

Research progress on ultra-small self-focusing optical fiber probe

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Abstract: Gradient-index (GRIN) fiber probe is an all-fiber ultra-small optical lens, which has broad application prospects in endoscopic image detection in small spatial tissues such as cardiovascular. However, its development lacks a systematic theoretical system. This paper discusses the key issues of the design, fabrication and performance testing methods of the probe. Based on the characteristics parameters of GRIN fiber probe, comparative analysis is conducted between the analytical method and numerical simulation methods. An integrated high precision optical fiber welding and cutting device is presented for the fabrication of ultra-small GRIN optical fiber probe. In addition, the method and device for detecting the focusing performance of ultra-small GRIN fiber probe are analyzed. As a result, a system method for design, fabrication and performance testing is provided for the research of GRIN fiber probes.

Key words: optical coherence tomography (OCT); ultra-small optical probe; self-focusing optical fiber lens; GRIN optical fiber probe; fiber welding and cutting

超小自聚焦光纤探头的研究进展

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摘要: 梯度折射率 (Gradient-index, GRIN) 光纤探头是一种全光纤型超小光学镜头, 在心血管等狭小空间组织内窥影像检测中具有广阔的应用前景。但其发展一直缺少系统的理论体系。本文讨论探头设计、制作和性能测试等方面的关键问题。基于 GRIN 光纤探头聚焦性能的特征参数, 对解析设计方法与数值仿真设计方法进行比较分析。针对超小 GRIN 光

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纤探头的制作难题,研究一种光纤熔接和切割的高精度一体化集成装置,描述 GRIN 光纤探头的制作方法。此外,分析了超小 GRIN 光纤探头聚焦性能检测的方法及装置。本文为超小 GRIN 光纤探头的设计、制作及性能测试提供了一个方法体系。

关键词: 光学相干层析;微小光学探头;自聚焦光纤镜头;GRIN 光纤探头;光纤熔接与切割

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1 Introduction

Optical coherence tomography(OCT^[1-3]) is becoming increasingly promising in the fields such as biomedical and surgical operations due to its advantages including rapid imaging speed, high resolutions, and non-contact detection, *etc.*. Following the X-ray computed tomography(XCT) and magnetic resonance imaging(MRI), OCT is another tomography technology which can be used to obtain the internal structure information of the samples by detecting interference signal. In OCT system, optical probe is a key component that transmits and focuses light beam(*e. g.* Gaussian beam) inside a sample of interest, and then collects the reflected or scattered light carrying information about the sample and sends the information to the signal processing system. Its focusing performance plays an important role in determining the imaging quality of the OCT system. For example, the focal waist location and spot size of the probe respectively determine the penetration depth and lateral resolution to a large extent. However, most biological tissues are optically nontransparent, so the detection depth of OCT is limited, generally in the range of 1 – 3 mm^[4]. The development of small endoscopic optical probes has become an important growing branch of OCT technology.

Gradient-index(GRIN) fiber probe is defined to be as an all-fiber-type ultra-small optical probe, which typically consists of a single-mode fiber(SMF), a no-core fiber(NCF), and a GRIN fiber lens. It could be suitable for the imaging detection

in deep, narrow tissues or organs such as cardiovascular system, and has been investigated by some researchers in recent years. Lin^[5] presented a novel application approach in the study of two-segment lensed fiber collimator. Swanson^[6] was granted an invention patent for ultra-small GRIN fiber probe. Then, Reed and Jafri et al. developed in-vivo OCT imaging system^[7-8]. Since 2007, Dr. Mao *et al.* studied the fabrication method and performance testing method of such GRIN fiber probe^[9-10]. Jung^[11] analyzed a miniaturized OCT probe model, comprising of a “SMF + NCF + GRIN lens”, with the ABCD matrix algorithm for a Gaussian beam. Lorenser^[12] modeled the ultra-small GRIN fiber probe with the Beam Propagation Method(BPM). In recent years, the group headed by Prof. Sampson D. D. at the University of Western Australia has obtained application solutions of breast cancer and preliminary testing results of optical image with the OCT system based on GRIN fiber probe^[13]. In addition, Schmitt R. studied the testing scheme of micro-deep holes by using endoscopic detection system based on this probe^[14-15].

Ultra-small GRIN fiber probe has many advantages on endoscope detection. However, the design theory of GRIN fiber probe has been largely overlooked or only simplified in the above studies. In addition, this kind of probe is difficult to fabricate due to its ultra-small size. Since 2011, our research group has researched the design theory of the GRIN fiber probe through analytical method and numerical simulation technology^[16-22]. And the fabrication method of the fiber probe based on fiber cutting and fiber welding were preliminary studied^[23]. These

design methods published previously are described in this paper. Advantages of each method are presented. Based on the existing researches, we have recently developed a high precision optical integration machine with functions of fiber welding and fiber cutting. In addition, detection method for the focusing performance of the probe is overviewed together with the coupling efficiency testing method.

2 Optical model of the GRIN fiber probe

Fig. 1 displays a typical model of GRIN fiber probes, which is composed of a single-mode fiber (SMF), a no-core fiber (NCF), and a GRIN fiber lens. The SMF is connected with the detection arm of the OCT system, and guides the light beam into the NCF. The NCF is a kind of special fiber with homogeneous refractive index. Adding the NCF is able to improve the focusing performance of the probe by expanding the beam and thus to overcome the problem of limited mode field diameter of the SMF. However, the length of NCF should be chosen appropriately. On one hand, when the NCF is too long, overflowing of some light energy may exist off the probe side which will finally reduce beam coupling efficiency. On the other hand, when the NCF is too short, it may result in the failure of expanding beam and improving the focusing performance of the probe. GRIN fiber lens is the most critical part of the probe that performs a self-focusing function due to the continuous change of refractive index. When the length of the GRIN fiber lens goes close to $1/4$ pitch (or the integer times), the lens will get a really short focal length for strong focusing performance; When the length is close to $1/2$ pitch (or the integer times), a longer focal length will be got with a bigger spot size. In the study of the imaging performance of an OCT system, a longer focal length is needed in order to obtain a deeper detection depth. In

addition, focusing spot size is as small as possible to get a higher lateral resolution. Therefore, a tradeoff is adopted to determine the length of GRIN fiber lens. An ideal design for ultra-small GRIN fiber probe can be obtained by using a NCF spacer with the characteristics of beam-expanding to improve the focusing performance. The length of NCF and the length of GRIN fiber lens are in the submillimeter range; therefore it is a challenging problem to achieve high precision cutting and welding of such short fiber components. It is noted that, the refractive indices of the NCF and the core of GRIN fiber at the axis should match that of the SMF at the core, in order to minimize the influence of the complicated reflection of input beam by different optical interfaces on OCT imaging quality.

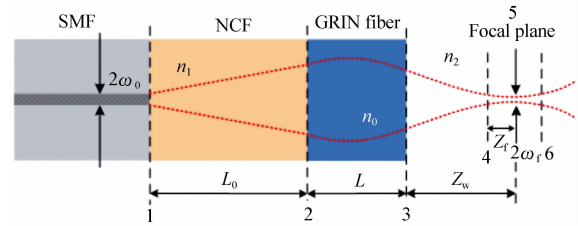


Fig. 1 Model of GRIN fiber probe

3 Design methods of GRIN fiber probe

3.1 Analytical design method

The optical characteristic parameters is the theoretical basis for design of GRIN fiber probe, which are defined as in Ref. [16]. Working distance is the distance between the output end of the probe and the focal plane, characterizing the detection depth of the OCT system. Focused spot size is the waist diameter of Gauss beam focused by the probe, characterizing the lateral resolution of the OCT system. Depth of field is twice of the Rayleigh range of the Gauss beam, characterizing the range of the detection depth of the OCT system. A brief overview is described below. As shown in Fig. 1, an approximate Gaussian beam is output from the SMF with a wave-

length of λ and a radius of ω_0 , then transmits into the NCF with an index of n_1 , and then transmits into the GRIN fiber lens with an index profile described by the formula (1). The light beam is eventually focused into a spot with a waist radius of W and a waist location of Z_w in air. The refractive index of air is n_2 . The refractive index at the center of the GRIN fiber lens is n_0 . L_0 and L represent the length of the NCF and the length of the GRIN fiber lens, respectively. Planes 1 to 6 denote the input plane, two interfaces between the NCF and the GRIN fiber lens, two interfaces between the GRIN fiber lens and the air, and the focal plane, respectively. The refractive index of a GRIN fiber lens can be described as the following quadratic equation.

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

$$2w_f = w_0 \sqrt{2P_0 - 2P_1 \cos(2gL) + 4P_2 \sin(2gL)}, \quad (3)$$

Where

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

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

$$P_2 = a^2 \left(L_0 + \frac{n_1 z_w}{n_2} \right) \left(\frac{n_1}{n_0 g} - \frac{n_0 L_0 g z_w}{n_2} \right) - \frac{n_0 g z_w}{n_2}$$

The expressions of the Rayleigh range can be described as (4):

$$Z_f = \frac{n_2 \pi w^2(z_w)}{\lambda}. \quad (4)$$

According to formulas above, we can comprehensively analyze the relationship between the focusing performance and the structural parameters of the GRIN fiber probe, the results can be used to optimize ultra-small GRIN fiber probes with specific optical performance requirements. For example, MATLAB is adopted to further solve these expressions of the characteristic parameters by means of drawing the function plots between the characteristics and the length of the fiber spacer L_0 and the length of GRIN fiber lens L . As shown in Fig. 2, Fig. 2 (a) illus-

Where r is the radius, and g is the gradient constant. Assigning $a = \lambda/n_1 \pi w^2$, according to Ref. [16], the expression of the working distance can be described as formula (2) by adopting the complex beam parameter matrix transformation method.

$$Z_w = \frac{S_1 \cos(2gL) + S_2 \sin(2gL)}{S_0 - S_3 \cos(2gL) - S_4 \sin(2gL)}, \quad (2)$$

Where

$$S_0 = n_0^2 g^2 + n_0^2 g^2 L_0^2 a^2 + n_1^2 a^2$$

$$S_1 = -2n_1 n^2 L_0 a^2$$

$$S_2 = n_0 n_2 g + n_0 n_2 g L_0^2 a^2 - \frac{n_2 n_1^2 a^2}{n_0 g}$$

$$S_3 = n_0^2 g^2 + n_0^2 g^2 L_0^2 a^2 - n_1^2 a^2$$

$$S_4 = 2n_0 n_1 g L_0 a^2$$

The expressions of the spot size can be described as formula (3).

trates the contour relationship plots of working distance and spot size. Fig. 2 (b) shows the relationships between working distance and spot size and the length of NCF L_0 , given a constant length of the GRIN fiber lens $L = 0.1$ mm. Fig. 2 (c) shows the relationships between working distance and spot size and the length of a GRIN fiber lens L , given a constant NCF length $L_0 = 0.36$ mm. According to Fig. 2, it is obvious that NCF can improve the focusing performance of the GRIN fiber probe and increase the working distance while still keeping the focusing spot small. In addition, the working distance shows periodicity with the increasing of the length of the GRIN fiber lens, which depends on the pitch length of the lens.

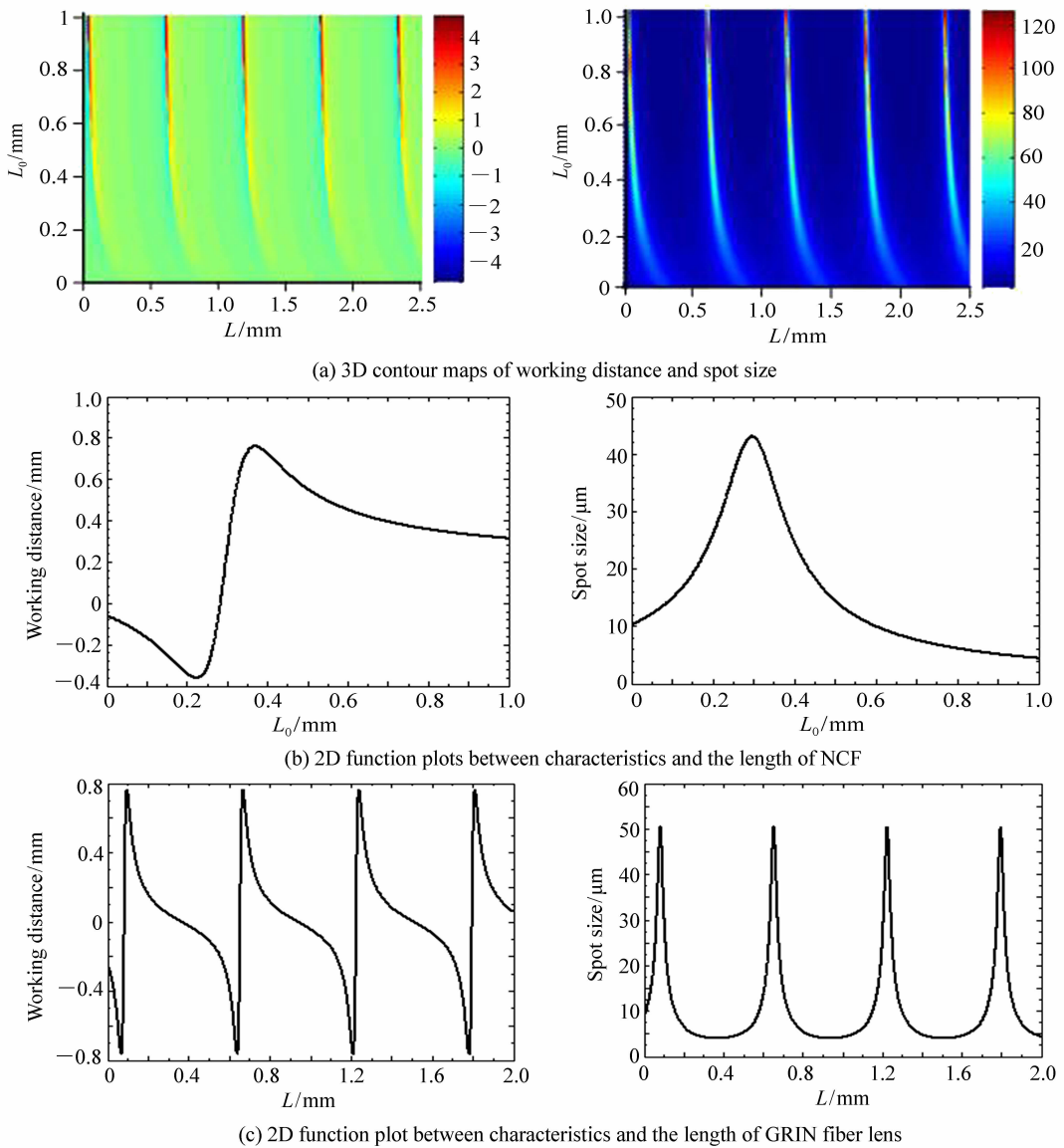


Fig. 2 Relationship between characteristics and the lengths of probe components

Generally speaking, one tends to design an OCT system with working distance and depth of field as long as possible and lateral resolution as high as possible, respectively. In addition, the lateral resolution decreases with the increase of spot size. Therefore, the length of the NCF and the length of the GRIN fiber lens should be chosen to achieve a trade-off between the working distance and the lateral resolution of an OCT imaging system in order to optimize the design of GRIN fiber probe. As a special and useful case of interest, according to Fig. 2 (b), when the NCF length ranges from 0.32 to 0.4

mm, given the length of GRIN fiber lens $L = 0.1$ mm, the working distance is located into 0.5 to 0.76 mm, and correspondingly the spot size is located into 26 to 40 μm . Therefore, in order to meet such different requirements of the OCT imaging probe, the use of NCF length, 0.32 to 0.4 mm, may be a good tradeoff, which means that the working distance is greater than 0.5 mm and the spot size less than 40 μm .

From Fig. 2, we find another important conclusion that the characteristic parameter can change sharply within some length ranges of the NCF or

GRIN fiber lens. Since the length of the GRIN fiber probe is less than 1 mm, any small error in either the length of the NCF or that of the GRIN fiber lens during fabrication can have a great impact on its optical focusing performance. In Ref. [21], the partial derivatives of the mathematical expressions and 2-D curvature graphs of characteristics are adopted to analyze this mutation in detail when designing the lengths of the NCF and the GRIN fiber lens. The selected lengths of the two components of the GRIN fiber probe should meet the specific performance and avoid obviously mutational range.

3.2 Numerical design method by using GLAD

As presented above, analytical design method can help analyze and design such ultra-small GRIN fiber probe with special demands of optical properties by means of the mathematical expressions of characteristic parameters. The use of NCF can improve the focusing performance of GRIN fiber probe by means of its effect of expanding beam. However, it is difficult to obtain the beam profile at locations of interest, e. g. input plane, two interfaces between the NCF and the GRIN fiber lens, two interfaces between the GRIN fiber lens and the air, and the focal plane, *etc.*. The beam parameters and the beam profile within the ultra-small GRIN fiber probe path are very difficult or even impossible to measurement by experimental method due to its very limited size.

In order to solve such issues, the numerical design method was proposed to model GRIN fiber probes in Ref. [18] by using the optical software of GLAD which has the capability of modeling almost any type of physical optical systems.

GLAD treats optical beams as complex amplitude distribution, and gives a much more powerful analysis capability. It models the GRIN fiber probe by assigning relative parameters of light source and optical components. Take a special case of the GRIN fiber probe as an example, Fig. 3 shows the full profile of all points along the optical path through the probe with the length of NCF $L_0 =$

0.36 mm and the length of GRIN $L = 1.24$ mm. Fig. 3(a) displays beam profile as a function of distance from the surface of the SMF to a total distance of 3.52 mm. Fig. 3(b) demonstrates beam width vs. axial position. From Fig. 3, we can acquire the best focus position at about 2.35 mm, and thus the working distance 0.75 mm, and the spot size $36 \mu\text{m}$. It is obvious that the beam is expanded through the NCF, then focused and thus narrowed down through the GRIN fiber lens.

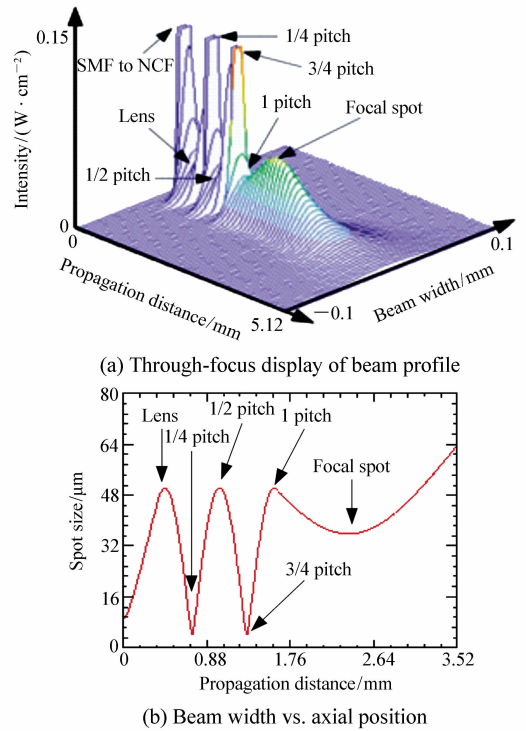


Fig. 3 Beam profile of all points along the optical path going through the probe

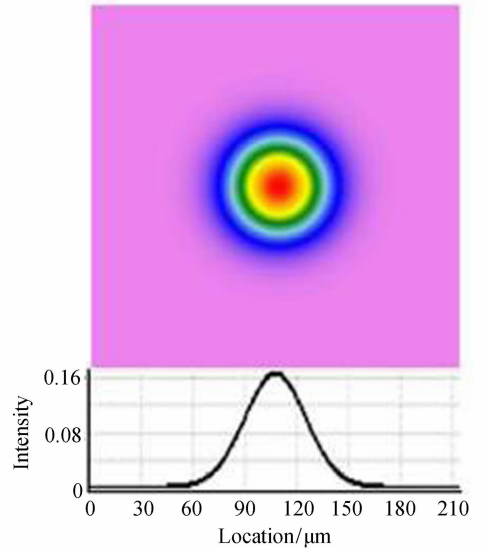
3.3 Numerical design method by using Virtual-Lab

GLAD can help obtain the beam profile at all locations along the propagation direction in addition to the internal probe. However, it is a kind of programming language and is very difficult for a general user to get a quick grasp. And the design process of GRIN fiber probe is very complicated. Therefore, the authors proposed another numerical design method by means of the commercial optical software Vir-

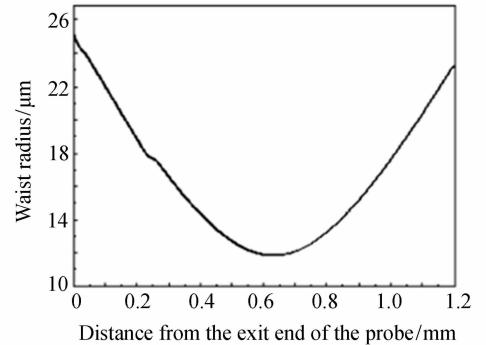
tualLab as described in Refs. [19-20]. VirtualLab is a unified optical modeling platform and numerical analysis software for physical optics, designed by German LightTrans Company. Based on the theory of electromagnetic field, it can be used to model all light sources and arbitrary transmission by the usage of field tracking. Model is built in the form of Light Path Diagram(LPD). The light source, components and detectors used in the system, can be called from the optical element library and their optical characteristic can be edited flexibly.

Fig. 4 is the LPD to model GRIN fiber probe. The element “Gaussian Wave” represents the input Gaussian beam. The output of SMF can be considered as the incident position of the Gaussian beam. Optical element “NCF” represents the coreless fiber. Optical element “GRIN fiber lens” indicates the self-focus fiber lens. Optical element “Detector” indicates the beam parameter detector for detecting the waist size of Gaussian beam. Optical element “Virtual Screen” is to observe the intensity distribution of Gaussian beam. By double-clicking the corresponding symbol, we can flexibly change parameters to complete the configuration of the light source and optical elements. Fig. 5(a) shows the intensity distribution of Gaussian beam at the output end of a GRIN fiber probe by setting the length of NCF as 0.36 mm and the GRIN fiber length as 0.11 mm. Fig. 5(b) shows the plot of beam radius versus the axial position. It can be monitored that the Gaussian beam is focused and then gradually diverged at the

exit end of the probe. The position with minimal beam radius along the Z-axis is the waist position of the output Gaussian beam. The radius of the waist position is spot size.



(a) Beam intensity width versus axial position



(b) Beam radius versus axial position from the output plane of GRIN fiber probe

Fig. 5 Beam focal performance at different locations along the propagation path

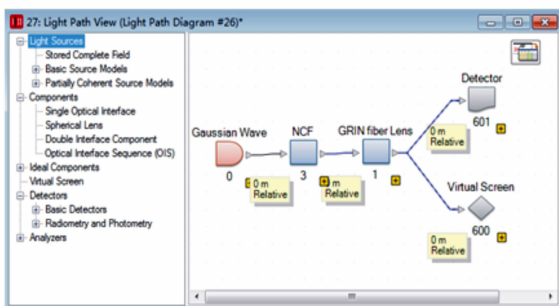


Fig. 4 Light path diagram of GRIN fiber probe

4 Fabrication of GRIN fiber probe

Fabrication of GRIN fiber probe is a very difficult and important task due to its limited size, it needs high-precision manufacturing devices and methods. In order to solve this problem, we have recently developed an all-in-one integration fabrication device of ultra-small GRIN fiber probe as shown in Fig. 6, which is made of fiber welding unit and fiber

cutting unit. The characteristic of this encapsulation device is to achieve the integration of fabrication device of ultra-small GRIN fiber probe. The steps of fiber cutting and fiber welding are operated on the same device during fabricating the ultra-small GRIN fiber probe, which further simplifies the fabrication process and improves the fabrication efficiency of ultra-small fiber probe.



Fig. 6 All-in-one integration device for fiber welding and cutting

This machine can cut and weld bare fibers with high cutting precision about $5\ \mu\text{m}$. The length of NCF and GRIN fiber can also be measured by this

device. And the measurement accuracy is about $1\ \mu\text{m}$. The fabrication process of the GRIN fiber probe is shown in Fig. 7, and the main steps are as follows: (1) Fuse the NCF to the single-mode optical fiber; (2) Cut the NCF to certain length as fiber spacer by taking the fusion point A as the origin between SMF and NCF; (3) Fuse the GRIN fiber lens to the fiber spacer; (4) Cut GRIN fiber to pre-calculated length as the focusing lens by taking the welding joint B as the origin between the fiber spacer and the GRIN fiber lens. Through the above methods, we have fabricated six groups with different sizes of the probe and measured the lengths of probe components with high magnification rate microscopic, as shown in Tab. 1.

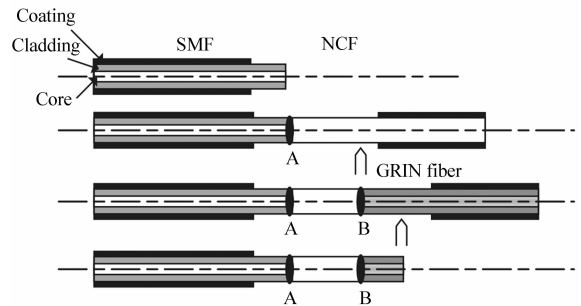


Fig. 7 Process of fabricating a GRIN fiber probe

Tab. 1 Preset length and the measured length of probe components

	Group	NCF length/mm	GRIN fiber lens length/mm
Preset length	1	0	0.360
	2	0	0.410
	3	0.160	0.200
	4	0.240	0.140
	5	0.360	0.110
	6	0.300	0.150
Measured length	1	0	0.356
	2	0	0.407
	3	0.164	0.200
	4	0.242	0.141
	5	0.356	0.108
	6	0.300	0.146

5 Properties detection methods of GRIN fiber probe

The miniaturization of dimension and focusing spot is the main advantage of GRIN fiber probe, however, it is difficult to detect the focusing performance of the probe with high precision and speed by traditional beam detection methods, *i. e.* the mechanical scanning and array detection method, owing to the low efficiency and poor real-time performance in mechanical scanning method^[24-25] and the resolution limited by pixel sizes in array detection method^[26-27]. Based on the characters of focusing performances, this paper describes a non-contact detection method with infinity optical transformation technology as presented in Ref. [28]. The accurate position of the probe is realized through the precise adjustment mechanism. Finally, the focusing performances are obtained by using curving fitting method with measured data captured from the measurement system.

The working distance of GRIN fiber probe generally does not exceed 1 mm, and the focus spot size is about 40 μm . The above characters indicate that the focusing position is too close to the output plane of lens with a micro focus spot. Hence, during the measurement of focusing performances, the output plane of the lens should avoid direct contact with the detector, due to the limitation of dimension and beam parameters of the probe. Fig. 8 presents the

property testing method. The distribution of light intensity at various distances along the direction of propagation after the lens is captured through changing the distance between the lens and the detector along the optical axis. Then, the working distance and the spot size are calculated from the measured intensity distribution.

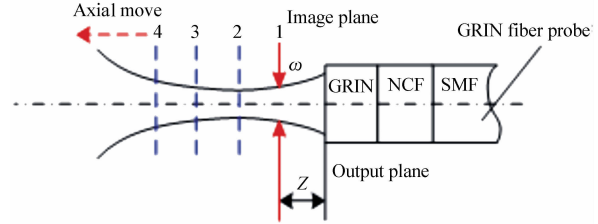


Fig. 8 Schematic diagram of the property testing method for the GRIN fiber probe

In order to achieve the reliable mind about detecting the focusing performance of the micro fiber lens as shown in Fig. 8, an infinity optical transformation system is presented in Fig. 9 based on precise adjustment mechanism. The center of the light from a source through the lens is aligned with the center of the detector by accurately adjusting the lens position. Then, the light is captured with magnification by the infinity optical transformation system in a non-contact mode. The CCD camera converts the optical signals to electrical signals which are then transmitted into a computer. Finally, the computer software analysis the beam information and provides illuminating displays for beam parameters, such as beam width, peak power, and intensity distribution, *etc.*

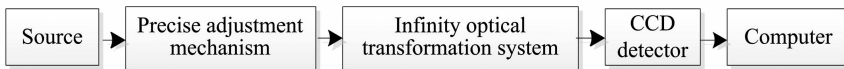


Fig. 9 Schematic diagram of the focusing performance measurement of the GRIN fiber probe

The measurement system corresponding to Fig. 9, can be composed of a Beam Analyzer USB (Duma Optronics Ltd.) with 1.0 μm resolution, a superluminescent diode source (SLD-I310-18, Fiberlabs), a microscopic objective lens (M Plan Apo

NIR 10X, Mitutoyo), and a precise adjusting platform, *etc.* In the process of detection, the small fiber probe is fixed on the adjusting platform. The light source is connected to the lens by single-mode fiber, and the CCD detector will capture the magni-

fied beam under the effect of the optical transformation system for analyzing the beam parameters. Before measuring the beam profile from the lens, we use the precise adjustment mechanism(attached a fiber jig) to adjust the position of the probe and make exit beam vertical to the CCD receiving plane. Finally, in order to collect the beam parameters at various distances along the direction of propagation, the probe moving to change the distance between the probe and the detector by adjusting the platform.

Tab. 2 shows the properties comparison between the testing data and the calculation data using different design methods. It is obvious that, the calculation results of working distance and spot size are almost the same as those experimental data. Therefore, the presented design methods for investigating

GRIN fiber probe are feasible and effective. In terms of the differences between the experimental and calculation results, there could be the following reasons. Firstly, the cutting lengths of NCF and GRIN fiber lens cannot be completely precisely consistent with the pre-calculated lengths, results in errors of beam expanding and focusing between the experimental and calculation data. Secondly, the actual indices of the center of GRIN fiber lens and the NCF as well as the core of SMF are not same, which leads to beam back reflection between different interfaces. However, this phenomenon is not taken into account in the calculation programe. Thirdly, the measurement error of the experimental system is another reason. Moreover, there may be some other factors to be investigated.

Tab. 2 Properties comparison between the testing values and the simulating data

Types	Samples	NCF/mm	GRIN fiber lens/mm	Working distance/mm	Spot size/ μm
Experimental results ^[9-10]	1	0.36	0.10	0.75	31
	2	0.36	0.11	0.60	29
	3	0.36	0.12	0.50	26
Analytical calculation results	1	0.36	0.10	0.75	32.4
	2	0.36	0.11	0.63	23.7
	3	0.36	0.12	0.51	18.4
Numerical calculation results using GLAD	1	0.36	0.10	0.73	33
	2	0.36	0.11	0.64	28
	3	0.36	0.12	0.52	25
Numerical calculation results using Virtual Lab	1	0.36	0.10	0.75	32
	2	0.36	0.11	0.63	24
	3	0.36	0.12	0.51	19

In addition, the coupling efficiency of GRIN fiber 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 Ref. [29-35], 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. Variation and influencing factors were analyzed and verified by establishing the corresponding experiment

system for testing. The detection scheme of coupling efficiency was investigated by the theoretical calculation method of coupling efficiency of the probe, and Fig. 11 shows the actual detection system corresponding to Fig. 10. The output and receiving ends of the probe with fiber clamps are placed on two five-dimensional adjustment platforms and fixed to the optical isolation platform. The output and receiving ends of the probe are connected to the output laser and power receiver respectively. The microscope is used to adjust the relative position of the two fiber probes to ensure that the central axes of the two

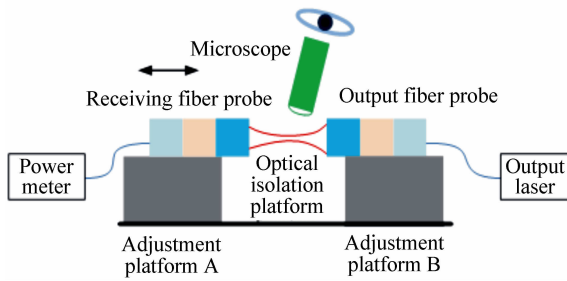


Fig. 10 Detection scheme of the coupling efficiency

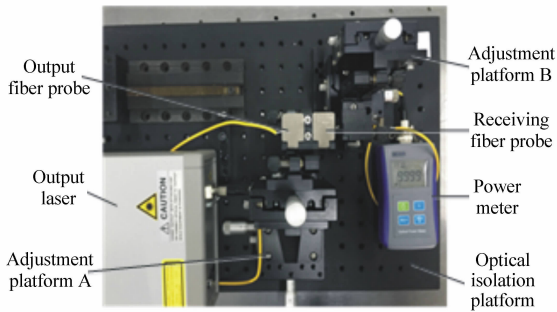


Fig. 11 Detection system of the coupling efficiency

probes overlap with each other. During the experiment, the fixed five-dimensional adjustment platform is used for placing the output end of the probe, and that for placing the receiving end of the probe is used to change the axial distance between the two probes. During the experiment, the adjustment platform for placing the receiving fiber probe is gradually adjusted to only change the axial distance between fibers. The corresponding power value received by the power meter at every position is recorded until the power value drops near zero. After recording all the power values, the coupling efficiency is calculated to analyze the relationship between the coupling efficiency and the axial distance of the probe. It is noted that, the actual coupling efficiency of ultra-small GRIN fiber probe was investigated by introducing the energy loss factor and position error factor and a method was proposed to estimate the energy loss factor based on the simulated annealing algorithm. The result indicates that the ultra-small GRIN fiber probe has a superior focusing performance, and the mechanism of energy loss of the probe itself

should be further explored in the future.

6 Conclusions

Study of the gradient-index lens based small optical probes is an important topic for the miniaturization of OCT systems^[36-40]. GRIN fiber probe is an ultra-small optical probe that may be used for the imaging of small lumen, narrow space in the deep tissues and organs (*e. g.* Cardiovascular) of human beings and small animals. In this paper, some different design methods are described. The calculating data are well agreement with the previously published experimental results and thus demonstrate the effectiveness of the design methods. Therefore, the authors argue that these design methods can be used as a design theory of GRIN fiber probes^[41-46].

From this paper, we give the other conclusions. Different analytical and numerical methods can solve the problem of the design of the GRIN fiber probe, and each one enjoys its own advantages. The analytical design method, by using the expressions of optical characteristics parameters of GRIN fiber probe, can help analyze the function relationships between the focusing properties of the probe and its different influencing factors comprehensively. For example, the three-dimensional graphs of characteristics parameters can be adopted to intuitively judge the influence of different lengths of NCF and GRIN fiber lens on the probe focusing performance. The application of GLAD makes it easy to analyze the propagation performance of the beam at all locations going through the probe directly. The utilization of Virtual-Lab is convenient for probe modeling and parameter setting.

This paper proposed a high precision fiber welding-cutting device with the welding unit and cutting unit. The device is utilized to fabricate several groups of the GRIN fiber probes and measure the lengths of their components with high magnification rate microscope. The result shows that the measured

lengths are similar to the preset lengths, which further verifies the designed device requirements about fabrication of the probe, and it can be used in the researches of miniaturized optical probe and OCT system.

In addition, it is very difficult to detect the focusing performance of the probe with high precision and speed by traditional beam detection methods due to the miniaturization of dimension and focusing spot. Based on the characters of focusing performances, this paper describes a non-contact detection method with infinity optical transformation technolo-

gy. And the detection scheme of coupling efficiency of GRIN fiber probes was described, which reflects the comprehensive focusing performance of probes. As a result, a system of design, fabrication and testing methods is provided for the miniaturization research of optical probes. It is noted that, GRIN fiber probe can be used to many other fields in addition to endoscopic optical coherence tomography. By combining it with other techniques or systems, such as those described in Refs. [30-46], relevant issues can be explored in different applications in the future.

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