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基于GRIN镜头的小型OCT探头的数值分析

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摘要：利用光学软件GLAD的数值仿真技术设计了用于光学相干层析技术成像的基于梯度折射率（GRIN）镜头的小型化探头。首先，简述了梯度折射率镜头的基本特性，讨论了基于梯度折射率镜头的光学探头的设计方法；然后，对由单模光纤、玻璃棒隔片和梯度折射率镜头构成的探头模型进行了仿真。结果显示，利用GLAD的数值仿真技术为小型化探头的设计及其光学性能的验证提供了一种直观而有效的方法。另外，玻璃棒隔片存在一个适当的长度范围，可以改善设计的光学探头的传光性能。在所给仿真条件下，如设定梯度折射率镜头长0.1 mm、玻璃棒隔片长度为0.8～1.1 mm，则探头的工作距离将超过1.0 mm，而聚焦光斑的尺寸<40 μm。

关　键　词：光学相干层析术；小型探头；GRIN镜头；GLAD
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Numerical analysis of GRIN lens based miniature probes for optical coherence tomography

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Abstract: Numerical simulation technology was investigated by using the optical software GLAD to design Gradient Index (GRIN) lens based miniature probes for imaging of Optical Coherence Tomography (OCT). Firstly, the basic features of the GRIN lens were overviewed, and design methods for GRIN lens based optical probes were discussed. Then, the probe model consisting of a single mode fiber, a glass rod spacer and a GRIN lens were simulated. The simulating results show that the numerical simulation technique using GLAD can provide an intuitive and effective method for design of miniaturized probes and verification of their optical performance. In addition, the spacer can improve the optical properties of the GRIN lens based optical probes for there exists a suitable range of the spacer lengths in the glass rod. It shows that the working distance of the probe will be greater than 1.0 mm and the focus spot size less than 40 μm when the constant length of GRIN lens is to be 0.1 mm and the

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spacer length range from 0.8 to 1.1 mm.

Key words: Optical Coherence Tomography (OCT); miniature probe; Gradien Index (GRIN) lens; GLAD

1 Introduction

Optical biomedical imaging techniques, for example, Optical Coherence Tomography (OCT), are becoming increasingly promising imaging tools for both diagnosis and guiding surgery because of its fast imaging speed, high image resolution, non-contact detection, *etc*[1-2]. In an OCT system, the probe is one of the key parts. The quality and optical parameters of the probe will directly determine properties of the OCT system. For example, the focal length and waist diameter of the beam will determine the working distance and transverse resolution of the OCT system, respectively.

In recent years, the Gradient Index (GRIN) lens has been proposed, and then become a key component in miniaturized probes for OCT, since it is easy to assemble for its plane surfaces and good off- and on-axis performance. In 2002, Swanson *et al*. proposed the design of GRIN fibers based miniature optical probes, which could be used for the imaging of narrow space in the deep tissues and organs of human beings and small animals[3]. Reed, Jafri *et al*. demonstrated the usages of such probes[4-6]. However, all of them did not present its performance characteristics in detail. Since 2007, Dr. Mao You-xin studied the fabrication method and performance testing method of an ultra-small fiber probe composed of a Single-mode Fiber (SMF), a No-core Fiber (NCF) and a GRIN fiber. Dr. Mao investigated the focal length and waist diameter using the method of ray matrix transformation of the complex beam parameter[7-8], but it lacked of the analysis of the beam's transmission in the internal probe. As a matter of fact, properties of a probe may not be able to improve effectively with an improper fiber spacer (e. g. no-core-fiber). On one hand, if the spacer length is too short, the working distance can not be effectively increased because of the failure of beam expanding. On the other hand, if the use of the spacer length is too long, some light energy of the optical beam may overflow from the spacer side, which will finally reduce the coupling efficiency and the sensitivity of an OCT system. Therefore, it is necessary to study optical beam profiles at all locations within the probe and the influence of a spacer length on the performance of the probe.

For an ultra-small fiber probe, it is very difficult to detect its internal beam propagation characteristics experimentally. In this paper, we proposed a numerical simulation technique to analysis the optical performance of the GRIN lens probes. GLAD, a physical optics modeling software, was used to solve the intensity distribution of Gaussian beam along the direction of propagation in any section of the probe. Besides, we also studied the influence of the glass rod or spacer on the working distance and transverse resolution of an OCT system. Thus, this article eventually provides an effective method for the design and performance verification of the GRIN lens based miniature probes used in the OCT system.

2 Fundamental theory of GRIN lens

A GRIN lens has many advantages for the design of miniature probes used in OCT compared to a conventional lens. As Fig. 1(a) shown, a conventional lens works in this way: due to big refractive index difference between air and homogeneous lens material, an incoming light ray is first refracted when entering the shaped lens surface, then propagates in a direct way within the homogeneous material, and is refracted again after emerging through the exit surface of the lens. The rays focus on a spot and create an image on condition of a well-defined surface shape of the lens. It is obvious that the fabrication of the conventional lens surfaces requires high precision, which limits the miniaturization of the lenses and raises the costs of production. Unlike conventional lenses, the focusing performance of a GRIN lens depends on a continuous change of the refractive index within the lens material. Plane optical surfaces are employed instead of complicated curved surfaces. The light rays are continuously bent within the lens and finally focused on a spot as shown in Fig. 1(b). As a result, we can fabricate miniaturized lenses cost-effectively and integrate it with other planar optical components easily like optical fibers. The lens parameters, such as focal length and focus spot size, can be adjusted simply by changing the length of the lens.

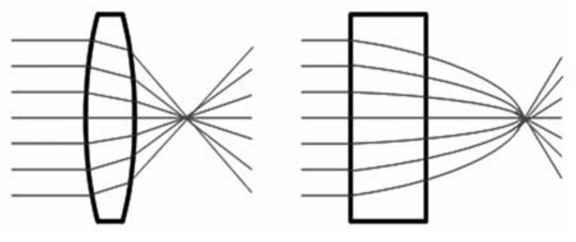

(a) (b)

Fig. 1 Performance comparison between conventional spherical lens (a) and GRIN lens (b)

In the following, some technical details are described about the optical design of GRIN lens based miniaturized probes for the OCT. A radial refractive index profile of nearly parabolic shape, which realizes a continuous cosine ray trace within a GRIN focusing lens, is expressed as:

$$n(r)=n_0\,\mathrm{sech}(gr)\ , \tag{1}$$

Where n_0 represents the refractive index at the center of the profile, r the radius and g the gradient constant.

The period or pitch length P is given by

$$P=2\pi/g\ , \tag{2}$$

Which does not depend on the entrance height and the entrance angle of the light ray (see Fig. 2).

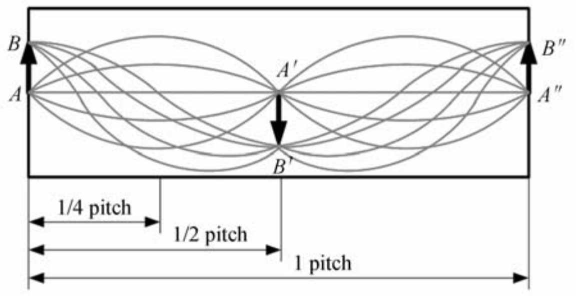


Fig. 2 Ray traces within a GRIN focusing lens with different pitch lengths

Various lens imaging designs can be realized using the same index profile by choosing different lengths of the lens. A 1/4-pitch lens images a point source on the entrance surface of the lens into an infinite or collimated beam. A 1/2-pitch lens images an object on the entrance surface inverted on the exit surface of the lens. A 1-pitch lens images an object on the entrance surface of the lens identically on the exit surface. In order to ensure an optimum imaging quality, the refractive index profile should fit an ideal shape as accurate as possible. For focusing lenses, the ideal shape is described by formula (1). The geometrical gradient constant g characterizes the steepness of the index gradient, and it determines the working distance together with the lens length to some extents.

3 GRIN lens based miniature probes

In OCT imaging, a GRIN lens in the miniaturized probes is used to focus the scanning beam inside the tissue of interest. A simple small probe may just consist of a SMF, a small GRIN lens and a prism. The prism is attached to the front side of the lens to deflect the scanning spot of the rotating probe to the side. The surfaces of the lens and prism can directly touch the medium of interest (i. e., the tissue, water or some other index-matching media) without sacrificing the lens performance. The focus position with respect to the surface of the lens can be adjusted by cutting the lens at different thicknesses along the optical axis. However, due to the exceptional focusing capabilities of GRIN lenses and small Mode Field Diameter (MFD) of the SMF, the focal plane position inside the object medium is typically limited to a few hundred microns. Furthermore, general bio-tissues have a high absorption of light, which results in a small coupling efficiency and a low sensitivity of OCT. One of the effective methods to this problem is the use of a spacer or a glass rod and fuses it between the SMF and the GRIN lens (see Fig. 3). By adjusting the length of the rod, we are able to control the size, divergence and the position of the scanning spot by expanding the optical beam of the SMF.

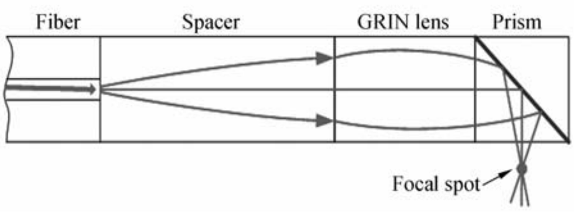


Fig. 3　GRIN lens with a spacer and a prism

From described above, the GRIN Lens can be used to design many kinds of probes together with SMFs, prisms and spacer rods. Because of the high absorptive capacity and high scattering properties of biological tissues and strong focused effect of the GRIN lens as well, the probes have disadvantages on a small working distance and low coupling efficiency. Theoretically, the spacer or rod can improve the probe performance with a longer working distance by means of expanding the optical beam, and it will also reduce the transverse resolution due to the increase of the spot size. Furthermore, if the spacer is too long, there may exist overflowing of some light energy off the rod side that will finally reduce beam coupling efficiency and sensitivity of the OCT system. Therefore, the choice of the spacer length should properly balance the working distance, transverse resolution and the coupling efficiency, *etc*. It should be noted that, in order to ensure minimum back reflection, the indices of the NCF and the center of GRIN lens should match to the core index of the SMF.

4　Numerical analysis of optical probes

For a small, especially ultra-small probe, the measurements of the beam parameters and the beam profile within the probe path are difficult, even impossible to achieved in experiments. In order to overcome the issue, we use the numerical simulation technology by means of the optical modeling software, GLAD, to analyze the beam profile at all locations along the propagation direction in addition to the internal probe, and thus obtain the influence of spacer or other optical components on the probe properties.

4.1　Introduction to GLAD

The software, GLAD, has been developed to model almost any type of laser or physical optical systems, including full diffraction propagation, detailed treatment of laser gain, and many other laser effects. It treats optical beams as complex amplitude distribution and gives a much more powerful capability for analysis on ray tracing programs. The software is able to analyze beam parameters including the effects of diffraction, active media, apertures, lenses and mirrors, and aberration. GLAD has a global coordinate system that allows complex systems to be described. The physical optical description used in GLAD and the way GLAD is organized to provide great generality and flexibility so that a wide diversity of systems may be modeled.

For an optical probe composed of a SMF, a glass spacer and a GRIN lens, a fiber-to-focus GRIN lens coupling system can be modeled in the GLAD. According to formula (1), the index of GRIN lens can be approximately expressed as:

$$n(r) = n_0(1-\frac{g^2}{2}r^2) . \tag{3}$$

By assigning relative parameters of light source and optical components in the GLAD, one can obtain the through-focus behavior of the light beam and thus intuitively understand the optical propagation through the probe.

4.2 Numerical simulation model of the probe

Fig. 4. shows the model of the GRIN lens based probe investigated in this article. The model consists of an optical fiber, a fused silica rod, a GRIN lens, and an air path. Light is output from a single mode fiber with a wavelength $\lambda=1.32$ μm and a Gaussian beam of radius $\omega_0=4.5$ μm into a silica rod with an index $n=1.49$. The GRIN lens is placed at the end of the silica rod, whose index profile is described by formula (3). The refractive index at the center of the GRIN lens is $n_0=1.49$. L_0 and L_1 denote the length of spacer and the length of GRIN lens respectively. The objective is to scan the beam profile at all points along the system path and analyze the impact of the spacer on the optical performance of the GRIN lens.

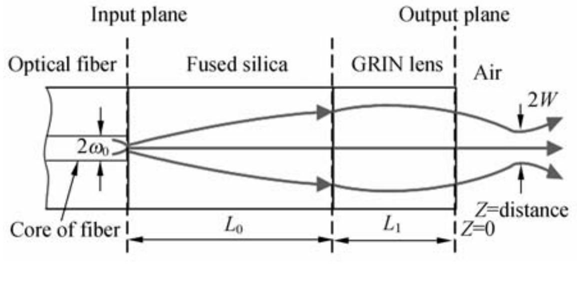
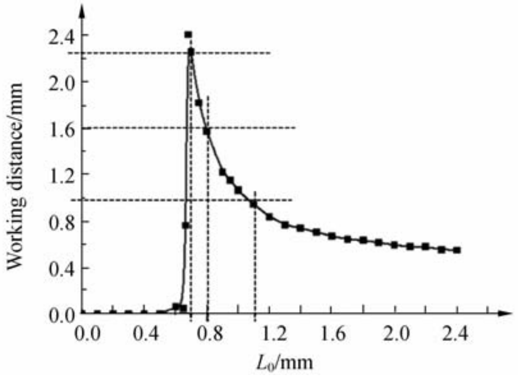


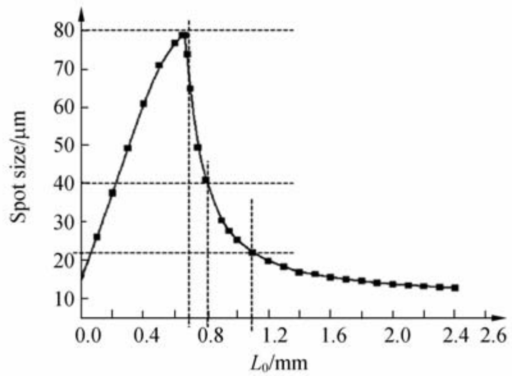
Fig. 4 Schematic diagram of a GRIN lens based probe

4.3 Analysis of simulating results

In order to more comprehensively research the influence of the glass rod on the optical performance of the GRIN lens, we simulate how the focal length and waist size of the beam change with different lengths of the rod on condition of a constant length of GRIN lens $L_1=0.1$ mm (see in Fig. 5). From Fig. 5(a), we can find the relationships between the spacer length and the working distance (or defined as the length from the output plane to the focus point of the optical beam). First of all, the working distance will be less than 0.2 mm when the silica length is less than 0.6 mm. Secondly, the working distance may sharply increase to 2.2 mm when the spacer length is about 0.7 mm. Thirdly, the working distance decreases with the increase of the spacer length when it is greater than 0.7 mm. Correspondingly, Fig. 5(b) demonstrates impact of the spacer length on the spot size (defined as the Full-Width-Half-Maximum of the focus point). When the rod length increases from 0 to 0.7 mm, the spot size will increase from 15 μm to about 80 μm. When the rod length is greater than 0.7 mm, the spot size will decrease with the increase of the rod length.



(a) Working distance *vs.* the length of fused silica

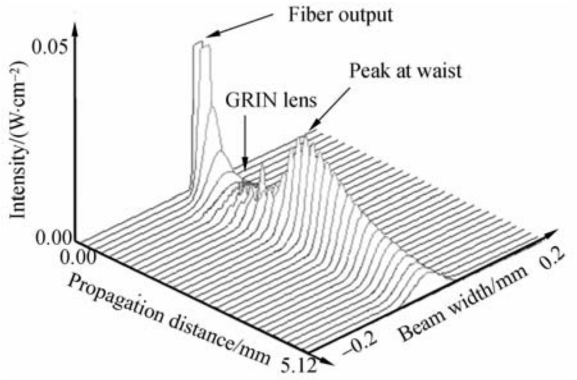


(b) Spot size *vs.* the length of fused silica

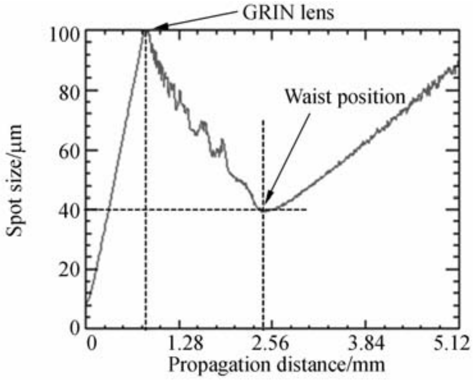
Fig. 5 Influence of glass rod on the optical performance of GRIN lens

In the following, we discuss the way to determine the length of glass rod according to Fig. 5. On one hand, a probe with a working distance less than 0.4 mm has a limited imaging depth for the OCT used in biomedical imaging. Judging from Fig. 5(a), the rod length will locate into the range from 0.7 mm to 1.1 mm if we need a working distance greater than 1.0 mm. And then the spot size will range from 22 μm to 80 μm as shown in Fig. 5(b) correspondingly. On the other hand, the spot size greatly determines the transverse resolution of the OCT system. The transverse resolution decreases with the increase of the spot size. When we design a GRIN lens with spot size less than 40 μm, the use of the rod length should be greater than 0.8 mm according to Fig. 5(b), which means that the corresponding working distance will be less than 1.6 mm. Therefore, to balance the two aspects described above, we may use the rod length within the range of 0.8～1.1 mm, which indicates that the working distance will be greater than 1.0 mm and that the spot size less than 40 μm. Generally speaking, we tend to design an OCT system with working distance as big as possible and the transverse resolution as high as possible. In order to meet the different requirements of the OCT probe, one can obtain useful data to flexibly balance the lens parameters for the optimal lens design by using GLAD simulation tool as shown in Fig. 5(a) and Fig. 5(b).

From analyzed above, an example is taken to show the full profile at the optimized position by setting the length of the fused silica rod $L_0 = 0.8$ mm and the length of GRIN lens $L_1 = 0.1$ mm. GLAD *vs*_5.5 was used to obtain beam profiles at all locations along the direction of light propagation from the output of optical fiber or input plane (see Fig. 6). Fig. 6(a) displays the beam profile as a function of distance from the surface of the optical fiber to a total distance of 5.12 mm. Fig. 6(b) demonstrates the beam width vs. the axial position. From the two figures shown in Fig. 6, we can acquire the best focus position at about 2.47 mm and the minimum waist at about 40 μm. Obviously, the two figures can help us intuitively understand the optical propagation through the system of GRIN lens because they display the beam profiles of all points along the optical path.



(a) Through-focus display of beam profile



(b) Beam width *vs.* axial position

Fig. 6　Characteristics of beam propagation through the probe

5　Conclusions

In recent years, OCTs have been widely investigated in signal analysis, image processing and other aspects of research[9-11], but it lacked of publications about the ultra-small optical probe. Miniaturization of the optical probes used in OCT systems is a key issue, which determines whether the systems could be used to image deep, narrow biological tissues or organs. In this paper, we analyzed the basic features of the

GRIN lens and its application in the design of optical probes. The software GLAD was used to simulate the plots of focal length and waist size with various lengths of the spacer rod. We also simulated the intensity distribution of the Gaussian beam propagating through such a probe with a selected length of the fused silica rod and a selected length of the GRIN lens.

According to this paper, the software GLAD has been demonstrated to be an intuitive and effective tool to design the GRIN lens based miniature probes, and particularly verify their properties of light transmission by simulating profiles of the beam intensity distribution at any section along the direction of propagation, which is very difficult or impossible to achieve experimentally. In addition, we conclude that, there exists a limited length range of the spacer that can improve the optical performance of a small probe for the OCT on condition of a constant length of the GRIN lens. However, the reason why both the working distance and spot size decrease with increasing the length of spacer rod when it is greater than 0. 7 mm as shown in Fig. 5 needs further comprehensive research.

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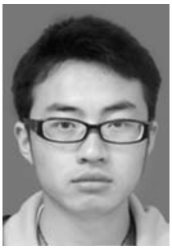

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