Eyewear-style three-dimensional endoscope derived from microstructured polymer fiber with the function of image transmission*

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(Received 12 June 2012; revised manuscript received 14 August 2012)

A method of fabricating multi-core polymer image fiber is proposed. Image fiber preform is fabricated by stacking thousands of polymer fibers each with a 0.25-mm diameter orderly in a die by only one step. The preform is heated and stretched into image fiber with an outer diameter of 2 mm. Then a portable eyewear-style three-dimensional (3D) endoscope system is designed, fabricated, and characterized. This endoscopic system is composed of two graded index lenses, two pieces of 0.35-m length image guide fibers, and a pair of oculars. It shows good flexibility and portability, and can provide the depth information accordingly.

Keywords: three-dimensional endoscope, image fiber, polymer

PACS: 07.60.Vg, 42.81.–i, 42.70.Jk **DOI:** 10.1088/1674-1056/22/2/020701

Project supported by the National Natural Science Foundation of China (Grant No. 61275106 and 61275086)

1. Introduction

Surgeons perform open operations with the benefit of depth perception as a result of binocular vision, which is derived from the images of two eyes viewing the object from different angles. Three-dimensional (3D) imaging is very useful,[1] as accurate depth is generated in it from a series of depth cues: parallax, disparity, and stereopsis. Since the first laparoscopic cholecystectomy performed in 1987, minimally invasive surgery (MIS) has been developed and popularized rapidly.[2] Because of the small opening in MIS, the recovery time is much shorter, there is less scarring, and fewer complications arise from infections.[3]

During MIS, an endoscope is one of the necessary tools that surgeons use. As the first generation equipment, two-dimensional (2D) endoscopic vision impaired performance to a level as high as 35%–100% compared with direct vision.[4] Then the second-generation MIS endoscope, 3D system, provided surgeons with the depth information of the image, which reduced this endoscopic handicap by 41%–53%.[4] But the devices for 3D image acquisition were at a lower developmental level than devices for 3D image presentation.[5]

In this study monolithic multi-core polymer image fiber is fabricated. With the image fiber, a flexible eyewear-style direct-observational 3D endoscope prototype is designed and fabricated. Two images from slightly different angles are guided into the person's left and right eyes by two pliable polymer image fibers, and a stereo view with depth information is synthesized by the human brain. This avoids photoelectric conversion and complex computing and is helpful for improving stereoscopic image quality.

2. Fabrication of polymer image guide fiber

The progress of fabricating polymer microstructured image guides[6–8] and the application of polymer microstructured fiber[9,10] have been reported before. However, the small number of pixels and the hexagonal grids affect the integrity of the image. For improving the image quality, we develop a new method to fabricate monolithic multi-core polymer image guides without obvious grids. The preform fabrication needs only one step, different from some conventional methods of step-by-step stacking.[11,12]

Here we try to stack and draw a microstructured polymer fiber preform made of low loss fiber. One of the most important issues for the image guide is to minimize crosstalk between neighboring fibers, by insuring that the light traveling in each fiber is confined within its core. This guarantees that the resolution of the image obtained by the fiber bundle is truly determined by the core size of each fiber. The radial distribution of the intensity in a cylindrical dielectric waveguide depends on the indices of refraction for the core and cladding material. This is typically parametrized in terms of the V number of the waveguide which is defined as

$$V = 2\pi\frac{R}{\lambda}NA, \quad NA = \sqrt{n_1^2 - n_2^2}, \tag{1}$$

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61275106 and 61275086).

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where R is the radius of the core, λ is the wavelength, NA is the numerical aperture, and n_1 and n_2 are the indices of refraction for the core and the cladding, respectively.[12] For a large value of V such that the mode fields can be contained most efficiently within the core region,[13,14] PMMA and fluoroplastic are chosen as core and cladding material, whose indices of refraction are 1.49 and 1.40, respectively. Then NA is 0.5 in the visible region of the spectrum. Additionally, the light transmits in the fiber with the mechanism of frustrated total internal reflection. The thickness of fiber cladding has an effect on the light leak. The depth to which the evanescent wave penetrates in the cladding material of Z_0 is defined as

$$Z_0 = \frac{\lambda}{2\pi\sqrt{\sin\theta - \left(\frac{n_2}{n_1}\right)^2}}, \tag{2}$$

where θ is the angle of incidence on the fiber. It is calculated that the maximum theoretical value of Z_0 is about 0.5 μm in the visible region of the spectrum. Thick cladding can prevent light leak and crosstalk, conversely reducing the resolution. By comprehensive consideration, the thickness of single fiber cladding is determined to be 2 μm and the core diameter is about 18 μm.

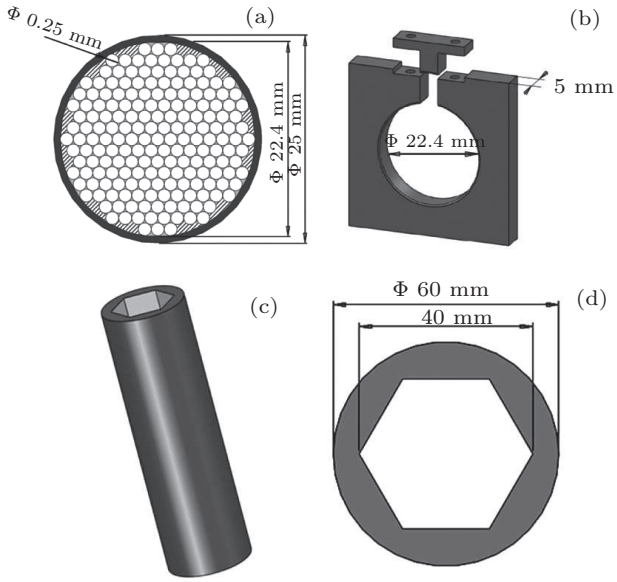


Fig. 1. (a) Schematic cross-section structure of fibers stacking in a circle die; (b) schematic design of an auxiliary ring for arranging fibers; (c) schematic diagram of regular hexagon die; (d) the size of the regular hexagon die cross section.

In the experiment, the customized fibers each with a 0.25-mm diameter (core diameter is 206 μm and cladding thickness is 22 μm) are used, which are provided by Sichuan Huiyuan Plastic Optical Fiber Co., Ltd.[14] An inner-polishing stainless steel tube of 22.4-mm inner diameter is chosen as the forming die. The fibers are arranged in the triangle form for the closest stacking. It is essential and important to calculate the accurate number of fibers accommodated in the die. With the area of the die hole divided by that of the fiber cross section, then multiplied by the factor which is the ratio of the area of the fiber cross section to its circumscribed regular hexagon, the number of fibers is determined to be 7300. The grey areas in Fig. 1(a) can be ignored because the fiber's diameter is much smaller than that of the die. However, for utilizing the die space effectively and reducing the probability of fibers stacking in a disorderly way, the regular hexagon die (with a diagonal length of 40 mm) is used. As a result, about 1.92×10^4 fibers are accommodated in it. The regular hexagon is a perfect shape for splicing several image fibers together, which is expected to be used as a guide to fabricating a high resolution image guide.

The flexible polymer fiber is good to use, but it brings people difficulties in stacking thousands of fibers in parallel. The polymer fiber with a diameter of 0.25 mm is like a curved line in the natural state. For inserting the fibers into the tube, an auxiliary tool (Fig. 1(b)) is designed and fabricated according to the principle of arrangement order in the smallest volume. It is a ring with a gap like the letter "Ω" in shape, its inner diameter is also 22.4 mm, and thickness is 5 mm. One end of the fibers are stacked in the ring off the gap, and the ring is closed with the T-type cover when the ring is full of fibers. Since the ring thickness is just 5 mm, it is almost impossible for fibers to intersect, fibers are arranged in an orderly way and most of the fibers can be accommodated inside the ring. Because of the micro errors of fiber diameters and the micro gaps between fibers, about 7120 fibers are accommodated inside the ring in practice. Then the fiber bundle passes through the ring and enters into the tube section-by-section.

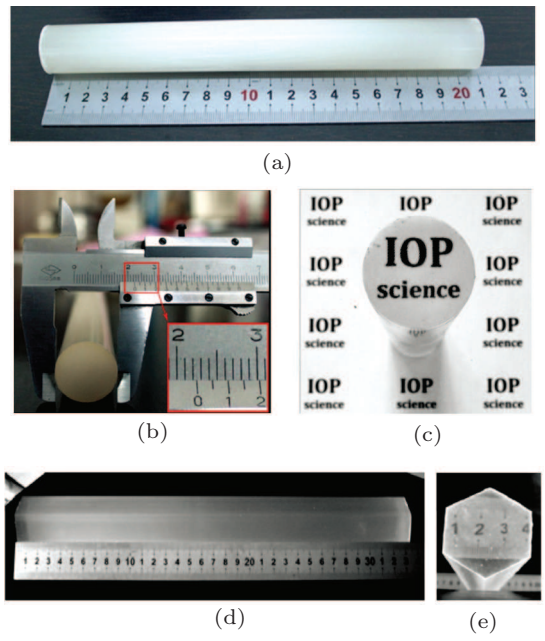


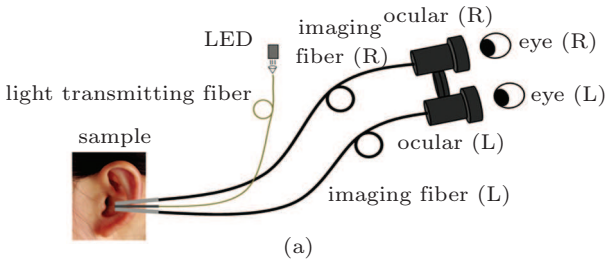
Fig. 2. (color online) ((a), (b), (c)) Circle imaging fiber preform with the length being 210 mm and the diameter being 22.4 mm, and the image transmitted to the output end of the preform; ((d), (e)) the regular hexagon imaging fiber preform with the length being 330 mm and the diagonal length of end-face being 40 mm.

The fiber bundle in the tube is heated in an oven at 135 °C

for 8 h in a protected nitrogen environment. Fibers fuse together and form the preform. Figures 2(a) and 2(b) show the pictures of it. Its length is 210 mm and diameter is 22.4 mm. Figure 2(c) confirms that the image is transmitted unchangeably to the output end by the preform. Then the preform is stretched with a diameter of 2 mm and pixel size of 22 μm. On testing, the transmission loss is about 0.8 dB/m at 532 nm, and the resolution is about 23 lp/mm. It can be used for some general purposes. Figures 2(d) and 2(e) show the hexagon preform. It has more pixels, but its shape is not suitable for coupling with a circular lens.

3. Endoscope system

The schematic experimental setup and demonstration unit for the 3D endoscopic system are represented in Figs. 3(a) and 3(b). It is based on the principle of binocular stereo vision, comprised of illumination, imaging objective lenses, image guide fibers and oculars. The white light from an LED of 2-W power transmits through several polymer fibers each with a 0.25-mm diameter and illuminates the sample. Then the sample is imaged by two graded-index lenses with different viewing angles. The graded-index lens length and diameter are 0.25 P and 2.5 mm, respectively. The image plane is nearly in the end face of the corresponding lens (see Fig. 4). The two images enter into and transmit through the image guide fibers fabricated above and they are observed by the surgeon's eyes through an ocular system. The tip size of the system is about 8 mm (see Fig. 3(b)). Certainly, it can be reduced by using image fibers and objective lenses each with a smaller diameter. Commercialized 20X oculars with a large viewing field



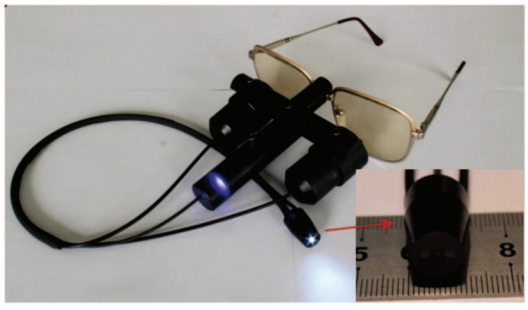


Fig. 3. (color online) (a) Principle structure of the endoscope system; (b) the demonstration unit of the eyewear-style image fiber 3D endoscope.

and high eye-point are used. As shown in Fig. 5(a), point A is the position of the virtual image viewed by the eyes (E_L and E_R), L is the distance of distinct vision (250 mm), d is the average pupil distance (62 mm), and β is the angle difference of view which is determined to be 14.1° by L and d. In Fig. 5(b) point A' is the sample, G_L and G_R are the objective lenses, β' should be 14.1°, consistent with that of the eyes. Figure 6 shows the images of a bolt observed from left and right channels. When observing the two images by left and right eyes simultaneously, the stereo image is formed in the viewer's brain.

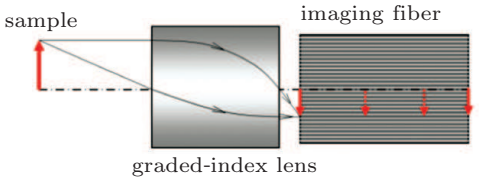


Fig. 4. (color online) Graded-index object lens imaging.

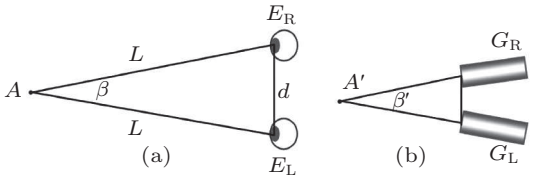


Fig. 5. Schematic diagrams of (a) imaging by bin-objective lenses and (b) viewing by binocular eyes.

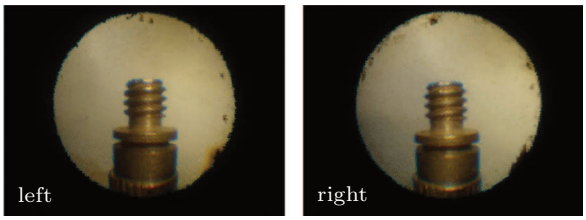


Fig. 6. (color online) Images of a bolt observed from left and right channels.

4. Conclusions

A method of fabricating a preform of polymer image fiber is developed, which can be used for solving the difficulty in arranging thousands of flexible and un-straight fibers in an orderly way and in parallel. The preform is stretched into an image fiber with a diameter of 2 mm. It is flexible and monolithic, the pixel size is about 22 μm, the transmission loss is 0.8 dB/m at 532 nm, and the resolution is about 23 lp/mm. By utilizing this imaging fiber, a 3D endoscope based stereo binocular is designed and fabricated. The objective lenses are arranged with an angle of 14.1°, and integrated into one probe of 8-mm diameter. A surgeon who observes the two images from different view angles can form a stereo image and gain

the depth information of the sample. This stereo endoscope transmits images into the surgeon's eyes directly. It is light, flexible, and easy to operate. However, more work should be done to develop a mini-stereo-endoscope with higher resolution.

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