Numerical simulation of a gradient-index fibre probe and its properties of light propagation*

Wang Chi(王 驰)[a)†], Mao You-Xin(毛幼馨)[b)], Tang Zhi(唐 智)[a)], Fang Chen(方 臣)[a)], Yu Ying-Jie(于瀛洁)[a)], and Qi Bo(齐 博)[c)]

[a)] *Department of Precision Mechanical Engineering, Shanghai University, Shanghai* 200072, *China*

[b)] *Institute for Microstructural Sciences, National Research Council Canada, Ottawa, Canada*

[c)] *Key laboratory of Specialty Fiber Optics and Optical Access Network, Shanghai University , Shanghai* 200072, *China*

(Received 14 April 2011; revised manuscript received 26 May 2011)

In order to verify the properties of the light propagating through a gradient-index (GRIN) fibre probe for optical coherence tomography (OCT), numerical simulation using the optical software GLAD is carried out. Firstly, the model of the GRIN fibre probe is presented, which is consisted of a single mode fibre (SMF), a no-core fibre (NCF), a GRIN fibre lens and an air path. Then, the software GLAD is adopted to numerically investigate how the lengths of the NCF and the GRIN fibre lens influence the performance of the Gaussian beam focusing through the GRIN fibre probe. The simulation results are well consistent with the experimental ones, showing that the GLAD based numerical simulation technique is an intuitive and effective tool for the verification of the properties of the light propagation. In this paper, we find that on the conditions of a constant GRIN fibre lens length of 0.1 mm and an NCF length of 0.36 mm, the working distance of the probe will be 0.75 mm and the focus spot size is 32 μm.

Keywords: optical coherence tomography, gradient-index fibre probe, gradient-index lens, GLAD

PACS: 42.79.Ry, 42.60.Jf, 42.55.Wd, 02.60.Cb **DOI:** 10.1088/1674-1056/20/11/114218

1. Introduction

The gradient-index (GRIN) fibre probe is a kind of ultra-small optical probe for optical coherence tomography (OCT) imaging,[1,2] which typically consists of a single-mode fibre (SMF), a no-core fibre (NCF) and a GRIN fibre lens. In an OCT system, the GRIN fibre probe transmits and focuses light beams into the sample of interest, then collects the back-reflected light that carries the information about the sample and sends it to the signal processing system. Therefore, the GRIN fibre probe is a key part of the OCT system, whose properties of light transmission play an important role in determing the imaging quality of the OCT system. For example, the focal length and the spot size determine the working distance and the lateral resolution of the OCT imaging, respectively.

The miniaturization of optical imaging probes is a critical topic in the enhancement of the OCT for *in vivo* human and animal studies and has been investigated by some researchers in recent years. In 2002, Swanson *et al.*[3] opened the patent of the GRIN fibre based miniature optics probes. Then Reed *et al.*,[4] Jafri *et al.*,[5] and Li *et al.*[6] demonstrated the usage of such probes for *in vivo* OCT imaging systems. However, none of them presents the design theory of the probes. Since 2007, Mao *et al.*[7,8] have studied the fabrication and the performance testing methods of the GRIN fibre probes. However, they have not obtained the profiles of the beam propagating within the probes.

It is important to investigate the properties of the light transmission within the GRIN fibre probes for the optimal design and the fabrication of the probes. However, it is very difficult or impossible to test the internal beam profiles in the probes experimentally due to the very limited size of the probes. In this paper, we propose a numerical approach to simulating the optical properties of the GRIN fibre probes. The physical optical software, GLAD, is used to simulate the intensity distribution of the Gaussian beam at all locations within the probes, by which the optical performance of the probes is further verified.

*Project supported by the International Cooperation Project of Shanghai Science and Technology Committee, China (Grant No. 09530708700).

†Corresponding author. E-mail: wangchi@shu.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

2. Overview of GRIN fibre probes

Figure 1 displays a typical model of the GRIN fibre probe, which is composed of a single-mode fibre (SMF), a no-core fibre (NCF), a GRIN fibre lens and an air path. The SMF is used to guide the light beam into the NCF. The NCF is a homogeneous glass rod named as the fibre spacer, which can increase the working distance of the probe by expanding the beam from the SMF to solve the problem of the limited mode field diameter (MFD) of the SMF. The length of the NCF should be chosen appropriately. If the NCF is too long, there may exist the overflowing of the light energy off the probe side, which will finally reduce the beam coupling efficiency, consequently reduce the sensitivity of the OCT system. On the other hand, if the NCF is too short, it may result in the failure of expanding the beam and the high fabrication compliance of the probe.

The GRIN fibre lens is a key part of the probe as shown in Fig. 1. It has the ability of self-focusing due to the continuous change of the refractive index within the lens material. It can be easily integrated with other planar optical components (such as the SMF and the NCF) by means of fusing or gluing, which is able to improve the structural strength and the stability of the probe. In the ideal case, the radial refractive index profile of the GRIN fibre lens has a nearly parabolic shape, which can be approximately described as[7−10] $n(r) = n_0(1-g^2r^2/2)$, where n_0 represents the refractive index in the centre of the profile, r is the radius and g is the gradient constant. During the design and the fabrication process of the GRIN fibre probe, the length of the GRIN fibre lens should also be selected properly. Otherwise, it may lead to the failure of focusing or the high fabrication compliance of the probe like the case of the NCF. It should be noted that in order to ensure a minimum back reflection, the indices of the centre of the GRIN lens, the fibre spacer and the core of the SMF should be as close to each other as possible.

For the optical probe shown in Fig. 1, light is output from a single mode fibre with wavelength $\lambda =$ 1.3 μm and enters into the NCF of index $n = 1.49$. The GRIN fibre lens is located at the end of the NCF, whose index profile is described by the above formula. The refractive index in the centre of the GRIN lens is n_0=1.49 and the gradient constant is $g = 5.5$ mm^{-1}. The L and L_1 denote the lengths of the NCF and the GRIN fibre lens, respectively. The outer diameters of the SMF, the NCF and the GRIN fibre lens are all 125 μm and the diameter of the core of the SMF is 50 μm. These parameters are the same as those in Refs. [7] and [8], and thus our simulation results can be compared with the experimental ones in Refs. [7] and [8].

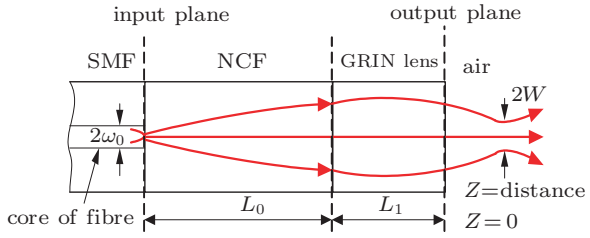


Fig. 1. (colour online) Model of GRIN fibre probe.

3. Numerical simulation of optical performances of GRIN fibre probes

For an ultra-small GRIN fibre probe, it is very difficult or even impossible to test the beam profile within the probe path. The numerical simulation technique is a good tool to cope with such a problem. By using the optical software GLAD, the beam profiles can be analysed at all locations along the propagation direction in addition to within the internal probe and thus the influences of the NCF and the GRIN fibre lens on the probe properties can be investigated. The software GLAD has been developed to model almost all types of laser and physical optics systems including the full diffraction propagation, the detailed treatment of the laser gain, and many other laser effects. It treats optical beams as complex amplitude distributions and gives a much more powerful capability for analysing compared with the ray tracing programs. The software is able to help analyse beam parameters including the diffraction, the active medium, the aperture, the lens and mirror, and the aberration. The physical optics description used in the GLAD and the way the GLAD organized provide great generality and flexibility, so a wide diversity of systems may be modeled.

3.1. Influence of the NCF length on focus property

In order to study the influence of the NCF length on the optical performance of the GRIN fibre probe,

we simulate the changes of the working distance and the spot size of the focusing Gaussian beam with the length of the NCF under the condition of a constant length of the GRIN fibre lens ($L_1 = 0.1$ mm, see Fig. 2). From Fig. 2(a), we can find the relation between the NCF and the working distance, which is defined as the length from the output plane to the focus point of the optical beam. The working distance will be almost zero when the NCF length is less than 0.26 mm. Then the working distance may quickly increase to 0.75 mm when the NCF length increases up to about 0.38 mm. Finally, the working distance decreases with the increase of the NCF length when the NCF length is larger than 0.4 mm. Correspondingly, figure 2(b) demonstrates the effect of the NCF length on the spot size, which is defined as the full width at half maximum of the focus point. When the NCF length increases from 0 mm to 0.3 mm, the spot size will increase from 15 μm to about 43 μm. When the NCF length is larger than 0.3 mm, the spot size will decrease with the increase of the NCF length. As a special and useful case, when the NCF length ranges from 0.32 mm to 0.4 mm, the working distance will be 0.5–0.75 mm, and the corresponding spot size will be 25–38 μm. The optimal design of the GRIN fibre probes can be discussed according to Fig. 2. Generally speaking, we tend to design an OCT system with the working distance as large as possible and the lateral resolution as high as possible. On one hand, the probe has a limited detection depth for OCT imaging when its working distance is less than 0.4 mm. On the other hand, the spot size determines the lateral resolution of the OCT system to a great extent. The lateral resolution decreases with the increase of the spot size. Therefore, in order to meet such different requirements of the OCT probe, the NCF length of 0.32–0.4 mm may be a good tradeoff, which means that the working distance is larger than 0.5 mm and the spot size is less than 38 μm.

3.2. Influence of length of GRIN fibre lens on focus property

In the following, we will analyse the influence of the length of the GRIN fibre lens on the optical performances of the GRIN fibre probe by using the GLAD. In order to compare our simulation results with the experimental ones presented in Refs. [7] and [8], the NCF length is set to be $L_0 = 0.36$ mm. Figure 3 shows the simulation results obtained. According to

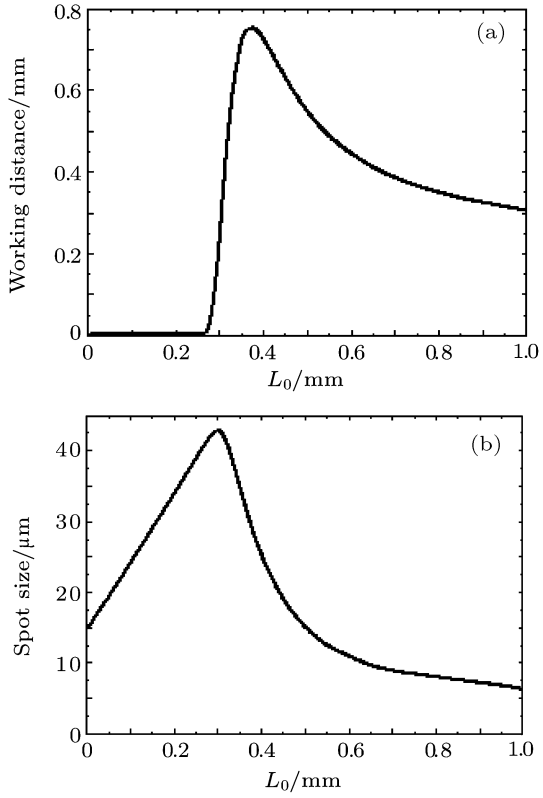


Fig. 2. Focusing performances: (a) working distance and (b) spot size, versus the NCF length.

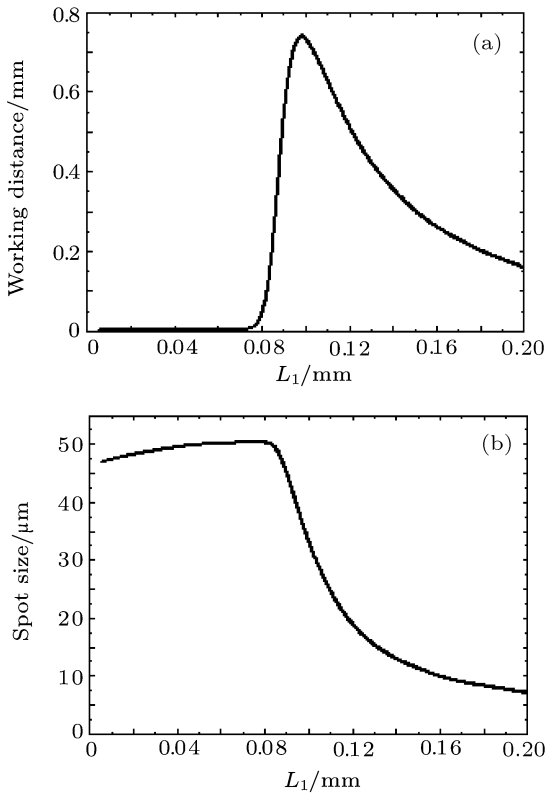


Fig. 3. Focusing performances: (a) working distance and (b) spot size, versus the length of GRIN fibre lens.

Figs. 3(a) and 3(b), when the length of the GRIN fibre lens is less than 0.08 mm, the working distance will be almost zero, and the corresponding spot size will range from 47 μm to 50 μm (close to the MFD of the SMF), which result from the failure of the beam focusing due to the too short length of the lens. When the length of the GRIN fibre lens ranges from 0.08 mm to 0.1 mm, the working distance will sharply increase up to 0.75 mm, which results from both the beam expansion of the NCF and the beam focus of the GRIN fibre lens. When the length of the GRIN fibre lens ranges from 0.1 mm to 0.2 mm, the working distance will decrease gradually from 0.75 mm to 0.15 mm and the spot size will decrease down to 7 μm due to the deepening of the beam focusing with the increase of the length of the lens. As special cases of interest, when the lengths of the lens are 0.09 mm, 0.10 mm, 0.11 mm and 0.12 mm, the working distances are 0.59 mm, 0.73 mm, 0.64 mm and 0.52 mm, and the spot sizes are 45 μm, 33 μm, 28 μm and 25 μm, respectively.

3.3. Comparison of beam property between the simulation and the measured results

Details about the fabrication and the property test of the GRIN fibre probe can be found in Refs. [7] and [8]. Below is a brief overview of the relevant experimental design. In the GRIN fibre probe, a standard Corning SMF-28 single mode fibre is used as the principal light guide. A no-core fibre from the Prime Optical fibre Corporation, Taiwan, China, is adopted as the fibre spacer, which is made of pure silica without a core and has the same cladding diameter as that of the SMF. A GRIN fibre provided by the Optical fibre Solution, New Jersey, USA, is employed as the focusing lens. The NCF is fusion spliced via arc welded to the Corning SMF-28 and then accurately cleaved to the theoretically determined length. The GRIN fibre is then fusion spliced to the cleaved NCF and precisely cleaved at the pre-calculated length.

In order to characterize the beam parameters of the GRIN fibre probes, figure 4 shows a schematic diagram of the property detection system developed in Refs. [7] and [8], which is composed of a beam profile measurement system (BeamView Analyzer, Oregon, USA), an infrared CCD camera (Electrophysics, New Jersey, USA) and a superluminous diode (SLD) source (Covega, Maryland, USA) with 60 nm 3 dB bandwidth at central wavelength of 1310 nm. A 40 JIS (Japanese industrial standard) microscopic objective lens and an associated objective tube are attached to the input window of the camera to increase the image resolution. During the measurement of the working distance and the spot size, the distributions of light intensity at various distances along the direction of propagation behind the lens are first accurately measured by the beam profile system with a horizontal resolution of 1.0 μm and a vertical resolution of 1.1 μm. Then, the working distance and the the spot size are obtained from the measured intensity distributions.



Fig. 4. Schematic diagram of property test system for GRIN fibre probe.

Table 1 shows the comparison between the testing data from Refs. [7] and [8] and the simulating results shown in Fig. 3. It is obvious that the simulation results of both the working distance and the spot size are almost the same as those data obtained experimentally. Therefore, the simulation technique is verified. The difference between the experimental and the simulation results may be caused by the following reasons. Firstly, the cutting lengths of the NCF and the GRIN fibre lens cannot be precisely equal to the pre-calculated ones, which results in errors of the beam expansion of the NCF and the beam focus of the lens. Secondly, the actual indices of the centre of the GRIN fibre lens, the NCF and the core of the SMF are not exactly the same, which leads to the beam back reflection at different interfaces. The phenomenon has not been taken into account in the simulation. Thirdly, the measurement error of the experimental system may be another reason. There may be some other factors causing the difference between the experimental and the simulation results. The relevant issues will be discussed in our further work.

Table 1. Comparison between testing and simulation results.

	Sample	Length of NCF/mm	Length of GRIN fibre lens/mm	Working distance/mm	Spot size /μm
Experimental results[7,8]	1	0.36	0.09	0.63	34
	2	0.36	0.10	0.65	31
	3	0.36	0.11	0.60	28
	4	0.36	0.12	0.50	23
Simulated results	1	0.36	0.09	0.59	45
	2	0.36	0.10	0.73	33
	3	0.36	0.11	0.64	28
	4	0.36	0.12	0.52	25

4. Case study: beam profiles through probe

Here we take a specific design of the GRIN fibre probe for example. The beam profiles of the internal probe are obtained by setting the length of the NCF as $L_0 = 0.36$ mm and the length of the GRIN fibre lens as $L_1 = 0.1$ mm. Figure 5 shows the beam width versus the axial position. From the result shown in Fig. 5, we can acquire that the best focus position is at about 1.21 mm and the minimum waist is about 32 μm. Figure 6 displays the beam profiles along the direction of the light propagation from the input plane of the NCF to 2.56 mm away.

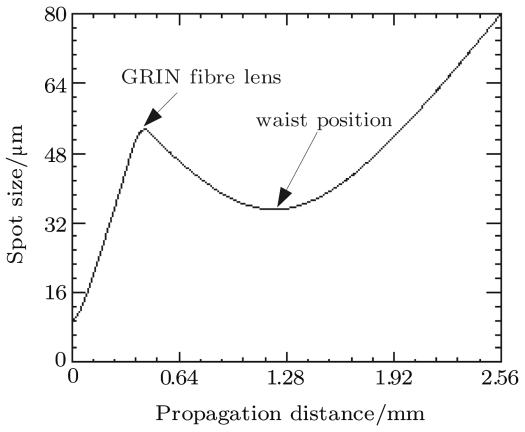


Fig. 5. Beam width versus axial position.

It is obvious that the two figures can help obtain an intuitive understanding of the optical propagation through the GRIN fibre probe, since they display the beam profiles of all points along the optical path. We can easily find that the beam is expanded through the NCF, then focused and thus narrowed down through the GRIN fibre lens.

In order to further evaluate the beam expansion in the NCF and the focus of the GRIN fibre lens, the light intensity distributions at several typical locations are selected from Fig. 6 and displayed in Fig. 7. Figures 7(a)–7(d) show those beam profiles in planes from the SMF to the NCF, from the NCF to the GRIN fibre lens, from the lens to the air and of the focal spot, respectively. The figures show that the peak value of the beam intensity is 1 W/cm^2, which is obtained at the input plane between the SMF and the NCF, then reduces down to 0.04 W/cm^2 at the interface between the NCF and the GRIN fibre lens. It further reduces down to 0.03 W/cm^2 at the output plane from the lens to the air path, and then goes up to 0.075 W/cm^2 in the focal plane. It should be noted that the peak value of the beam intensity, 1 W/cm^2 in the input plane, is the normalized value assigned in the simulation. The beam size goes through the process of widening via the NCF and then narrowing via the lens. Therefore, the figures show the process of beam expansion through the NCF and the process of beam focusing through the lens. Furthermore, they demonstrate that the beam size at any section within the probe is smaller than 125 μm (the outer diameter of the probe used), which means that the design of the probe enjoys the high utilization of light energy.

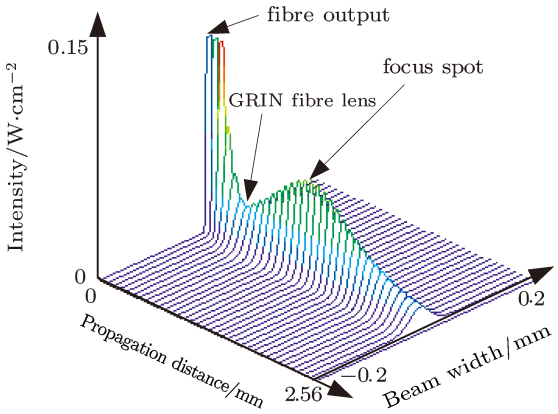


Fig. 6. (colour online) Through-focus display of beam profiles.

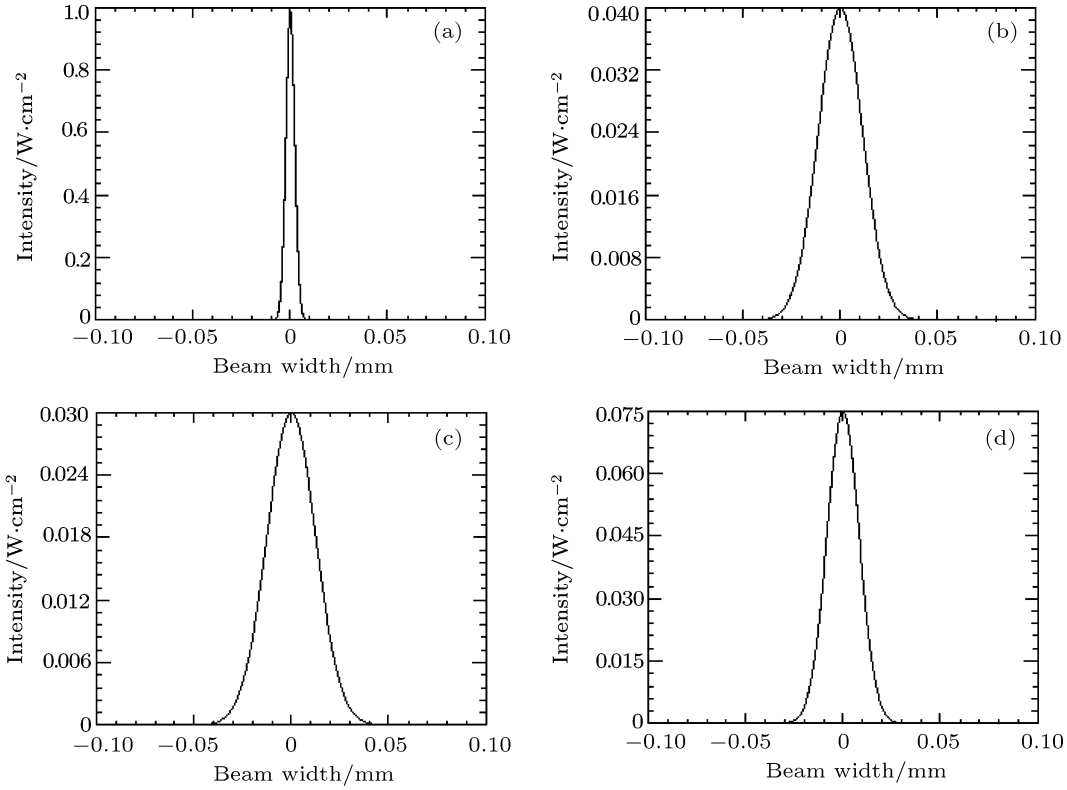


Fig. 7. Beam profiles at typical locations: (a) SMF to NCF, (b) NCF to lens, (c) lens to air, and (d) focus spot.

5. Conclusion

In recent years, there have been a few theoretical articles dealing with the self-focusing performance of the gradient-index material,[11,12] the propagation property of the Gaussian beam,[13,14] the imaging quality enhancement of the optical coherence tomography,[15] etc. In addition, Jung *et al.*[16] reported a numerical analysis of the gradient-index lens based optical probe. In this paper, the model of the GRIN fibre probe is presented. The software GLAD is adopted to simulate the effects of the lengths of the NCF and the GRIN fibre lens on the light propagation property of the probe. The simulation results are well consistent with the experimental ones previously published, which demonstrates the validation of the numerical methods proposed in this paper. In addition, taking a design of the GRIN fibre lens with a NCF length of 0.36 mm and a GRIN fibre lens length of 0.1 mm for example, the beam profiles at all sections within the probe are obtained.

We draw the following conclusions from this study. Firstly, the GRIN fibre probes can be designed with the SMF, the NCF and the GRIN fibre lens, which can be used for the miniaturization of the OCT system. The numerical technique using the GLAD can be used to study the optical performance and the influencing factor of the probe. For example, the focusing property can be simulated with a fixed NCF length and a continuous change of the length of the GRIN fibre lens. Secondly, as an extension of the former conclusion, the numerical software GLAD can evaluate the beam profiles at all locations along the direction of light propagation, which may not be obtained experimentally. Particularly, those profiles at characteristic locations, such as the input plane, the interface between different optical components and the focus plane, can help analyse intuitively the degree of beam expansion via the NCF and the degree of beam focus through the GRIN fibre lens. Therefore, the numerical software GLAD is an effective tool for optimizing the design of the GRIN fibre probes.

The content of this paper is at the initial stage of the investigation of the GRIN fibre probe and its optical characteristic, there remain a few issues to be further studied. Taking Fig. 2 for example, the reason why the working distance is almost 0 when the NCF length is less than 0.26 mm and then quickly increases to 0.75 mm when the NCF length increases up to about 0.38 mm needs further study. According

to Ref. [16], the spacer (i.e. the NCF) is very sensitive to even a short length variation since it may change the parameter of the incident beam entering the GRIN lens. In addition, experimental studies on the fabrication and the property of the GRIN fibre probe also need further exploring. For example, we may be able to reduce the errors of the measurements of the working distance and the spot size through the further studying.

Acknowledgement

Wang Chi gratefully thanks the InfoTek Information Science & Technology Co,. Inc. for providing the dongle or key for the GLAD, and the GLAD technical support for their help with the simulation programs.

References

[1] Huang D, Swanson E A and Lin C P 1991 *Science* **254** 1178

[2] Yang Y L, Ding Z H and Meng J 2008 *Acta Opt. Sin.* **28** 955 (in Chinese)

[3] Swanson E, Petersen C L and McNamara E (U.S. Patent) 6 445 [2002-09-03]

[4] Reed W A, Yan M F and Schnitzer M J 2002 *Opt. Lett.* **27** 1794

[5] Jafri M S, Farhang S and Tang R S 2005 *J. Biomed. Opt.* **10** 051603

[6] Li H, Standish B A and Mariampillai A 2006 *Lasers Surgery Med.* **38** 754

[7] Mao Y X, Chang S D and Sherif S 2007 *Appl. Opt.* **46** 5887

[8] Mao Y X, Chang S D and Flueraru C 2010 *J. Biomed. Sci. Eng.* **3** 27

[9] Kogelnik H W and Li T 1966 *Appl. Opt.* **5** 1550

[10] Emkey W L and Jack C A 1987 *J. Lightwave Technol.* **LT-5** 1156

[11] Li H M 2008 *Chin. Phys.* B **17** 759

[12] Liu A J, Qu H W and Chen W J 2011 *Chin. Phys.* B **20** 024204

[13] Li J L and Lv B D 2008 *Acta Phys. Sin.* **57** 1656 (in Chinese)

[14] Lu S Z, You K M and Chen L Z 2011 *Chin. Phys.* B **20** 034202

[15] Wang K, Zeng Y And Ding Z H 2010 *Acta Phy. Sin.* **59** 2472 (in Chinese)

[16] Jung W, Benalcazar W and Ahmad A 2010 *J. Biomed. Opt.* **15** 066027