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Spherical fused silica microlenses fabricated by the melting method

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Fiber ends are irradiated by a focused CO_2 beam causing material to melt. Surface tension shapes the melted material into a spherical microlens that remains joined to the fiber. Such lenses can be used to form images or to focus light. Back focal distances and other parameters of the lenses have been measured.

Keywords: Microlenses.

Los extremos de fibras ópticas fueron iluminados con luz enfocada de un laser de CO_2. El resultado fue la fundición de esos extremos. Debido a la tensión superficial el material fundido se convirtio en una microlente esférica que quedo adherida a la fibra. Tales lentes se pueden utilizar para formar imágenes o enfocar luz. Las distancias focales posteriores y otros parámetros de las lentes fabricadas han sido medidos.

Descriptores: Micro-óptica.

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1. Introduction

Photonic devices need micro-optical elements such as microlenses and micromirrors in order to connect detectors and modulators [1,2] to light sources. There are several methods of elements fabrication, such as melting, reactive ion etching, photolysis and others [1]. Reference 3 shows that it is possible to fabricate spherical microlenses by melting the end of fibers with a torch. Instead now we have used a CO_2 laser to melt the end of the fibers and form spherical lenses. In this paper we show, perhaps for the first time, that fabricated lenses can be used to form images or to focus light. We did not attempted to use the microlenses to feed light into the fibers.

2. Method of fabrication

The basic structure of optical fibers consists of a core, a cladding and a jacket. To make the lenses at the end of the fiber first the jacket is removed leaving only the core and the cladding. Then the fiber is cleaved to obtain a flat end. Radiation from a CO_2 laser ($\lambda = 10.6\mu$m) is focused, using a germanium lens, near the cleaved end of the fiber resulting in a microlens at its tip (Fig. 1). The parameters involved in the melting process are the diameter of the fiber, the power of the CO_2 laser and the exposure time. With the fiber diameter and the beam power fixed, varying the exposure time can control the lens characteristics. These fabricated lenses may have surfaces with weak curvatures or they may be spheres of different diameters. Microlenses remain attached to the fiber after the irradiation by the CO_2 laser. Figure 2 shows a sequence of lenses with different shapes and diameters made with fibers all having the same diameter. Each fiber has had a different exposure time. Notice that the fiber that was subject to the shortest exposure time (Fig. 2a) has a slightly rounded edge. As the exposure time increases the tip of the fiber becomes spherical, like those made with the longest exposure time as shown in Fig. 2c. In the process of fabrication two phenomena may occur: a) the temperature of the glass surface is elevated causing part of the glass to vaporize, b) heat is conducted into the body of the fiber causing the glass to melt. Thus to make a lens with a given optical power there is an optimum exposure time. If the exposure time is longer than ideal, vaporization of the material will dominate, the fiber will be shortened and the lens will not be truly spherical. In our case optimum exposure time was found by trial and error. Parameters that were kept fixed during the fabrication time were diameter of the fiber, laser power, focusing lens and the distance between the fiber and the lens. Several fibers were placed, one at a time, near the focal region of the lens. Each fiber was illuminated with an arbitrary time. After several attempts, lenses with different radii of curvature were found. The microlenses that we fabricated are composed of a mixture of the materials that compose the core and the clad. When glass is melted the lens is form by surface tension. The way these lenses form images is shown in Fig. 3. As we said before we did not use the lenses to feed light into the fiber.

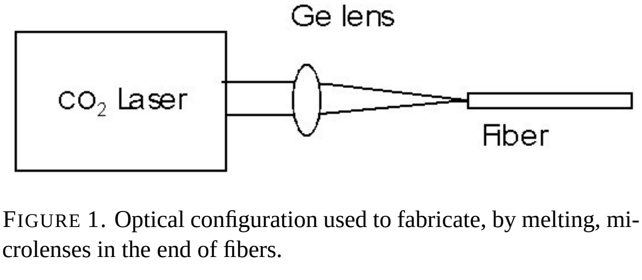
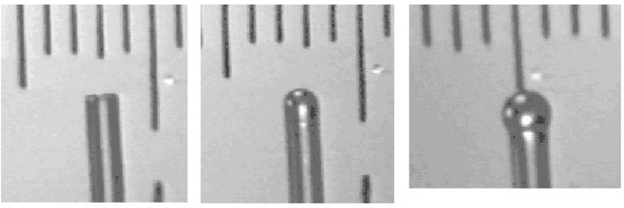


FIGURE 1. Optical configuration used to fabricate, by melting, microlenses in the end of fibers.



a) t_e= 125 ms b) = t_e= 250 ms c) t_e= 4 s

FIGURE 2. Fiber ends that were irradiated with the indicated exposure times (t_e). Distance between two consecutive marks in scale is 100 μm.

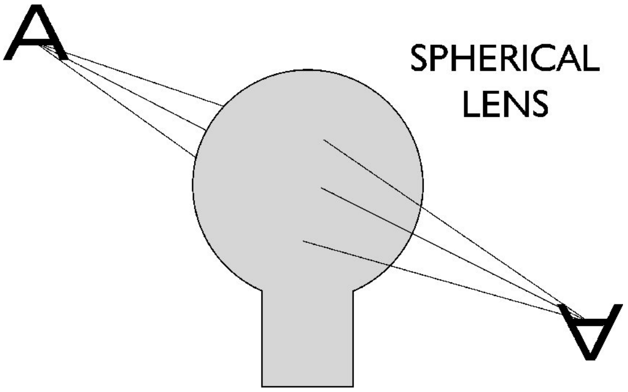


FIGURE 3. Lens made by melting. Its dimensions are larger than that of the clad. Lens can focus light or form an image.

3. Profiles of the lenses

A suitable instrument to characterize the shape of the profile of a micro-lens is the scanning electron microscope (SEM). The profile of one fabricated lens was investigated with the SEM; two views (side and top) of the lens were taken and are shown in Fig. 4 a, b. To find out how close to a circular shape the profile of the lens was, an image processing procedure was used. The following steps. The contrast of each digital image in Fig. 4 was enhanced and a thresholding was applied to produce binary images. Then, the edges of the lens were detected using the Sobel algorithm [4]. After this, another thresholding was applied to obtain binary images again. Finally, a thinning algorithm that preserves conectedness was applied to obtain one pixel wide contours. The final images of the segmented contours were slightly edited by hand to eliminate undesired structures. This final profile is shown in Fig. 4 a,b with white pixels. In Fig. 4a it is seen that the profile is not a circle but a segment of it. This was done to avoid the straight parts of the fiber. Once the profile was segmented, 3 of its points were taken to obtain the radius and the coordinates of the center of a theoretical circle. This theoretical circle was compared with the actual profile of the lens by subtracting the distance from the center to each point of the profile. To find the best fitting circle the coordinates of the center of the theoretical circle were varied by small amounts and the subtraction was calculated again. This procedure was repeated until a minimum value in the subtraction method was obtained. This tells us the characteristics of the best fitting circle. In Fig. 5a is plotted in the left ordinate axis the deviation of the profile from the best fitting circle. In the abscissa axis is plotted the pixel number that belonged to the rim. It is possible to see that the deviation of the lens surface in most part of the selected profile is not more than ± 1 micron. This means the lens is deviated about ± 2 wavelengths from the ideal profile. This deviation could cause a degradation of the image given by the lens or if the lens is used to focus light, the focus region will not be sharp.

The procedure outlined in the last paragraph was applied to the photograph shown in part b of Fig. 4. Results showing the deviations from the theoretical circle are shown in Fig. 5 part b. This graph shows a deviation from the digital circle of about ±1.5 microns or about ± 3 wavelengths. In Fig. 5a it is possible to see that the mean of the curve is a radius with a value of about 141 μm however in Fig. 5b the mean value is about 133 μm. These measurements tell us that the lens resembled a toroidal one [5].

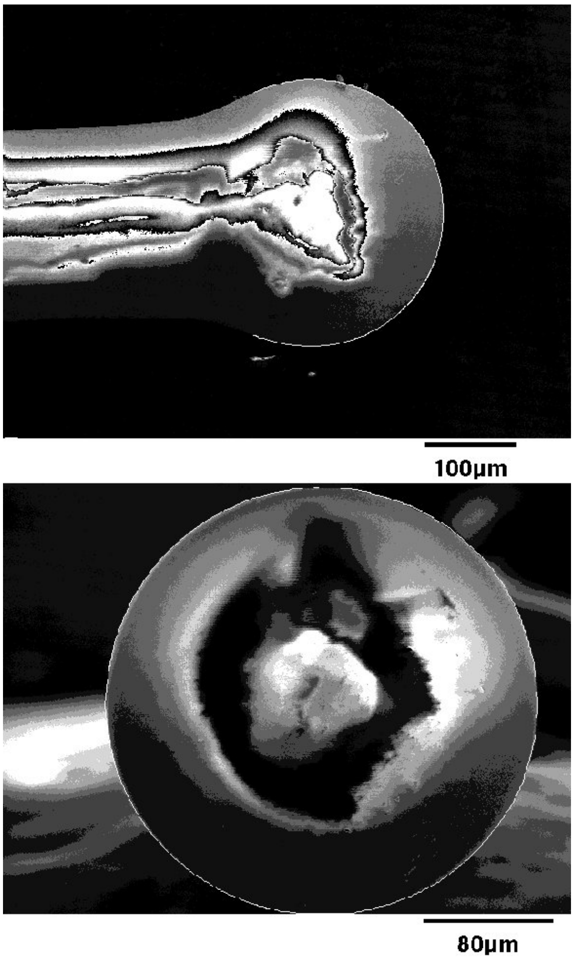


FIGURE 4. a) Side and b) top view of a microlens taken with an electron microscope. Both views show the segmented profile in white pixels. These profiles were obtained by processing the digital images of the corresponding views.

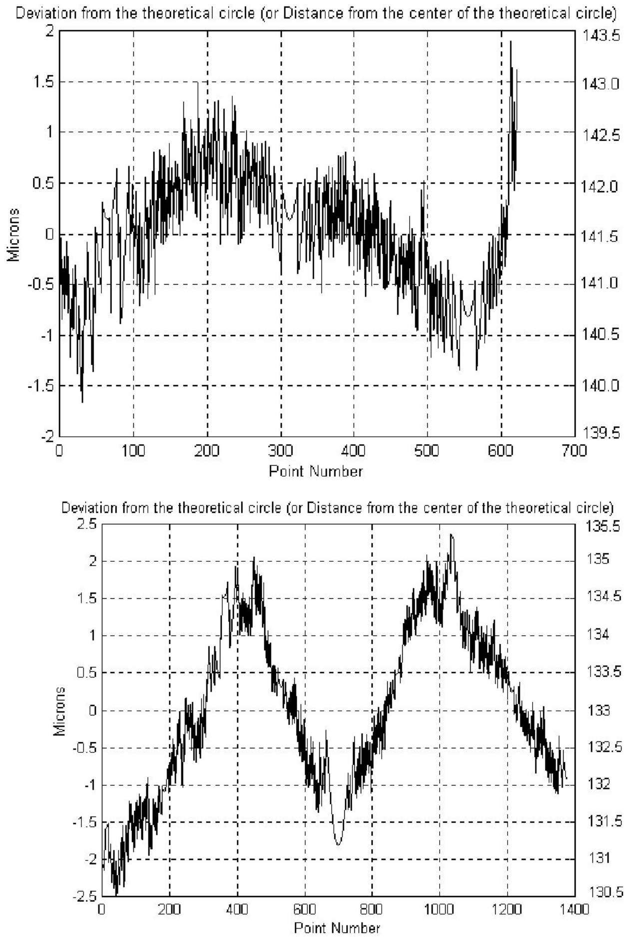


FIGURE 5. Graphs showing in the ordinate axis the deviation of the actual profile (or the distance from the center of the theoretical circle) with reference to the best fitting circle for the side a) and b) top views of the fiber in Fig. 4. The abscissa axis represents the pixel numbers of the rim.

4. Ray tracing

Commercially available optical design software was used to trace rays through a microlens with the characteristics shown in Table I. These characteristics describe the lens shown in Fig. 4a. We have chosen a diameter of the entrance pupil of 130 μm. This diameter just comprises the central part of the lens. Top of the lens and stem of the fiber have been neglected. Also the fact, exposed earlier, that the lens is toroidal has not been considered. The value of the refractive index shown in Table I was determined in the following way. In the fabrication of the fiber, fused silica was chosen as cladding material (n=1.458). The difference in refractive index from the cladding and the core was about 0.01. The mean of the two indices is about 1.463. Cladding diameter is about ten times the diameter of the core thus the microlenses are formed mainly by glass taken from the cladding. The refractive index of the lens should be lower than the mean, so we chose 1.460. Regarding the thickness of the lens, it was determined from the photographs given by the electronic microscope (Fig. 4).

TABLE I. Characteristics of a lens used to trace rays using an optical design software [6]

Radius of curvature	141.2 μm
Diameter of the entrance pupil	130 μm
Refractive index	1.46
Thickness	282μm

The result of the ray trace is shown in Fig. 6, part (a) shows the situation when the object is at 2f from the lens and part (b) when the object is very far (infinity) from the lens. In part (a) we can see that rays that are far from the optical axis cross it in a region remote from the paraxial focus thus the lens shows spherical aberration however, in part (b) of this figure spherical aberration is not pronounced. In reality the lens should present more pronounced aberrations because rays crossing the lens outside the entrance pupil are more deviated than the ones shown in Fig. 6.

5. Imaging

Even though the fabricated microlenses suffer from aberrations, as indicated above, they are able to form images. As a test, alphabetic characters were printed on a sheet of white paper and used as objects, they were illuminated with a white light source. Figure 7 shows two images formed by two different microlenses. The lens shown in Fig. 2a produced the image in Fig. 7a. Only the edge of this fiber behaves as a lens forming a horizontal and blurred image of the letter P. Figure 7b shows the image of the letter A formed by the lens shown in Fig. 2c which is a well formed spherical lens.

The resolving power of those microlenses was found using a test target (USAF 1951). Lenses with a good spherical shape were able to resolve the bars in element 5, group 6. Distance between the bars of this group is about 17 μm. Photograph in Fig. 8 shows the image of element 5 groups 1, 2, 3 given by one of the tested microlenses.

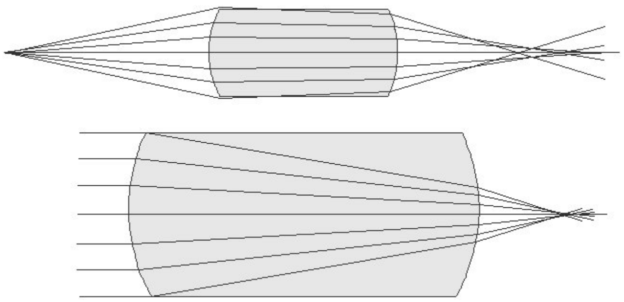


FIGURE 6. Ray diagrams of a spherical lens with the characteristics shown in Table I. In a) object is at 2f and in part b) object is very far from the lens (infinity).

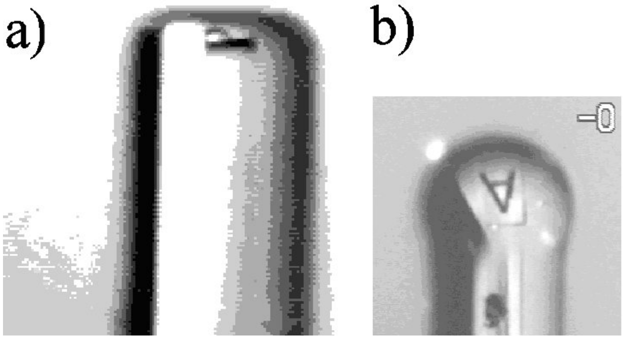


FIGURE 7. Images of printed characters given by two microlenses. The lens that formed the image shown in (a) was made with a short exposure time. The rim can form only a horizontal and blurred image of character P. The lens that produced the image in (b) was formed with an optimum exposure time. An image of character "A" is shown.

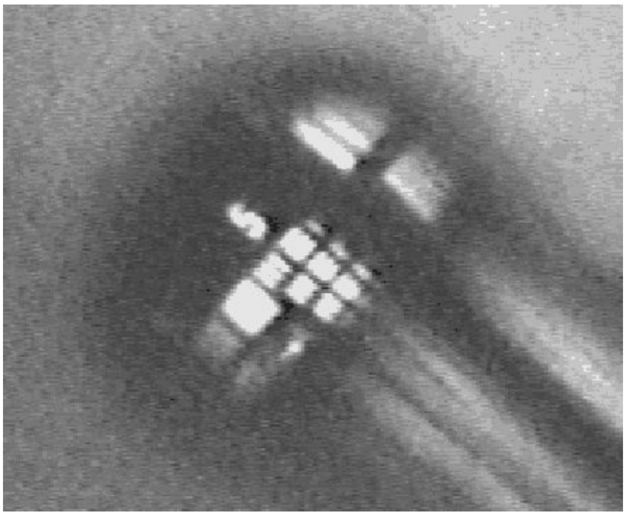


FIGURE 8. Image given by a microlens of group 5, elements 1,2,3 of a test target (USAF 21951).

To test the reproducibility of the melting method the same exposure time was used to form microlenses on several fibers. Then, they were glued to a plane substrate so the fibers were all on a plane. The image of an object produced by each of these lenses was examined with a microscope. All the lenses formed images in the same plane indicating that they had the same focal length.

In fabricating these micro-lenses we have used fibers with diameters ranging from about 125 μm to about 200 μm. Spherical lenses with diameters from 150 μm to 300 μm were made. Back focal distances were measured by locating the image of a distant object(43 cm). These back focal distances (f_b) ranged from about 45 μm to about 90 μm. These values were compared with the ones obtained theoretically from the following formula [6]:

$$f_b = f - R = (nR)/2(n-1) - R,$$

where n is the refractive index, R is the radius of curvature and f the effective focal length. Considering the values R=141.2 μm (taken from Fig 5 a), n=1.46 (Table I) and using this formula a back focal distance of 82.9 μm was calculated. This value is close to the experimental value of 85 ± 5 μm measured as mentioned previously.

At present we are investigating the application of this proposed method to make lenses with larger diameters by melting the ends of thicker fibers. Also we are experimenting with materials other than glass.

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1. *Micro-optics elements, systems and applications*, Ed. H.P. Herzig (Taylor and Francis, Philadelphia, 1998).
2. N.F. Borrelli, *Microoptics technology fabrication* (Marcel Dekker, New York 1999).
3. D. Kato, *J. Appl. Phys.* **44** (1973) 2756.
4. R.C. Gonzales and R.E. Woods, *Digital image processing* (Addison Wesley, Massachusets, 1992)
5. Carmen Menchaca and D. Malacara, *Appl. Opt.* **25** (1986) 3008.
6. F.C. Allard, *Fiber Optics handbook for engineers and scientists* (Mcgraw-Hill, New york, 1990) p. 3.80.