing performance parameters and the experimentally measured values of such ultra-small GRIN fiber probes.

2. Theoretical basis

2.1. GRIN fiber lens

GRIN lens is a special columnar optical lens, whose refractive index profile changes gradually along the cross-section of optical axis. It enjoys the characteristics of focusing and imaging. The beam propagation method within the GRIN lens is different compared to the conventional lens. As shown in Fig. 1(a), the beam traveling through conventional lens is straight. The rays focus on a point by control of the curvature of lens. Unlike conventional lens, the light rays propagate in a smooth curve within the GRIN lens and finally focus on a point by the continuous bending of the lens refractive index as shown in Fig. 1(b). When a GRIN lens is made by gradient-index fiber, the lens is also called the gradient-index fiber lens (GRIN fiber lens) or self-focusing optical fiber lens, which not only possesses the advantage of plane end but also can be easily integrated with other planar optical components (such as the single-mode-fiber and the no-core fiber) by means of fusing or gluing. It can be made into ultra-small self-focusing lens (millimeter level), namely, small self-focusing optical fiber lens, which has a broad application prospect in the development of ultra-small endoscopics.

Ideally, the radial refractive index profile of the GRIN fiber lens has a parabolic shape, consistent with the refractive index profile of general self-focusing lens, which can be approximately described as [18]:

$$n(r) = n_0\left(1 - \frac{1}{2}g^2r^2\right) \tag{1}$$

Here, n_0 represents the refractive index in the center of profile, r the radial distance from the center axis, and g the focusing constant. The focusing constant g reflects the focus degree for the incident light within the GRIN fiber lens.

2.2. Focusing constant g and the optical performance of GRIN fiber probe

Based on the model of GRIN fiber probe, the effect between the focusing constant g and the optical performance of GRIN fiber lens is further analyzed. Fig. 2 displays a typical model of the GRIN fiber probe, which is composed of a single-mode fiber (SMF), a no-core fiber (NCF) and a GRIN fiber lens [19–21]. NCF can increase the working distance of the probe by expanding the beam from the SMF to solve the problem of limited mode field diameter (MFD) of the SMF.

According to the literature [19–21], with the method of ray matrix transformation of the complex beam parameter, the expression of the working distance z_ω and the spot size $2\omega_f$ can be respectively described as:

$$z_w = \frac{S_1\cos(2gL) + S_2\sin(2gL)}{S_0 - S_3\cos(2gL) - S_4\sin(2gL)} \tag{2}$$

$$2\omega_f = \omega_0\sqrt{2P_0 - 2P_1\cos(2gL) + 4P_2\sin(2gL)} \tag{3}$$

where

$$S_0 = n_0^2g^2 + n_0^2g^2L_0^2a^2 + n_1^2a^2,\ S_1 = -2n_1n_2L_0a^2,$$

$$S_2 = n_0n_2g + n_0n_2gL_0^2a^2 - \frac{n_2n_1^2a^2}{n_0g},$$

$$S_3 = n_0^2g^2 + n_0^2g^2L_0^2a^2 - n_1^2a^2,\ S_4 = 2n_0n_1gL_0a^2,\ a = \frac{\lambda}{n_1\pi\omega_0^2},$$

$$P_0 = 1 + a^2\left(L_0 + \frac{n_1z_w}{n_2}\right)^2 + \frac{n_0^2g^2z_w^2}{n_2^2} + a^2\left(\frac{n_1}{n_0g} - \frac{n_0L_0gz_w}{n_2}\right)^2,$$

$$P_1 = \frac{n_0^2g^2z_w^2}{n_2^2} + a^2\left(\frac{n_1}{n_0g} - \frac{n_0L_0gz_w}{n_2}\right)^2 - a^2\left(L_0 + \frac{n_1z_w}{n_2}\right)^2 - 1,$$

$$P_2 = a^2\left(L_0 + \frac{n_1z_w}{n_2}\right)\left(\frac{n_1}{n_0g} - \frac{n_0L_0gz_w}{n_2}\right) - \frac{n_0gz_w}{n_2}$$

According to Eqs. (2) and (3), the working distance and the spot size are sine function expressions about focusing constant g, self-focusing optical fiber lens length L and no-core fiber length L_0. Their relationship has the periodic characteristics of sine function. The working distance and focusing spot size can be affected by changing the value of g with the constant structure size. As shown in Fig. 3, we can find the relationship between focusing performance (including working distance and spot size) and focusing constant g, when the length of the GRIN fiber lens is $L = 0.1$ mm and the length of NCF is $L_0 = 0.36$ mm. The focusing performance of GRIN fiber probe changes greatly along the change of focusing constant g. Focusing constant g determines the focus degree of GRIN fiber probe to a great extent. Therefore, the precise

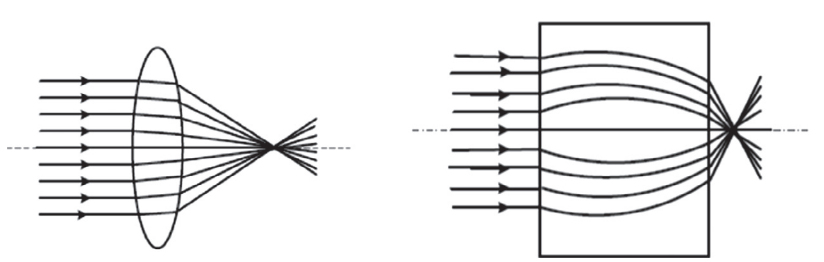
(a) ordinary lens with beam transmission
(b) GRIN lens with beam transmission

Fig. 1. Schematic diagram of light transmission through ordinary lens and GRIN lens.