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미세 내시경용 고 분해능 영상가이드의 성능 평가

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Evaluation of Image Quality in Super-resolution Image Guide for Ultrathin Endoscope

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요 약 : 현재 의료용으로 사용되고 있는 광섬유를 이용한 내시경은 굴절률이 다른 두 가지 유리로써(Step Index SI) 제작되고 있다. 이와 같은 내시경은 취급에 주의하여야 하는 근본적인 재료상의 문제점 외에도 영상 가이드의 최고 분해능이 5μm으로 제약되고 있는 실정이다. 본 연구에서는 플라스틱을 이용하여 고 영상 분해능(7μm ~ 2.5μm)을 가진 미세 내시경(Ultrathin Endoscope)용 영상 가이드의 분해능을 측정하였다. 그 각각의 플라스틱 광섬유 굴절률은 광섬유 중심으로부터 외곽까지 점차 감소하는 특성 (Graded Index, GRIN)을 가지고 있다. 플라스틱 GRIN 영상가이드의 분해능 측정 결과, 마이크로 광섬유의 지름이 작아질수록 그 분해능이 증가되었고, 유리를 이용한 SI 영상 가이드 분해능과의 비교 연구 결과, 2배의 분해능을 가진 (2.5μm) 플라스틱 GRIN 영상가이드 제작이 가능함을 보였다. 이와 같은 플라스틱 GRIN 광섬유 다발은 의료분야뿐 아니라 국방 및 산업분야의 새로운 광학적 설계에 많은 영향을 줄 것으로 기대된다.

Abstract : In general, fiber-optic medical endoscopes are made from glass step index (SI) fibers. These endoscopes have limitations in both image quality and mechanical properties. In particular, the image resolution of the SI endoscopes is limited to about 5 μm. In this study, the image resolution of plastic graded index (GRIN) super-resolution image guides with pixel sizes from 7 to 2.5 μm were measured and compared with those of glass SI image guides. There is an improvement in resolution of the plastic GRIN image guides as the microfiber diameter is reduced from 7 μm to 2.5 μm. The measured resolution of plastic GRIN image guide with 2.5 μm microfibers is more than a factor of two higher than that of glass SI image guide with 5 μm microfibers. This new design of optical systems could have a major impact on a wide array of future optical systems used in defense, industrial, and medical applications.

Key words : Endoscope, Super-resolution, Graded index, Plastic image guide

INTRODUCTION

Ultrathin endoscopes include needlescopes, ophthalmic endoscopes and angioscopes. In the 1980s, ultrathin image fiberscopes were fabricated and the diameter of an endoscope was reduced to less than 1mm. These kinds of ultrathin endoscopes are used in minimally invasive procedures to examine small parts of internal organs. The ultrathin needlescopes have 2000 to 6000 pixels and their outer diameters are about 0.2mm to 0.5mm. Attempts have been made to insert the ultrathin needlescopes into the mammary glands and to detect breast cancer at an early stage [1]. In general, this kind of needlescope makes it possible to obtain real-time images of inaccessible locations within the human body [2]. Also, the ophthalmic endoscopes allow direct viewing of certain internal stru-

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ctures of the eye such as the backside of the iris and the posterior chamber [3]. Ultrathin fiberscopes used in cardiology are angioscopes which can detect atheromatous plaque rupture and splitting, endothelial exfoliation and thin mural thrombi that could not be detected by angiography [4].

These ultrathin endoscopes are made from glass step index (SI) fibers which have limitations such as poor flexibility, difficulty in processing and high cost. In particular, the image resolution of SI image guide is also limited to about 5μm [5]. A step index (SI) optical fiber is one in which a fiber is composed of a core material surrounded by a cladding material where the refractive indices are n_1 and $n_2(n_1 > n_2)$, respectively. Light at greater than the critical angle, which is transmitted down the core material suffers total internal reflection with almost 100% efficiency at the core/cladding interface. Although the light reflects efficiently at the boundary, a small fraction of the light enters the cladding before reentering the core. If the cladding is not quite thick enough, some light may leak through the cladding into the adjacent fiber. This causes a reduction in both resolution, and contrast sensitivity. If the core diameter is reduced, at fixed cladding thickness, less light is transmitted and the image loses brightness. Hence, there is an optimum fiber core diameter, and cladding thickness for a given microfiber size. This optimization process has been studied [5]. The result is that maximum resolution is achieved with a core diameter equals 3μm, and radial cladding thickness of 1μm, i.e. the diameter of microfiber is 5μm.

In GRIN image guides, the light travels in a curved trajectory, always being refracted back towards the axis of the each single fiber. At angles greater than the critical angle, light never reaches the outer edge of the fiber. At angles less than the critical angle, the light enters the adjacent fiber, traverses the guide, and is absorbed on the periphery of the guide as in the case of the SI image guide. Especially, it is possible for GRIN image guide to improve image resolution with reducing core size to physical limit because there is no cladding on GRIN fibers as shown in Figure 1.

The structures of the two basic types of optical fiber, i.e. SI and GRIN fiber are shown in Figure 1. Also, the trajectories of typical light rays in SI and GRIN fiber and image guides, respectively are shown in Figure 2.

In this study, the image resolutions of plastic GRIN super-resolution image guides with pixel sizes from 7 μm to 2.5 μm were measured and compared with those of glass SI image guides.

CHARACTERIZATION OF IMAGE RESOLUTION

There are many parameters which can have an effect on the image quality in fiber-optic imaging system. These parameters can be divided into three main categories [6]. The first category includes the structural parameters such as fiber diameter, fiber spacing between core center to center, the irregurity of fiber shape, imperfections and fiber length. The second category is referred to the material parameters such as numerical aperture of the fiber and attenuation coefficient. The last category includes system parameters such as the numerical aperture of the light source and its wavelength.

Although all these parameters are important to characterize the image quality of the fiber-optic system, it is difficult to characterize all these parameters separately. Therefore, there are a few methods to assess the overall image quality of the fiber-optic imaging system. As a typical method, the modulation transfer function (MTF) is used to characterize the image resolution and contrast.

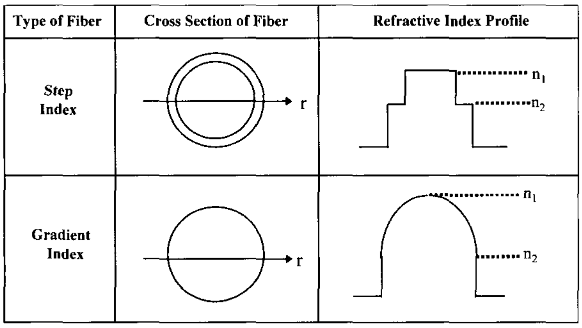


Fig. 1. The structures of the two basic types of optical fiber

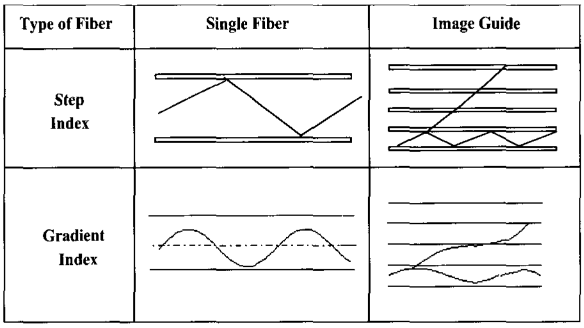
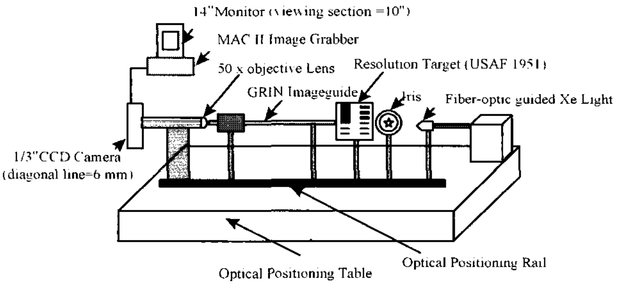


Fig. 2. The trajectories of typical light rays in SI and GRIN fiber



Magnification = microscope object lens x (monitor / CCD camera)
=50 x (10 x 2.54) / 0.6 = 2116.7

Fig. 3. Edge response function measurement setup

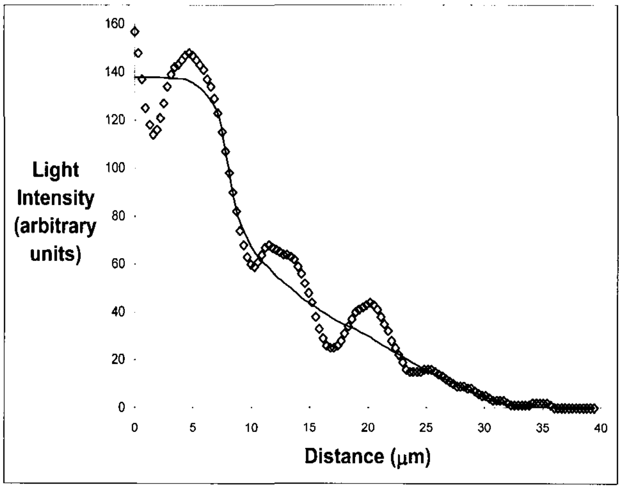


Fig. 5. The measured edge response function of the plastic GRIN image guide with 7μm diameter microfibers (The sold line is the best fits of the measured data)

In this study, the sharpness of the transmitted image is measured in the conventional way by studying the image of an edge of an object. An optical positioning table, rail and posts are used to measure the edge response function (ERF) of the transmitted image of the GRIN image guide as shown in Figure 3. As a target image, the USAF 1951 resolution target is used. A light source (Xe light source, Olympus Inc.) illuminates a sharp edge placed in direct contact with the polished surface of the image guide. The surface of the super-resolution image guide must be polished to within a few microns of surface roughness. The conventional polishing methods such as sand paper, polishing table and buffer wheel were not adequate to obtain a satisfactory polished-surface. Well-polished surfaces of the plastic image guides were achieved by using a proprietary diamond-polishing machine.

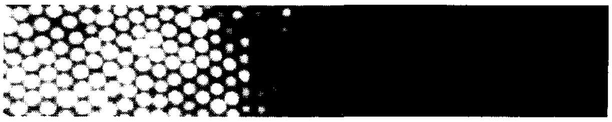


Fig. 4. The output sharp edge image of the GRIN image guide with average 3.5 μm diameter microfibers (2117X magnification)

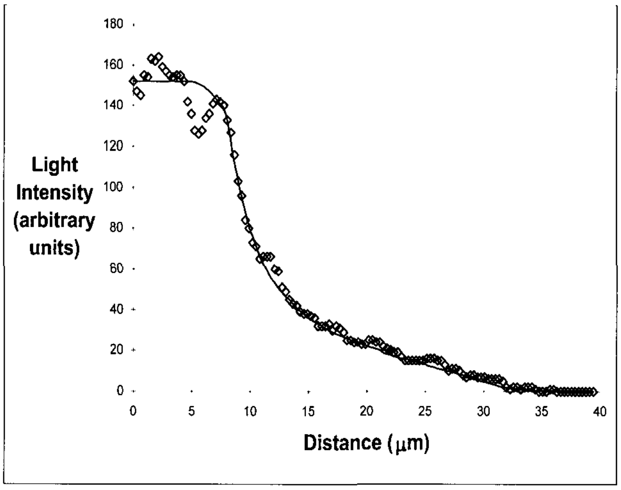


Fig. 6. The measured edge response function of the plastic GRIN image guide with 5μm diameter microfibers (The sold line is the best fits of the measured data)

The output image from the proximal end of a 20cm long image guide is read out by a 50X magnifying lens and a high resolution charge coupled device (CCD) camera system whose images are acquired by a Mac II based frame grabber and the magnification factor of the system is 2117 as shown in Figure 3. Figure 4 shows the output image of the sharp edge transmitted by a GRIN image guide made of 3.5μm diameter microfibers. The spatial resolution is investigated using the ERF. The ERF is the spatial intensity distribution across the image of an infinitely sharp edge. Figure 5 through Figure 8 shows the measured ERFs of the 7μm, 5μm, 3.5μm and 2.5μm microfiber diameter plastic GRIN image guides, respectively.

In all of the Figures (5 through 8), a sharp change in the light distribution can be observed corresponding to the edge of the object. Systematic fluctuation in the light intensity over distances of a few microns can also be observed corresponding to light transmission through individual or small groups of fibers. It should be noted that the appearance of regions of zero light between fibers is due to the numerical aperture of a GRIN fiber of radius, d, being a sensitive function of radius, r:

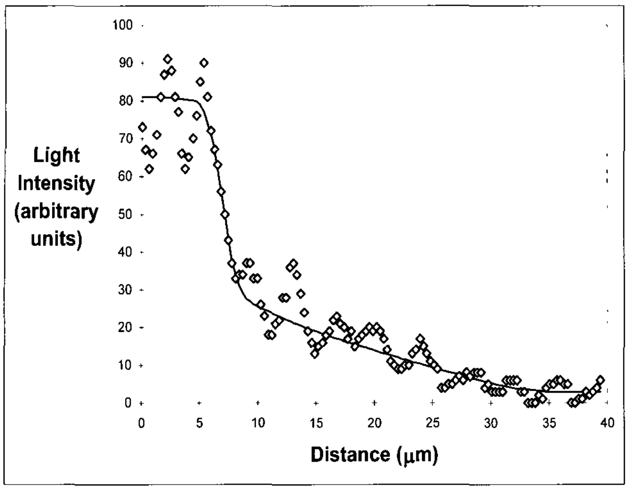


Fig. 7. The measured edge response function of the plastic GRIN image guide with 3.5μm diameter microfibers (The sold line is the best fits of the measured data)

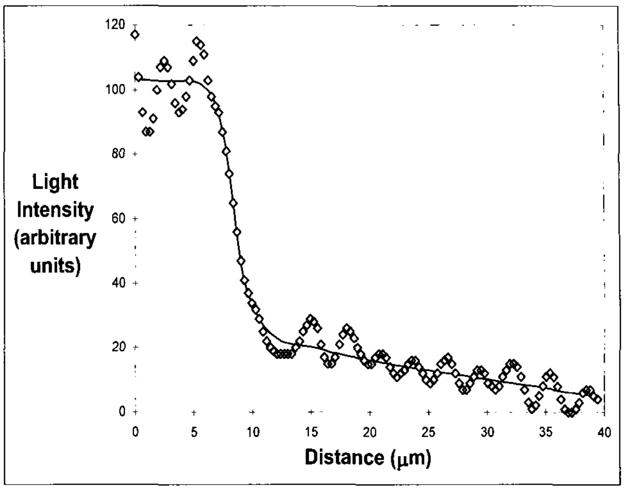


Fig. 8. The measured edge response function of the plastic GRIN image guide with 2.5μm diameter microfibers (The sold line is the best fits of the measured data)

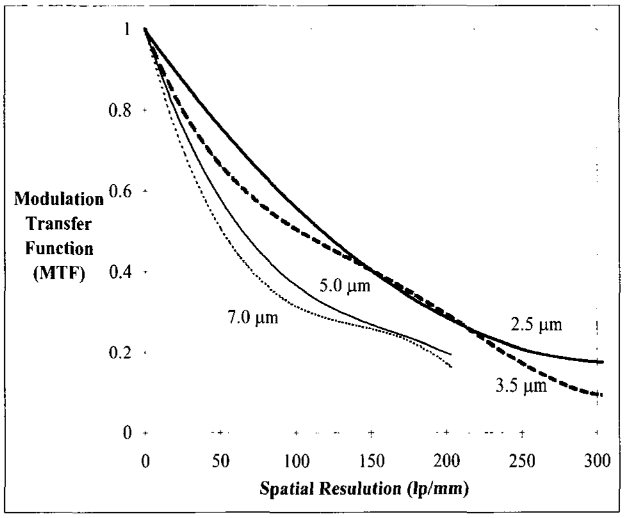


Fig. 9. The modulation transfer functions of plastic GRIN image guides with different microfiber diameter size

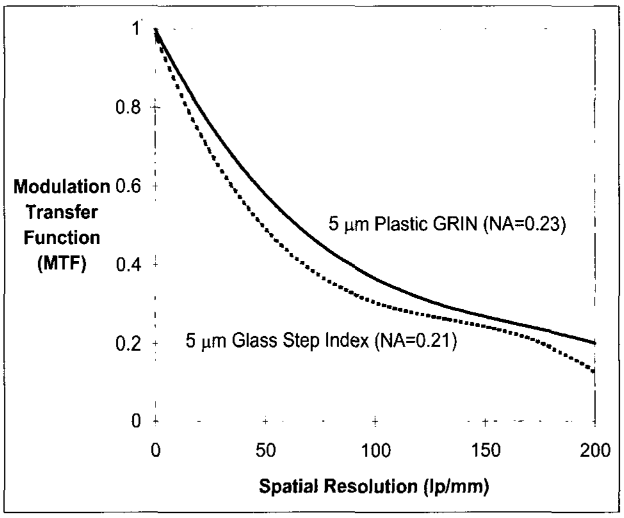


Fig. 10. The modulation transfer functions of glass SI and plastic GRIN image guides with 5 μm microfibers

$$NA\left(\frac{r}{d}\right)=NA(0)\sqrt{\left[1-\left(\frac{r}{d}\right)^2\right]} \qquad (1)$$

As a result, the transmitted light intensity drops towards the outer boundary of a fiber as $[1-(r/d)^2]$. To obtain MTFs of plastic graded index image guides, systematic fluctuations in the light intensity should be smoothed out by the best fits of measured data. The solid lines in Figure 5 through Figure 8 show the average value of light fluctuations in both sides of the sharp edge image.

RESULTS AND DISCUSSION

The MTF of the plastic GRIN image guide is obtained from the Fourier transform of the line spread function (LSF) which is the derivative of the edge response function (ERF). The resultant MTFs of the plastic GRIN image guides with different microfiber diameter, i.e., 7μm, 5μm, 3,5μm and 2.5μm are shown in Figure 9.

The MTFs of the GRIN image guides are different from those of SI image guides. The optimum resolution of the SI image guides was achieved when the diameter of the core is 3μm, and the cladding thickness is 1μm, (ratio of core/cladding equals 3.0) [5]. However, the GRIN image guide with 2.5μm diameter microfibers has higher spatial resolution than those with 7μm, 5μm and 3.5μm diameter microfibers as shown in Figure 9. Thus, it has been shown that the super-resolution image guides with less than 5μm microfiber diameters can be achieved by only GRIN fibers. The image resolution of plastic GRIN image guide with 2.5μm microfibers can be more than a factor of two higher than that of glass SI image guide with 5μm microfibers.

The measured MTF of the image guide with 5μm plastic GRIN fibers was compared with the known data [5] of the same size of glass SI fibers as shown in Figure 10. In Figure 10, it is to be expected that the 5μm plastic GRIN image guide has a MTF very similar to that of the glass SI image guide because the size of microfibers are similar and the numerical aperture (NA) of the SI image guide is 0.21, which is close to the NA of the GRIN image guide, which is 0.23. This agreement suggests that the present measurement technique is reliable and that the observed variation of MTF with microfiber diameter is correct.

CONCLUSION

The most important conclusion of this study is that fiber-optic image guides made from polymeric graded index fibers can achieve image super-resolution which is less than 5μm for the first time. Of course, similar super-resolution results could be obtained with glass graded index fiber optic image guides. However, it has never been done to fabricate glass GRIN image guide due to high cost and difficulties in manufacturing processes.

The fundamental limitation on the resolution of all previous fiber-optic image guides imposed by the thickness of step index cladding materials can be overcome. This new technology applied to optical systems could have a major impact on a wide array of future optical systems used in defense, industrial and medical applications.

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