

Design of a long working distance graded index fiber lens with a low NA for fiber-optic probe in OCT application

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ABSTRACT

A fiber-optic probe for optical coherence tomography (OCT) applications is typically includes a short section of graded index (GRIN) fiber fused onto a single-mode (SM) fiber. The GRIN fiber acts as a lens to focus the output of the SM fiber and to collect the reflected light from the sample. In this paper we will use the beam propagation method (BPM) to analyze the output beam characteristics such as beam radius and working distance, and then compare these with the measured results. With this tool we can design a GRIN fiber lens to achieve a long working distance without degrading the system performance.

Keywords: Graded index fiber, BPM, OCT, GRIN

1. INTRODUCTION

Optical coherence tomography (OCT) is an imaging technique that uses low-coherence interferometry to perform 2-D or 3-D cross-sectional imaging [1,2]. It can produce high resolution cross-sectional images of the microstructure of living tissue [1], and has been widely used in many medical areas like ophthalmology, dermatology and cardiology etc. for diagnostic imaging and imaging assistant surgeries.

To image deep within the body, fiber-optic probes can be used as the beam delivery system [3, 4]. A fiber-optic probe can be inserted directly or through endoscopes into the body's natural channels (e.g., airway, gastro-intestinal tract) and blood vessels to reach the area of interest. A fiber-optic probe can also be put inside a hypodermic needle and inserted through the tissue until it reaches the area to be imaged. The fiber-optic probes typically contain a section of SM optical fiber and **optical element** at the end of the fiber tip. The beam exit from the end face of a SM fiber has a small mode field diameter (MFD) and a short depth of focus (DOF). For example the MFD is $\sim 9.6 \mu\text{m}$ at 1300nm and the DOF is about 120um. Thus additional optical element is attached to the end of the SM fiber to generate the desired beam characteristics such as working distance, beam size and DOF etc. The **optical element** can contain ball lens, graded index (GRIN) rod lens or GRIN fiber lens.

In addition to being a fiber based device, a GRIN fiber lens offers many advantages over a ball lens or GRIN rod lens. First, the graded index (GI) multimode fiber used for a GRIN fiber lens typically has the same diameter and similar materials composition as the SM fiber. Therefore, when the two fibers are fusion spliced together using the standard fusion splicing technology developed for telecommunications applications, the back reflection is minimized and the optical insertion loss is low. Secondly, since the fibers are fusion-spliced together, the joint typically exhibits high mechanical strength. The most important advantage of a GRIN fiber lens is, perhaps the design flexibility of its optical properties, such as index profile, numerical aperture (NA) and core diameter. With the degrees of freedom offered by a GRIN fiber lens, various designs of the fiber optic microprobe optimized for different specific OCT applications can be achieved.

However, the prevalent approach to design a GRIN fiber-optic probe has been to use a GRIN fiber lens based on the GI multimode fibers that are commercially readily available. **Since they were designed for telecommunications applications, using these fibers for GRIN fiber lens imposes some technical limitations for achieving optimized GRIN lens designs for an OCT fiber-optic probe.** For example, the typical NA values available from the off-the-shelf telecommunication GI fibers are 0.2, 0.275 and 0.29. With these GI fibers the longest working distance is $\sim 1\text{mm}$ in air which may only be long enough for some end users of the probe. In order to achieve longer working distance-and other requirements- one approach is to add a section of coreless fiber between the SM and MM fibers. One way to simplify

this approach is to design a GRIN fiber with the appropriate NA for the application. The ray matrix method is typically used to simulate the propagation of light for a GRIN lens. However, the method may not be suitable for predicting the performance of the GRIN fiber lens with a lower NA; this is because that a larger percentage of light will propagate in the clad region of the GRIN fiber lens, violating the assumption of an infinite medium. In this paper we will use both the ray matrix method and the BPM to simulate beam propagation in several GRIN fiber lenses. From this we determined an optimal design for a GRIN fiber lens to reach a longer working distance without seriously degrading the system performance. Then based on the result of simulation, we manufactured a GI fiber with NA of 0.13, core size of 100 μm and clad diameter of 125 μm and fabricated a fiber-optic probe to validate the model. We present the comparison of the simulated predictions with the measured results.

2. BEAM PROPAGATION ANALYSIS BY RAY MATRIX AND BPM SIMULATION

A schematic of a typical GRIN fiber-optic probe is shown in Figure 1(a). The probe is made from a SM fiber with a GRIN fiber lens spliced at the end. The GRIN lens focuses the output from the SM fiber to the desired location and size. The lens can also collect the back-reflected light from the sample and couple it back into the SM fiber. As shown in Figure 1(a), the working distance is defined as the distance between the fiber end face and the location of the beam at which the radius of the beam is the smallest. A coreless fiber can also be spliced between the SM fiber and GRIN fiber as shown in Figure 1(b) to achieve a longer working distance. However this configuration involves more steps of cleaving and splicing and can result in a more complex manufacturing process and thus higher probe cost. Using a coreless fiber also requires tight length control of both the coreless fiber and the GRIN fiber lens in order to achieve the desired working distance and beam diameter. So using a single GRIN fiber lens is preferred to achieve a longer working distance.

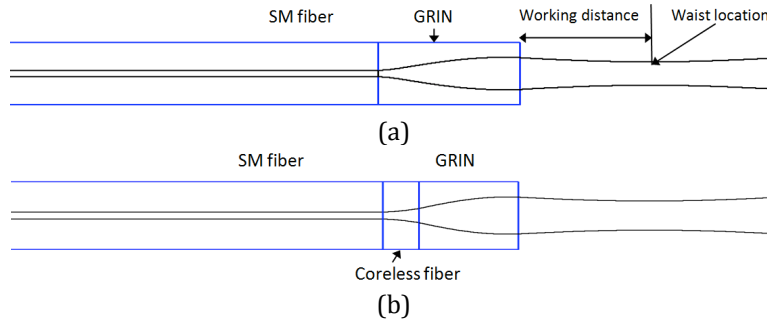


Figure 1 Optical fiber probes (a) with a section of GRIN fiber lens spliced to the end of a SM fiber, and (b) with a section of GRIN fiber lens and a short piece of coreless fiber spliced to the end of a SM fiber

The beam propagation through the GRIN lens can be calculated by using the paraxial ray matrix method [3,4], if we assume the output of the SM fiber is a Gaussian beam and the GRIN fiber has a quadratic index distribution:

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

where r is radial distance from the center, n_0 is refractive index at the center of the GRIN fiber, and g is the gradient. The g is related to the measured fiber NA and the core size a by:

$$g = \frac{NA}{a \cdot n_0} \quad (2)$$

From ref [3], we can derive the maximum working distance for a given GRIN lens with gradient g attached to a SM fiber with a mode field diameter (MFD) of $2\omega_0$ to be:

$$d_{\max} = \frac{\pi n_m}{2\lambda} \left(\left(\frac{\lambda}{\pi g \omega_0} \right)^2 - \omega_0^2 \right) \quad (3)$$

where n_m is refractive index of the medium that the beam enters into, λ is the wavelength and n is the refractive index of the SM fiber. From equation (3), we can see that to achieve a longer d_{max} , we could use a GRIN lens with a smaller gradient for a given SM fiber having a MFD of $2\omega_0$. If the diameter of the GRIN fiber lens is limited by that of the SM fiber, we will need to lower the NA of the GRIN fiber to achieve a smaller gradient as can be seen in equation (2). With a lower NA, a greater portion of light will propagate outside the GI core region. In this case, the paraxial ray method will not be adequate to simulate the beam propagation. Under this non-ideal situation, numerical modeling methods are required. The BPM [5] is an effective numerical method to simulate the wave propagation in inhomogeneous media. It can be applied to media with arbitrary cross-sections, as long as the refractive index variation in the axial direction is small. Thus it is ideal for simulating the propagation in a GRIN fiber lens. Several papers have reported using BPM to simulate the GRIN lens [6, 7]. In our simulation we use split step fast Fourier transform BPM (FFT-BPM), in which the electromagnetic field is calculated at a fixed spacing dz along the propagation direction z .

To show the differences of the results calculated by the BPM and the ray matrix method, we simulated beam properties with three types of GRIN fiber lens as shown in Table-1. The GRIN fiber length in our simulation is set to achieve the maximum working distance in equation (3). The working distance simulated by the BPM is also shown in Table-1.

Table 1 Properties of the GRIN fiber lenses used in our simulation and the calculated working distances

| | GRIN-1 | GRIN-2 | GRIN-3 |
|---|--------|--------|--------|
| Fiber NA | 0.2 | 0.12 | 0.13 |
| Core diameter (μm) | 110 | 100 | 100 |
| Calculate gradient ($/\mu\text{m}$) | 0.0025 | 0.0017 | 0.0018 |
| GRIN fiber length (μm) | 710 | 1029 | 956 |
| Calculated working distance in air | | | |
| Calculated by ray matrix method (μm) | 649 | 1526 | 1296 |
| Simulated by BPM (μm) | 650 | 1123 | 1098 |

In the calculations, the operating wavelength is $1.55 \mu\text{m}$, the MFD from the SM fiber is $10.5 \mu\text{m}$ at $1.55 \mu\text{m}$ and the light exiting from the GRIN lens enters into the air. In our FFT-BPM simulation, the spacing dz in the propagation direction is $1 \mu\text{m}$. The beam radius is calculated by fitting the simulated field amplitude at each location to a Gaussian distribution by using a least squares fitting.

As shown in Figure 2, we plotted the beam radius along the propagation direction z simulated by the BPM and calculated by the ray matrix method. The NA of GRIN-1 is 0.20 and the simulated beam radii along the transmitting distance z by using the two methods are almost the same. The field amplitude distribution after the beam exits the GRIN lens end face is also plotted in the insert of Figure. 2. It has a smooth distribution, as expected from the Gaussian beam propagation.

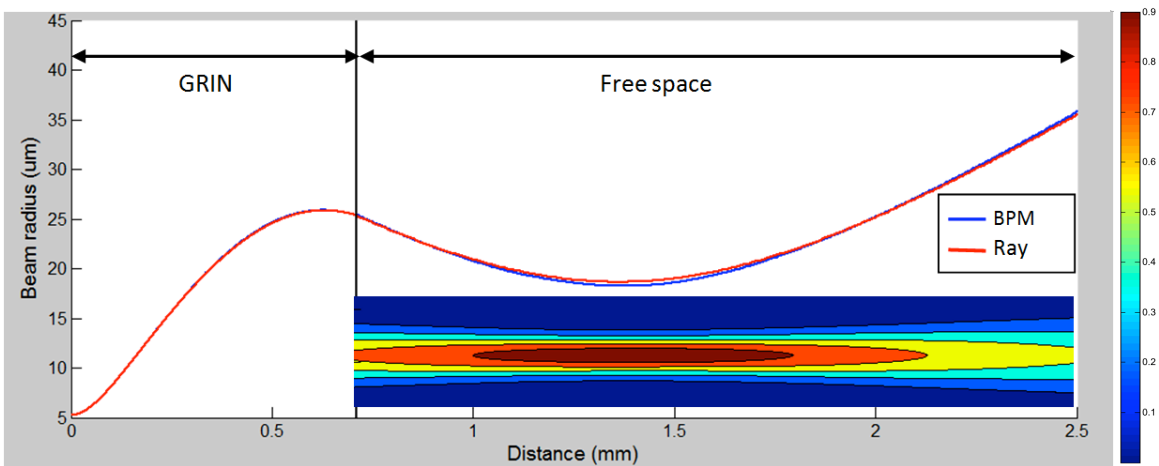


Figure 2 Beam radius simulated by the FFT-BPM and calculated by the ray matrix method with GRIN-1. The field amplitude distribution exiting the fiber simulated by BPM is also shown.

Next, GRIN-2 with an NA of 0.12 was simulated. We can see from Figure 3(a) that, the beam radiuses are the same by both methods before the beam diameter reaches its maximum inside the GRIN lens. The maximum beam radius in the GRIN lens is 39.2 μm . The percentage of power outside the GI core can be calculated by $P = \exp(-2a^2 / \omega^2)$; here a is the GI core radius and ω the beam radius. At 39.2 μm about 3.7% of the beam energy is outside the 100 μm diameter GI core. The beam radiuses simulated by the two methods after the light exits the GRIN lens are different: the beam waist radius is 26.6 μm and is located 1123 μm from the end face of the GRIN lens using the BPM, while by the ray matrix method the beam waist is 28 μm and the location is 1526 μm . The depth of focus (DOF) is also smaller by the BPM than by the ray matrix method. The DOF can be defined as the distance between the points where the beam radiuses become $\sqrt{2}\omega_0$, where ω_0 is the beam radius at beam waist. The insert in Figure 3 also shows the simulated beam field distribution after the beam exits from the GRIN lens, and it displays a couple additional peaks. The field amplitude distribution vs. radial distance at a location of 200 μm from the end face of the GRIN lens is also plotted in Figure. 3(b) with Gaussian fit. We can see that the simulated field amplitude distribution deviates from a Gaussian distribution. This shows that the ray matrix method can't accurately model the beam propagation through a lower NA GRIN lens with limited size.

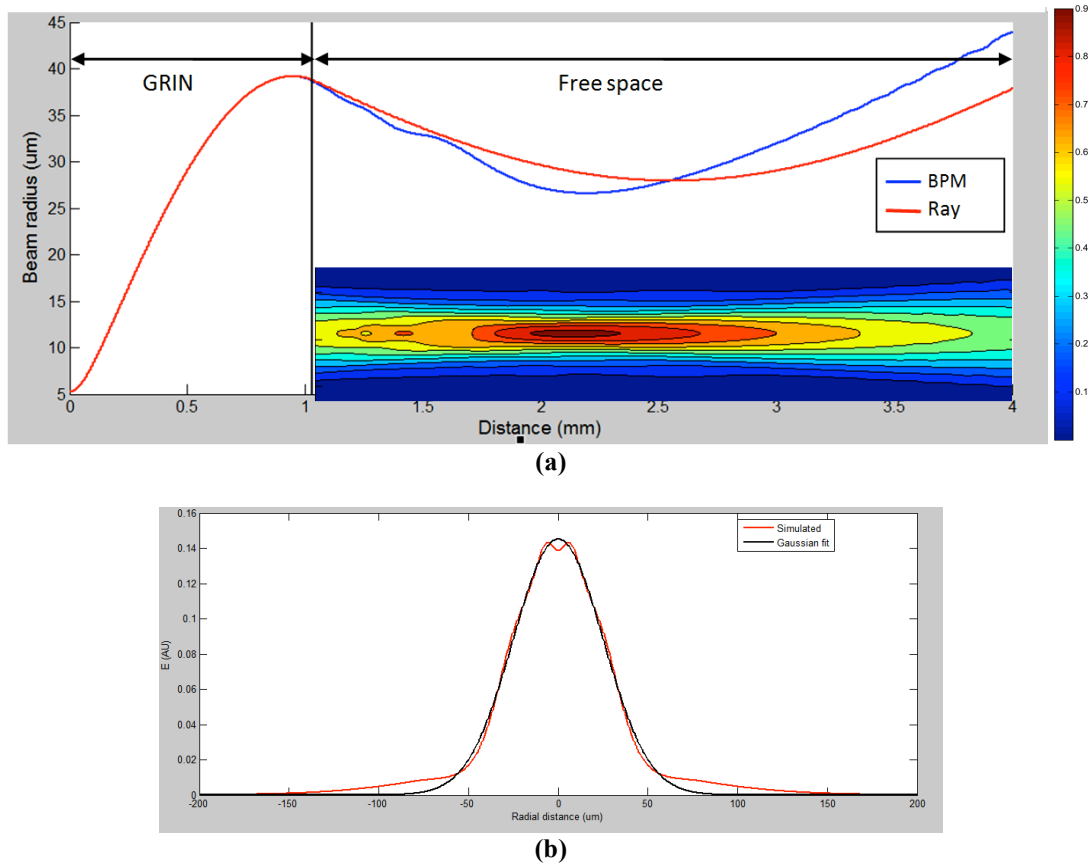


Figure 3 Beam radius simulated by the FFT-BPM and calculated by the ray matrix method for GRIN-2. The field amplitude distribution simulated by BPM is also shown. **(b)** The field amplitude distribution at distance $z = 0.2$ mm after the beam exits from the GRIN lens end face.

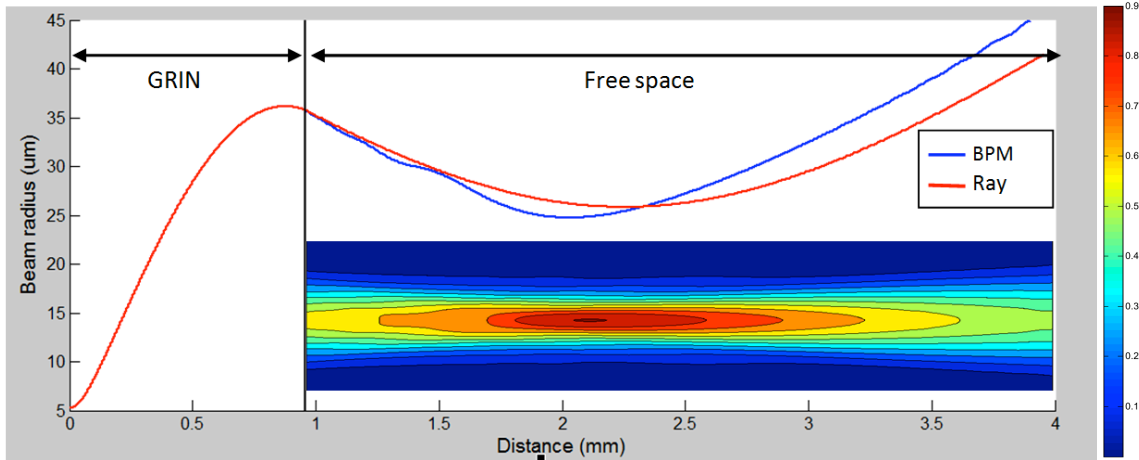


Figure 4 Beam radius simulated by the FFT-BPM and calculated by the ray matrix method with GRIN-3. The field amplitude distribution by BPM is also shown.

Lastly, GRIN-3 with an NA of 0.13 is simulated and results are shown in Figure 4. Similar to GRIN-2, the beam radii are the same by both methods before the beam diameter reaches its maximum inside the GRIN lens. The maximum beam radius in the GRIN lens is $36.1 \mu\text{m}$, and about 2.1% of the beam energy is outside the $100 \mu\text{m}$ GI core. The beam radii simulated by the two methods after the light exits the GRIN lens are different: the beam waist is $24.8 \mu\text{m}$ and is located $1098 \mu\text{m}$ from the end face of the GRIN lens by using the BPM, while by the ray matrix method the beam waist is $25.8 \mu\text{m}$ and its location is $1296 \mu\text{m}$ from the GRIN fiber lens end face. The insert in Figure-4 also shows the simulated beam field distribution after the beam exits from the GRIN lens, and it is smoother than that with GRIN-2.

3. EXPERIMENT

A GRIN fiber was manufactured by drawing a germanium (Ge)-doped silica preform. The preform was fabricated by modified chemical-vapor deposition (MCVD), in which layers of Ge-doped SiO_2 are deposited inside a cylindrical pure silica glass tube. By controlling the amount of Ge in the composition, the refractive indices can be finely controlled. The properties of the resultant fiber are shown in Table-2, and the measured the index profile is shown in Figure 5. The profile doesn't display significant central index depression and fits well to an ideal quadratic distribution.

Table 2. Properties of the GRIN fiber made

| Properties | Measured value |
|---------------------------------------|----------------|
| Fiber NA | 0.125 |
| Core diameter (μm) | 99.5 |
| Calculate gradient ($/\mu\text{m}$) | 0.00165 |
| GRIN fiber length (μm) | 1010 |

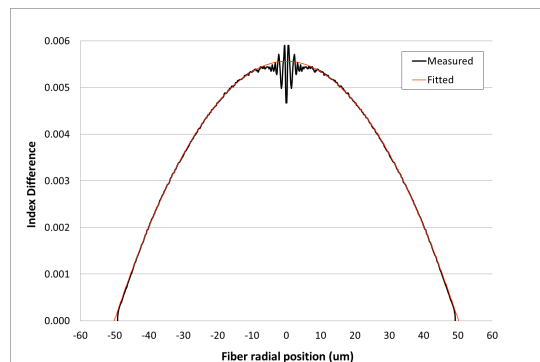


Figure 5. Measured index of profile of the GRIN fiber

A GRIN fiber-optic probe was made with GRIN fiber length of 1010 μm spliced to a SM optical fiber with a MFD of 10.5 μm at 1.55 μm and 9.6 μm at 1.31 μm . The 1010 μm length is slightly longer than the 1000 μm length to have the maximum working distance.

The beam radius at 1310 nm was measured by a beam profiler (Nanoscan from Ophir Optronics Solutions Ltd.) with a spacing of 0.25 mm along the propagation distance. The light source had a center wavelength of 1.310 μm and full width at half maximum (FWHM) bandwidth of 60 nm. For comparison, the beam radius simulated at 1.31 μm by the BPM using the actual GRIN parameters is shown in Figure 6. The closest distance from the end face of the GRIN fiber lens at which the profiler can measure the beam profile is ~ 0.5 mm. We can see that the measured beam radius values closely matched the simulated ones.

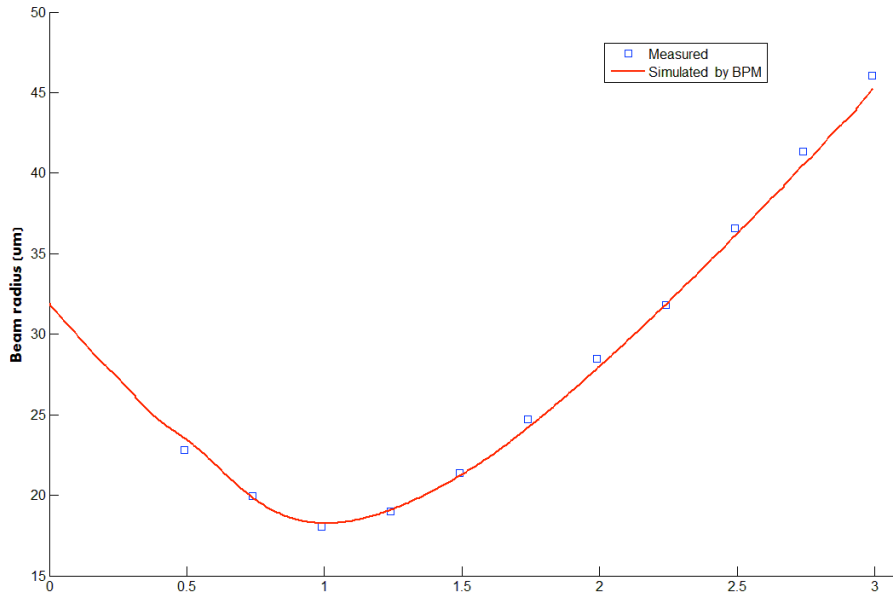


Figure 7. Beam radius vs. propagation distance by measurement and simulated by the BPM

4. CONCLUSION

To model the beam properties of a low NA GRIN fiber lens, the BPM is a more effective and accurate tool than the ray matrix method. From the BPM simulation, if the NA of a GRIN lens is too low, the output beam will no longer be Gaussian and will have many ripples in the intensity distribution that could degrade imaging quality. An optimal NA of 0.13 was chosen in our experiment and an illustrative GRIN fiber was manufactured. The experimental results agree well with our simulation. With the BPM simulation and the flexibility of MCVD manufacturing, improved GRIN optical-fiber probes with longer working distances can be achieved with a low NA GRIN fiber lens. Such GRIN lens optical-fiber probes can provide beam properties—without a coreless fiber component—by customizing the necessary GI fiber preform and the GRIN lens itself.

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