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Influence of no-core fiber on the focusing performance of an ultra-small gradient-index fiber probe

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ABSTRACT

The light-beam expansion effect of a no-core fiber on the focusing performance of an ultra-small gradient-index fiber probe is investigated with a view to optimizing the optical performance of such probes. By taking the variable relationship between the focusing performance (including the working distance and the focusing spot size) of the probe and the length of the no-core fiber as the criterion, the effective beam expansion length of the no-core fiber in the ultra-small gradient-index fiber probe is calculated based on the basic properties of the Gaussian beam. Verification and analysis are done by numerical calculations and experimental measurements, respectively. The obtained results show that the working distance of an ultra-small gradient-index fiber probe can be increased effectively by adding a no-core fiber; however, this will lead to increasing the focusing spot size. For the parameters of the fiber probe studied here, the effective beam expansion length of the no-core fiber spacer is less than 0.357 mm.

1. Introduction

Miniaturized probes for optical coherent tomography (OCT) are being developed for a rapidly increasing range of clinical applications [1]. An ultra-small gradient-index (GRIN) fiber probe, which is composed of a single-mode fiber (SMF), a no-core fiber (NCF) and a GRIN fiber lens, has a submillimeter diameter (125 µm without encapsulation). The relatively small size and excellent focusing performance of the ultra-small GRIN fiber probe opens wide prospects for various applications [2–6].

The research on ultra-small GRIN fiber probes has been ongoing. In 2002, Reed et al. proposed an all-fiber ultra-small lens consisting of SMF and a GRIN fiber lens for optical studies involving low-coherence interferometry [7]. In the same year, E. Swanson was granted the patent on a series of different structures of ultra-small optical probes, including the GRIN fiber probe composed of SMF +NCF+ GRIN fiber lens [8]. A few years later, Y. X. Mao reported the methods of fabrication and characterization detection of the ultra-small GRIN fiber probe [9]. W. Jung analyzed an OCT imaging probe composed of SMF +NCF+ GRIN lens by using the ABCD matrix algorithm for the Gaussian beam [10]. Lorenser applied the beam propagation method [11] to study an ultra-small GRIN fiber probe. Fu et al. optimized the sensitivity of the common path of an OCT system with a 2-degree polished ultra-small GRIN fiber probe tip [12]; Wang et al. demonstrated the model analysis and structure design of the ultra-small GRIN fiber probe [13–16].

The above shows the development feasibility and application prospect of an ultra-small GRIN fiber probe. Swanson et al. [8] presented the variations of probe structure instead of the design of optical parameters. McLaughlin et al. [1], Mao et al. [9], and Wang et al. [13] reported the design method and characterization of the fiber probes without the detailed analysis of the length of NCF. The light-beam expansion effect of the NCF and the influence on the focusing performance of the probe have not been analyzed comprehensively, which is a key problem in optical design of the GRIN fiber probe. The addition of NCF lengthens the working distance of the fiber probe. Nevertheless, a short length of NCF hardly ever increases the working distance of a GRIN fiber probe. On the other hand, when the length of NCF is beyond the range of the effective beam expansion determined by the core diameter of the GRIN fiber lens, the working distance will not be longer with the increase of the NCF length. In this case, the well-known structure design method [13] for ultra-small GRIN fiber probes is no longer applicable. Moreover, the focusing spot size becomes larger with the increase of the working

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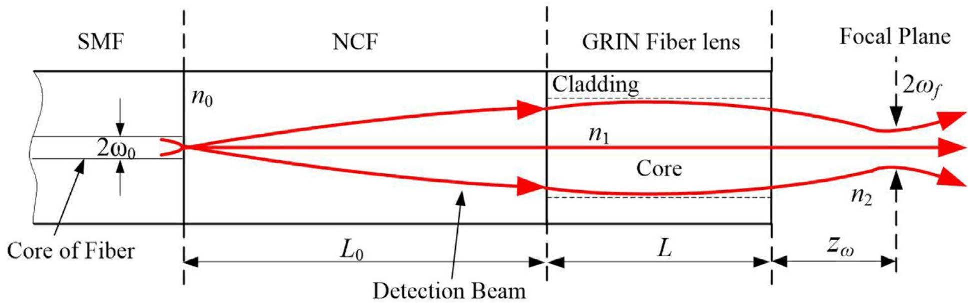

Fig. 1. Model of the ultra-small GRIN fiber probe.

distance, which has a negative impact on the lateral resolution of the imaging system.

This paper is devoted to investigation of the beam expansion as a function of the lengths of a NCF. The range of the effective beam expansion length of the NCF and its effect on the focusing performance of the ultra-small GRIN fiber probe are studied in order to optimize optical parameters while designing such probes.

2. Model of an ultra-small GRIN fiber probe and its characteristic parameters

In an imaging detection system, e.g., OCT based on the ultra-small GRIN fiber probe, the probe is an important component affecting the image quality. The ultra-small GRIN fiber probe consists of three parts: the SMF, NCF, and GRIN fiber lens (Fig. 1). All three parts have diameters of 125 µm. The incoming light passes through the SMF that is connected with the detection arm of the system and is expanded in the NCF. Thereafter, it enters into the GRIN fiber lens, which has substantially the same focusing effect as the GRIN lens, and is focused on a sample to be tested. Then, the reflected or scattered light containing information on the sample is collected by the ultra-small GRIN fiber probe and is transmitted back to the system for further image processing and data treatment.

The propagation process of the light beam through the ultra-small GRIN fiber probe can be analyzed by the complex beam parameter Gaussian matrix transformation method [17]. Following Fig. 1, assume that the light has the wavelength λ and the waist radius of the Gaussian beam is ω_0, the refraction index of the NCF is n_0, the length of the NCF is L_0, the GRIN fiber lens has the refractive index in the center n_1, the gradient constant g, the length L, and the refractive index of the transmission medium in the application environment is n_2. The focusing performance of the ultra-small GRIN fiber probe includes the working distance and focusing spot size. The working distance in this case is defined as the length from the output plane of the GRIN fiber lens to the focal plane. The focusing spot size, $2\omega_f$, is defined as the waist diameter of the light beam at the focal plane.

The working distance, z_ω, is expressed through the parameters of the ultra-small GRIN fiber probe as [14]

$$z_\omega = \frac{S_1\cos(2gL) + S_2\sin(2gL)}{S_0 - S_3\cos(2gL) - S_4\sin(2gL)} \tag{1}$$

where

$$S_0 = n_1^2g^2 + n_1^2g^2L_0^2a^2 + n_0^2a^2,\ S_1 = -2n_0n_2L_0a^2,$$

$$S_2 = n_1n_2g + n_1n_2gL_0^2a^2 - \frac{n_2n_0^2a^2}{n_1g},\ S_3 = n_1^2g^2 + n_1^2g^2L_0^2a^2 - n_0^2a^2,$$

$$S_4 = 2n_0n_1gL_0a^2,\ a = \frac{\lambda}{n_0\pi\omega_0^2}$$

The expression of the focusing spot size is given by [14]

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

where

$$P_0 = 1 + a^2\left(L_0 + \frac{n_0z_\omega}{n_2}\right)^2,\ P_1 = \frac{z_\omega^2n_1^2g^2}{n_2^2} + a^2\left(\frac{n_0}{n_1g} - \frac{n_1z_\omega L_0g}{n_2}\right)^2$$

$$P_2 = \frac{z_\omega n_1g}{n_2} - a^2\left(L_0 + \frac{n_0z_\omega}{n_2}\right)\left(\frac{n_0}{n_1g} - \frac{n_1z_\omega L_0g}{n_2}\right)$$

3. Method for determining the effective beam expansion length range of NCF

3.1. Calculation method of the effective beam expansion length of NCF

The NCF is made from highly pure silica without a doped core that provides an opportunity to solve the problem of small mode field diameter of SMF, in order to achieve a long working distance. According to Eqs. (1) and (2), z_ω and $2\omega_f$ depend much on the length of NCF. As a result, special attention has to be paid to optimization of the length of NCF. The GRIN fiber lens is a segment of the graded-index multimode fiber that consists of the fiber core and the cladding. The fiber core in a graded-index fiber has the refractive index that radially decreases continuously from the center to the cladding interface. Thus, the GRIN fiber lens has the effect of focusing the light beam. The waist radius of the light beam propagating in the GRIN fiber lens earlier increases and then decreases with the changing of the refractive index. This enables that the waist diameter of the light beam may exceed the core diameter of the GRIN fiber lens when propagating through it, and even the light beam after the expansion of NCF can fully enter the fiber core. Because the cladding of the GRIN fiber lens is incapable of focusing the light, the focusing performance of the GRIN fiber probe is limited by the core diameter, which is ignored in the design theory formulas, i.e., Eqs. (1) and (2).

After the expansion of the NCF whose length is L_0, the light-beam diameter does not exceed the core diameter of the GRIN fiber lens when propagating through it. Thus, the length of NCF L_0 can be defined as the effective beam expansion length. However, in a case when L_0 is beyond the effective beam expansion range, the maximum working distance of the probe will not be increased and the well-known structure design method of the ultra-small GRIN fiber probe is no longer applicable. If so, it is necessary to study the effective beam expansion length of the NCF by analyzing the model parameters of the ultra-small GRIN fiber probe.

By using the basic properties of the Gaussian beam, it is possible to calculate the range of effective beam expansion length of NCF. Let the intersection of the input plane of the NCF and the central axis be the coordinate origin $z(0)$. The electric vector $\boldsymbol{E}(r, z)$ of the Gaussian beam at any point on the axis z is given by [18]

$$\mathbf{E}(r,z) = \frac{A_0}{\omega(z)}\exp\left[\frac{-r^2}{\omega^2(z)}\right]\cdot\exp[-\mathrm{i}k\left(\frac{r^2}{2R(z)} + z\right) + \mathrm{i}\phi(z)] \tag{3}$$

where $\omega(z)$ represents the radius of the light beam, $R(z)$ represents the radius of curvature, and $\phi(z)$ represents the phase factor. These func-