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Manufacture of a 2D optical fiber array coupler with micrometer precision for laser radar applications

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Abstract

This article presents the manufacture of a 2D-fiber array coupler using UV-LIGA technology for the precise positioning of a two-dimensional (2D) optical fiber array. The precision of the alignment of the eight-by-eight fiber array was demonstrated to be less than 2 μm. The average concentricity error of the fibers to the positioning holes of the array coupler had a minimum and maximum error of 1.7 μm and 6.5 μm, respectively. The 2D fiber array coupler can fulfill the coupling and transmission requirements of 2D light spots for laser radar applications. The method developed here can easily be extended to the manufacture of larger arrays.

Keywords: 2D optical fiber array, micrometer precision, laser radar applications

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical fiber couplers are used to connect fibers to fibers, light sources or photodetectors in order to reduce optical losses and enhance the transmission of optical energy within photonic systems. Such systems have shown to be capable of transferring large quantities of data and processing information at high speed. As a multi-channel component in modern opto-electronic systems, the fiber array plays an important role in image transfer, optical sensing, interconnecting array devices or multi-channel optical devices [1–7].

Fibers are normally aligned as a one-dimensional (1D) array using a v-shaped groove array or side by side into trenches etched through the substrate, and packaged by UV light cured adhesive [8–10]. Few articles report the fabrication of 2D fiber arrays. About four decades ago, Miller developed a method of stacking 1D fiber arrays to realize a 2D configuration [11]. The fabrication was only limited to a two-row fiber array and proved difficult to extend to the manufacture of a square array [11]. Asako *et al* proposed a self-aligning method using array connectors for the optical interconnection between optical fibers and microlenses [12]. The method had an alignment accuracy of only 8 μm but was claimed by the authors to be suitable for mass production. More recently, Weiland *et al* proposed using electrostatic actuation to manufacture a 2D fiber array with a proven accuracy of sub-micrometer. However, the manufacturing process and alignment method were quite complex and not easily adaptable to mass production [13].

Here we present a method of fabrication for a 2D eight-by-eight fiber array based on UV-LIGA manufacturing

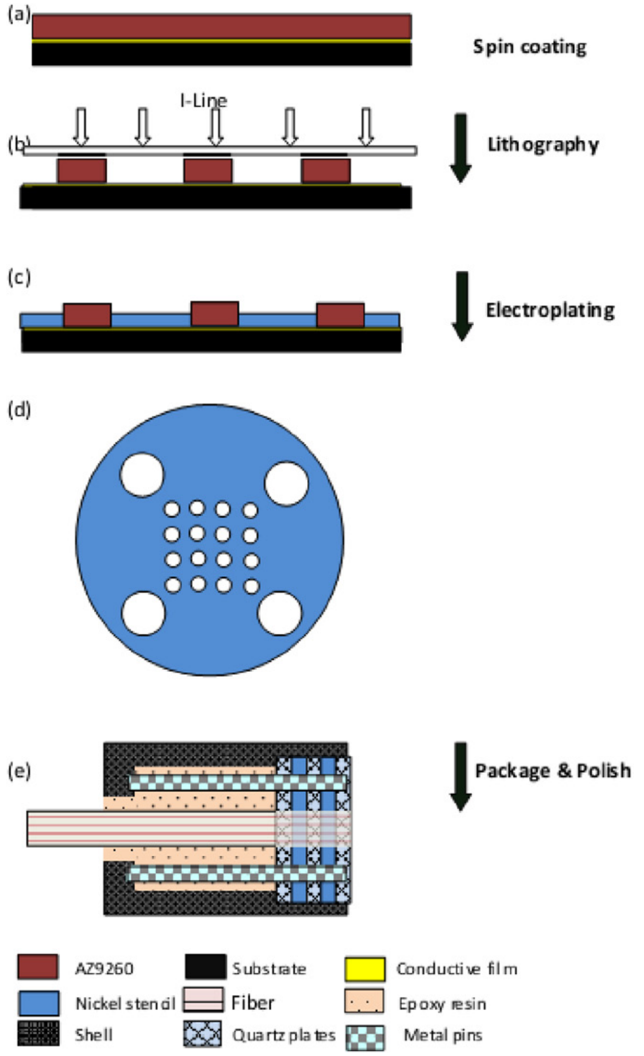

Figure 1. Schematic of the fabrication process of the 2D fiber array.

technology. This method is proved to have an alignment error of less than 2 *μ*m and has the potential for mass production and to be scaled up.

2. Fabrication method and process

2.1. Method

The fabrication process is shown in figure 1. First, a nickel-based stencil, shown in step d, is fabricated using the UV-LIGA process with a microhole array for the fiber positioning (steps a to c). Second, fibers are inserted into the micro holes of the nickel stencil to form a 2D fiber array. Third, the fiber array and nickel stencil are fixed by metal pins inside a hollow cylinder, and filled with epoxy resin, so that all components are packaged together into a stainless steel hollow cylinder (step e). Finally, the end surfaces of the fiber array are grained and polished to make its surface flat and optically smooth.

The multimode fiber used here has the following dimensions: core diameter 192 *μ*m, cladding diameter 200 *μ*m and plastic cladding diameter 235 *μ*m. The diameter tolerance of the core and the plastic cladding is about ±4.7 *μ*m, which is given by the manufacturer. After considering the dimensional variations in the fabrication process and error of the core diameter, the diameter of positioning holes for the photolithography mask were designed to be 245 *μ*m, and the pitch of the fiber array was set at 320 *μ*m as required by the laser radar system.

2.2. Fabrication process

The fabrication process starts with the creation of a 2D photoresist micro pillar array on a BK7 glass substrate deposited on top of a metal conductive film. The metallic Cr film with a thickness of 200 nm–300 nm is deposited by using an E-beam evaporator on the BK7 glass substrate. The substrate is then cleaned in an ultrasonic bath and baked on a hotplate to remove any solvent or water on its surface. The substrate is spin coated with a 40 *μ*m thick AZ9260 photoresist (AZ Electronic Materials). The photolithography process is carried out by exposing the photoresist under 365 nm wavelength UV light with exposure energy of 1200 mJ·cm^{-2} and followed by a 10 min development process using diluted AZ400K (AZ Electronic Materials). The mixture volume ratio of AZ400K and the deionized water is 1:3. Figure 2(*a*) shows an image of the 2D micropillars array captured by an Olympus MX61 microscope.

Using the micropillar array as the template, electroplating is carried out to manufacture the microstencil. For an electric current density of 4 mA·cm^{-2}, the process of electroplating lasts for 8 h, and the 27 *μ*m thick electroformed nickel stencil, shown in figure 2(*b*), is then peeled off from the substrate and cleaned.

The assembly of the fiber array and mechanical components forms the third step in the construction of the 2D fiber array. First, fibers are inserted into the holes of two stacked nickel stencils as shown in figures 3(*a*)–(*b*). Second, three quartz plates with a through square window fabricated in the center are used to sandwich two nickel stencils in between to form a five-layer structure. The five-layer structure is then confined and fixed by four metallic pins inserted through the five layers. Third, the fixed fiber array is packaged into a specially designed hollow cylinder-like stainless steel shell, as shown in figure 3(*c*). Finally, the whole package is filled with epoxy resin (Ausbond 152A, Ausbond (China) Co. Ltd). The epoxy resin was prepared by mixing part A (monomers) and part B (curing agent) with a weight ratio of 3:1. After removing the air bubbles and full cure, the epoxy resin fixed all the parts of the packages together firmly and with great rigidity.

The last and fourth step consists in grinding and polishing the resulting assembly. The redundant epoxy resin at the end of the fiber surface was cut off to expose the fiber array, as shown in figure 4. The exposed end surface was then grinded and polished to make it optically smooth to reduce light reflection and scattering.

3. Results and discussions

To characterize the precision of the positioning of the fiber array, the concentricity errors, i.e. the error between the center

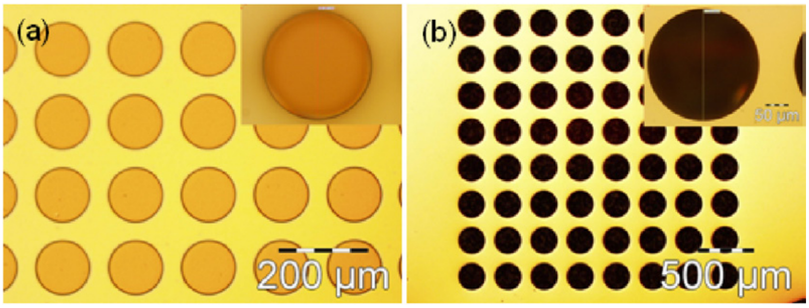

Figure 2. Optical microscopic images of the micropillars array in photoresist after photolithography (*a*) and nickel microstencil after electroplating (*b*), the dark region is photoresist in (*a*) and the light region is nickel in (*b*).

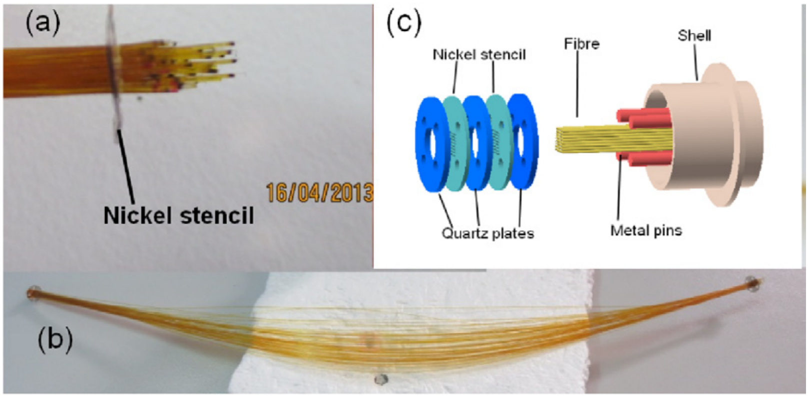

Figure 3. Images of the fiber array after fixed by one nickel microstencil (*a*), fixed by two nickel microstencils (*b*) and the exploded view of the fiber array.

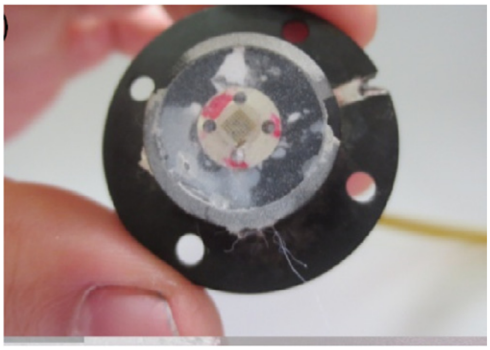

Figure 4. The end surface of the fiber array before being grinded and polished.

points of the fiber and its hosting microhole were measured for all of the 64 fibers as shown in figure 5(*a*). The concentricity error ranges from 1.7 μm to 12.7 μm for an average error of 6.5 μm. From the statistics, the spatial distribution of the concentricity error is very close to the normal distribution as is shown by the histogram and Gaussian fitting curve in figure 5(*b*), from which one can know that the mean error is 6.6 μm and the standard deviation is 2.4 μm. For most of the fibers (about 92%), the concentricity errors range from 2 μm to 10 μm. As mentioned above, the diameter error of the plastic cladding is ±4.7 μm. If one considers this error and the average error of 6.5 μm, then the concentricity error should fall in the range of 1.8 μm–11.2 μm. In this case, 96.9% of the error data fall in this range. This means that 96.9% of the concentricity error comes from the diameter error of the plastic cladding of the fiber. In fact, for the UV-LIGA microfabrication, the only error that affects the concentricity is the positioning error of the microhole defined in photomask, which is ±0.5 μm as given by the manufacturing company. If one further includes the measuring error of the optical microscope, which is about ±0.7 μm, the range for the concentricity error ranges from 0.6 μm to 12.4 μm. In this case, all of the error data in figure 5 will fall in this range. Therefore, it is concluded that the main contribution of the concentricity error is the diameter error of the plastic cladding of the fiber. If this error could be eliminated, the precision of our method should be better than 2 μm.

To test the coupling and transmission performance of the fiber array, a simple optical inspection experiment was carried out. A collimated laser beam was incident onto the fiber array coupler, and the light spots on the end of the fiber array were captured by an optical microscope (Mitutoyo MF) with a magnification of 30. The capture image of the light spots is shown in figure 6. The homogeneity of the brightness on the end surface is quite good, which means that good coupling and transmission of the light occurs in the fiber array. However, two light spots are missing in the image, which is attributed to the breakage of the fibers during the alignment and packaging process. This suggests that care should be taken during the whole aligning and packaging process of the fiber array coupler.

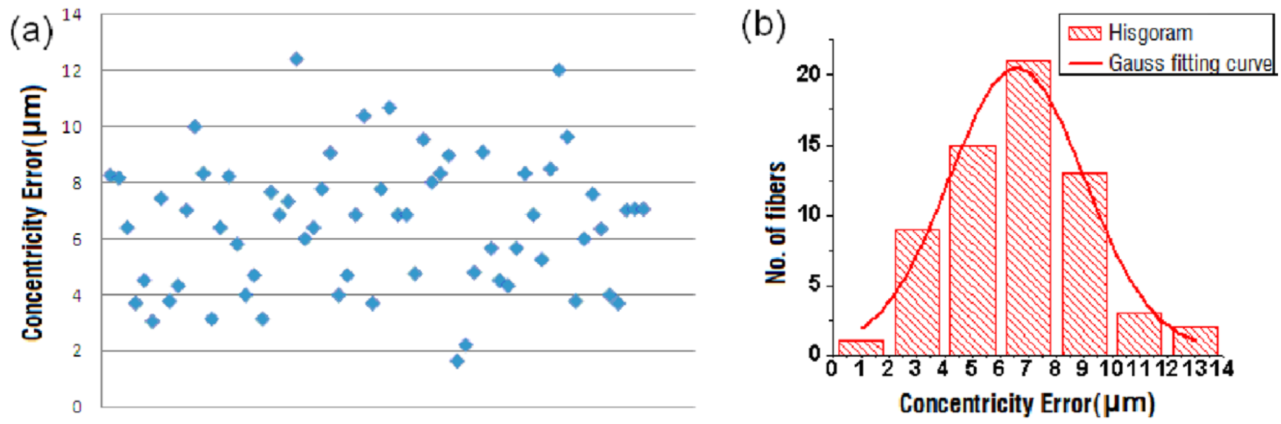

Figure 5. The concentricity error distribution of the fabricated 2D fiber array.

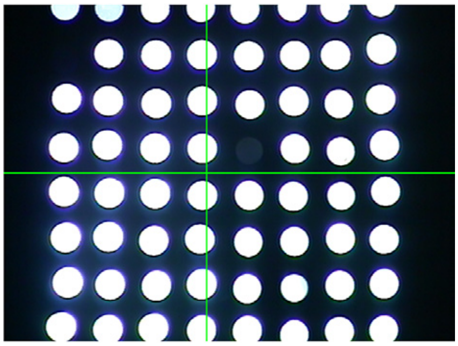

Figure 6. Image of the light spots at the end surface of the fiber array captured by a Mitutoyo optical microscope.

To further test its coupling efficiency, an optical testing system was set up as shown in figure 7. The system consists of a laser with a wavelength of 1064 nm, a Dammann grating, a concentrating lens, two 2D optical fiber array couplers and a power meter. During the testing, the total light energy (E_{input}) of 64 light beams diffracted from the Dammann grating was collected and measured by a power meter. Next, the total output light energy (E_{output}) from the fiber coupler was measured. Thus, the coupling efficiency of the fiber coupler can be calculated by dividing E_{input} by E_{output}. Considering that the fiber length in the test is only about 30 cm, the transmission loss can be ignored. In this case, a coupling efficiency of 38.9% was obtained. We attribute the low coupling efficiency to the non-matched numerical aperture between the incident light beam and the fiber, which can be improved by inserting a 2D microlens array in between the incident beam array and the fiber array. However, this will be another topic and shall be done in our future work.

4. Conclusions

In this work, we have demonstrated the successful fabrication of a 2D fiber array based on UV-LIGA technology, which meets the requirement of a laser radar system. The concentricity error of the fiber array is shown to be better than 2 μm if one considers the diameter error of the plastic cladding of the fiber. The developed method is shown to be compatible with the standard IC microfabrication industry process and is able to be extended to even larger scale fiber array fabrication. The fabricated 2D fiber array can find wide applications in optoelectronic systems or optical communication systems for efficient and low loss optical interconnection.

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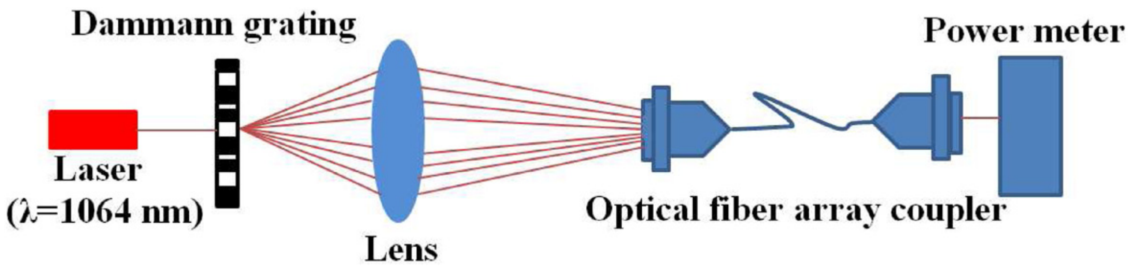

Figure 7. Optical setup used for the measurement of the coupling efficiency of the optical fiber array coupler.

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