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Coupling efficiency of ultra-small gradient-index fiber probe

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ABSTRACT

In this paper, the coupling efficiency of ultra-small GRIN fiber probe is studied for its focusing performance. Based on the light transmission characteristics of a Gaussian beam and the principle of optical imaging, with the analytical methods, the theoretical formula is deduced for the coupling efficiency of ultra-small GRIN fiber probe. Experiments were set-up and conducted for verification. Per the experimental results, for an ultra-small GRIN fiber probe with the focal length of 0.4 mm, the coupling efficiency measured at the focusing position was 57%, and above 44% within the 0–0.6 mm range. However, for a single-mode fiber, the coupling efficiency dropped to 17% when the distance increased to 0.2 mm. Thus, the ultra-small GRIN fiber probe boasts a superior focusing performance and coupling efficiency. This paper provides a theoretical basis for the application and research on ultra-small GRIN fiber probe.

1. Introduction

Optical coherence tomography (OCT) has become a novel and effective means for medical imaging due to its non-contact and fast high resolution imaging capabilities [1–3]. However, the translucent and highly scattering medium of most biological tissues limits the penetration depth of OCT technology to 1–3 mm. For the development of OCT technology, the study on endoscopic optical probe is significant to take full advantage of the high resolution by overcoming the limitation of detection depth. The ultra-small GRIN fiber probe, an all-fiber-type optical bio-compatibile probe, consists of a single-mode fiber (SMF), a no-core fiber (NCF) and a GRIN fiber, which is promising in the miniaturization of OCT endoscopic probe. Lin [4] presented a novel application approach in the study of two-segment lensed fiber collimator. Swanson [5] was granted an invention patent for ultra-small GRIN fiber probe and Reed [6] used it in to a low-coherence interferometer. Jafri [7] proposed an ultra-small GRIN fiber probe for a miniaturized OCT imaging system. Mao [8,9] has studied sample fabrication and testing method of ultra-small GRIN fiber probe.

The study of theoretical issues on the ultra-small GRIN fiber probe, such as the light transmission characteristics and the design method of structure parameters, has witnessed significant progress in recent years. Jung [10] analyzed a miniaturized OCT probe model, comprising of a “SMF+NCF+GRIN lens”, with the ABCD matrix algorithm for a Gaussian beam. Lorenser [11] modeled the ultra-small GRIN fiber probe with the Beam Propagation Method (BPM). Since 2011, our research group has been studying the method for analyzing ultra-small GRIN fiber probe [12]. Upgraded optical design software such as GLAD and VirtualLab have been used to model and analyze ultra-small GRIN fiber probe [13–15]. McLaughlin [16–18] conducted preliminary experimental studies of excised lung and breast cancer by combining the ultra-small GRIN fiber probe with high precision OCT technology. More recently, Filipkowski [19] claimed to have developed the world-smallest fiber-GRIN lens system for optofluidic applications by integrating a standard SMF with a GRIN microlens. Bi [20] studied the influence of the transmission medium on the focusing performance of the GRIN fiber probe. In addition, our group presented an investigation about the measurement of the focusing constant of gradient-index fiber lens and a novel integrated fiber-optic interferometer model [21,22].

Nevertheless, there are few studies on the coupling efficiency of ultra-small GRIN fiber probe. The above studies demonstrate the feasibility of the developing ultra-small GRIN fiber probe, but a complete development system has not been established yet. The coupling efficiency of probes, which reflects the comprehensive focusing performance of probes, is an important characteristic parameter for determining the detection performance of OCT system and it affects the sensitivity of OCT detection system. In this paper, based on existing research achievements, a theoretical equation for the coupling efficiency of probes is derived using an analytical approach based on the optical model of ultra-small GRIN fiber probe and transmission characteristics of the Gaussian beam. Next, variation and influencing factors were analyzed and verified by establishing the corresponding

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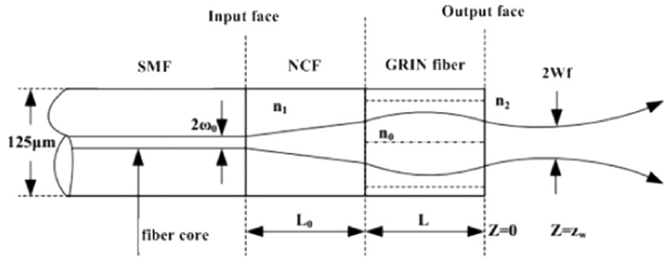

Fig. 1. Model of GRIN fiber probe.

experiment system for testing. The experimental result shows that the coupling efficiency is greater than 44% along the axial direction within a range of 0.6 mm for a given ultra-small GRIN fiber probe. This further indicates that ultra-small GRIN fiber probe boasts a superior focusing performance.

2. Overview of the model of GRIN fiber probe

Fig. 1 is a schematic of a typical GRIN fiber probe consisting of a single-mode fiber (SMF), a non-core fiber (NCF), and a GRIN fiber lens. After passing through SMF, the light beam is expanded by the NCF and focused by the GRIN fiber lens. The focusing performance of the probe is determined by the combined effect of expansion and focusing produced by the NCF and GRIN fiber lens respectively. In addition, the combined length influences the overall focusing performance of the probe finally. The focusing performance can be characterized by the working distance z_ω, spot size $2\omega_f$ and depth of field z_f, which directly influences the detection depth, the lateral resolution and the imaging depth range of the measurement system respectively. The working distance is defined as the length from the output plane to the focus plane. The spot size, i.e. beam waist diameter, is the Full-Width-Half-Maximum of the beam waist, and the depth of field is twice the Raleigh range. Per the model of probe shown in Fig. 1, the parameters are set as follows: L_0 is the length of the NCF, n_1 the refractive index of the NCF, L the length of the GRIN fiber lens, n_0 the refractive index at the center of the GRIN fiber lens, g the gradient constant, λ the wavelength of Gaussian beam, ω the beam waist, and n_2 the refractive index of the air.

From [23], the mathematical expressions for the working distance z_ω and spot size $2\omega_f$ of the GRIN fiber probe are represented as:

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

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

In these two equations,

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

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

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

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

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

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

Per Eqs. (1) and (2), given the source parameters and the refractive index of the probe components, the focusing performances of GRIN fiber probe vary sinusoidally with the length of the probe components. Typically, for a total length of GRIN fiber probe of less than 1 mm, and the diameter of bare optical fiber component is 125 μm the working distance does not exceed 1 mm, and the focus spot size is smaller than 35 μm. The above parameters indicate that the output plane of the probe should not be in direct contact with the detector in the process of measurement. Following the characteristic testing method of GRIN fiber probe [8,9] the focusing performance of the probe is detected by a beam profile measurement system, with the horizontal resolution of 1.0 μm and the vertical resolution of 0.1 μm respectively. The distribution of light intensity at various distances along the direction of propagation after the probe is first accurately captured by the measurement system. Then, the working distance and $1/e^2$ spot size are obtained from the experimental data of intensity distribution.

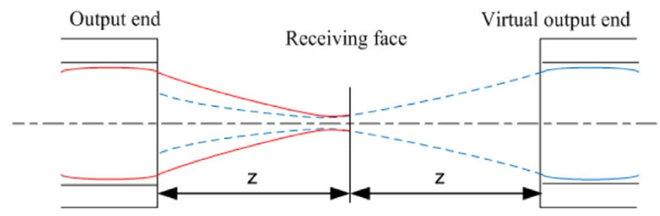

Fig. 2. Coupling efficiency of the GRIN fiber probe.

The coupling efficiency of the GRIN fiber probe is a physical quantity that represents the relationship between the received signal energy and output signal energy. As shown in Fig. 2, the coupling efficiency is equal to the ratio of received incident light energy to the output light beam energy during light propagation, and expressed as:

$$\eta = \frac{p_r}{p_o} \times 100\% \tag{3}$$

where p_r represents the received light power, and p_o the output light power. The power values are detected with a power or light spot detector. The coupling efficiency of the probe not only depends on its own focusing performance but also the distance from the output plane which has a great impact on the sensitivity of the measurement system. Thus, the coupling efficiency constitutes an important part of the research on optical parameters characterisation and focusing performance of the GRIN fiber probe.

3. Theoretical analysis on the coupling efficiency of the probe

The following three assumptions are made before the theoretical calculation:

(1) The output light intensity exiting from the probe completely conforms to the distribution of Gaussian beam;
(2) the reflective plane is an ideal mirror without energy absorption, which means the reflectivity is 100%;
(3) there is no energy loss in the process of light propagation.

The output light intensity exiting from the GRIN fiber probe satisfies the distribution of Gaussian beam, which can be expressed as:

$$I(r, z) = I_0\cdot\exp\left[-\frac{2r^2}{\omega^2(z)}\right] \tag{4}$$

where r represents the distance from the observed point to the center of spot, and I_0 is the peak radiant intensity of the beam.

$$I_0 = I(0, z) = \frac{2p_t}{\pi\omega^2(z)} \tag{5}$$

where p_t represents the output light power from the probe, and z the distance from the observed point to probe along the optical axis. The expression for the spot radius $\omega(z)$ at the distance z from the output plane of the probe is: