A 3-D Planar Microlens for an Effective Monolithic Optical Interconnection System

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***Abstract*—A three-dimensional (3-D) planar microlens with curved sidewalls was fabricated by using the recently developed 3-D diffuser lithography and the polydimethylsiloxane (PDMS) replication method. The sidewall of the fabricated 3-D planar microlens had a radius of curvature of 140 μm, and a well-defined focal spot with a width of 1.5 μm and a height of 3 μm was observed. An excellent single-mode fiber-to-fiber coupling efficiency of 71% was demonstrated by applying the developed 3-D planar microlens, which displayed more than two times the coupling ability compared to that of a conventional two-dimensional planar microlens with straight sidewalls. Finally, it was verified that the coupling efficiency was little affected by variation in the process conditions used for the photoresist mold fabrication.**

***Index Terms*—Diffuser, microlenses, optical detection, optical interconnection, polydimethylsiloxane (PDMS), three-dimensional (3-D) lithography.**

I. Introduction

MICROLENSES have been one of the key components for optical interconnection because they are essential for the focusing, collimation, and steering of an optical signal [1]. In addition, with the remarkable growth of fiber-based optical bio-detection systems, the importance of the microlenses for the effective optical interconnection in a biochip is increasing rapidly. For instance, microlenses have been used to couple optical signals from fibers into a microfluidic channel through microlenses, and vice-versa [2]–[4].

Among the various types of microlenses, surface-relief microlenses have very good focusing characteristics due to their ideal three-dimensional (3-D) spherical profiles, while their orthogonal optical axis to the substrate makes it difficult to integrate them into a monolithic optical system [5]–[8]. On the other hand, ball-type photoresist microlenses with a high coupling efficiency in a monolithic interconnection have been demonstrated [9]–[11]. However, as the microlens material is limited to the photoresist, its chemical and thermal instability may be a concern for the practical use of microlenses in interconnection systems.

Planar microlenses are known to be highly feasible solutions for monolithic integration. They are fabricated by a plastic replication from high aspect-ratio thick photoresist patterns, or by a lithography process followed by a dry-etching step. However, their straight sidewalls prevent them from focusing the incident signal in a vertical direction [2]–[4], [12], [13]. Their poor focusing ability degrades the overall efficiency of an optical system. Due to this, the creation of 3-D planar microlens which can focus an optical signal vertically as well as horizontally is necessary for an effective monolithic optical interconnection.

Manuscript received December 7, 2005; revised January 18, 2006. This work was supported by Korea Research Foundation Grant (KRF-2004-041-D00278) and by Brain Korea 21 Project, the School of Information Technology, Korea Advanced Institute of Science and Technology (KAIST), in 2005.

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Digital Object Identifier 10.1109/LPT.2006.871840

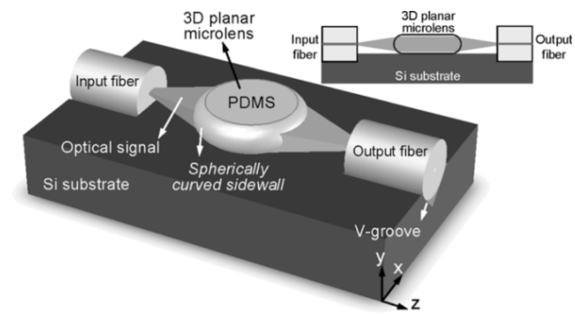

Fig. 1. Conceptual schematic view of the proposed fiber-to-fiber optical interconnection with the 3-D planar microlens and its cross-sectional view.

A process that utilizes polydimethylsiloxane (PDMS) replication from a photoresist mold has recently brought about the development of a 3-D planar microlens having curved sidewalls. A plano-convex type layout was used for the lens layout. The fabricated 3-D planar microlens had a focal spot size of 4.0 μm in width and 7.9 μm in height. It showed a maximum coupling efficiency of 43% between single-mode fibers (SMFs) [14]. The maximum coupling efficiency of the 3-D planar microlens, however, was still inferior to that of a conventional optical interconnection system although it was much higher than that of a two-dimensional (2-D) planar microlens.

In this study, the optical characteristics and fiber-to-fiber coupling efficiency of the 3-D planar microlenses were significantly improved by using circular and biconvex lens layouts and by optimizing the process conditions. As a result, a 3-D planar microlens with excellent focusing characteristics and an single-mode fiber-to-fiber coupling efficiency of over 70% was demonstrated.

II. Microlens Design and Fabrication

Fig. 1 shows a conceptual schematic view of the monolithic optical interconnection with the 3-D planar microlens and two SMFs placed on a V-grooved silicon substrate. The cross-sectional schematic view of the 3-D planar microlens can also be seen in the inset figure. It is shown that the diverging optical signal from the input SMF is effectively focused into the output SMF, as the 3-D planar microlens has curved sidewalls and it focuses the signal in both vertical and horizontal directions. A precise alignment between the microlens and the SMFs by an

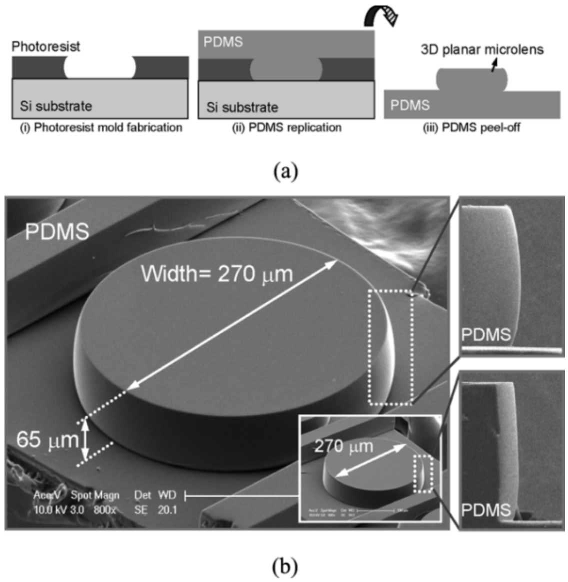

Fig. 2. (a) Process procedure of the 3-D planar microlens. (b) SEM photographs of the fabricated 3-D planar microlens and its sidewall cross section. In the inset figure, SEM photograph of the 2-D planar microlens was shown. The cross section of the 2-D planar microlens with the straight sidewall was also provided.

appropriate V-groove design may maximize the coupling efficiency.

The microlens fabrication procedure consists of two steps. The formation of the photoresist mold by 3-D diffuser lithography technology is followed by a PDMS (10 : 1 mixture of Sylgard A and B, Dow Corning Co., Ltd.) replication step. PDMS was chosen as the lens material due to its process simplicity, excellent nanometer-scale replicating ability [15], and good optical property (commonly used in contact lenses). Before the microlens mold fabrication, the radius of the photoresist sidewall curvature needed to be determined as the microlens layout design is performed precisely with a ZEMAX-EE optical design tool so that the fabricated microlenses can have a well-defined focal spot, meaning that they would have good focusing characteristics.

To examine the radius of curvature, 65-μm-thick AZ9260 positive photoresist (Clariant Co., Ltd.) was used. During the ultraviolet (UV) exposure step, the UV exposure time was optimized at 163 s (UV intensity at 405 nm: 17.2 mW/cm^2) and an F43-725 sandblasted diffuser (Edmund Optics Co., Ltd.) was used to obtain a radius of curvature of 140 μm at the photoresist sidewall. The radius of curvature can be adjusted by controlling the diffusion property of the diffuser. For example, when the F45-656 diffuser was used, with its larger diffusion angle compared to that of the F43-725 diffuser, a radius of curvature of approximately 85 μm was obtained. Moreover, the radius of curvature can be controlled easily by using a polymer-dispersed liquid crystal (PDLC) diffuser in which the diffusion property can vary depending on the voltage applied across the PDLC layer [16].

Based on the fundamental experimental results for the sidewall curvature and the appropriate design for the microlens photomask, the photoresist mold was fabricated. Following this step, the PDMS was poured onto the fabricated photoresist mold and spin-coated (3 s at 1000 rpm) for a uniform PDMS thickness of about 200 μm. The PDMS was then cured and peeled from the photoresist mold. Fig. 2(a) describes the process procedure schematically.

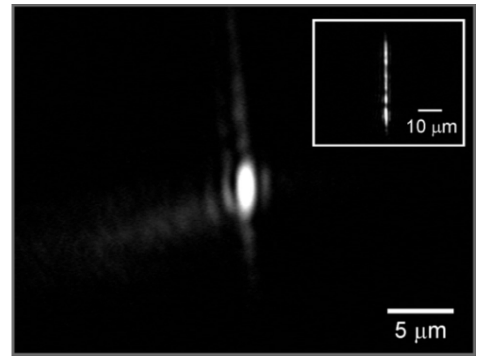

Fig. 3. CCD image of the 3-D planar microlens focal spot. Compared to that of the 2-D planar microlens in the inset figure, the incident light was well focused into the small elliptical spot (width: 1.5 μm; height: 3 μm).

In Fig. 2(b), a scanning electron microscope (SEM) photograph of the fabricated microlens, with its height of 65 μm, is provided. The microlens was designed to have a circular top view, and its width was 270 μm. The microlens sidewall curvature is clearly seen in the cross-sectional SEM photograph of the 3-D planar microlens compared to that of the 2-D planar microlens shown below. The sidewall profile of the 3-D planar microlens can fit into a part of a sphere with a radius of 140 μm. On the other hand, the 2-D planar microlens has a cylindrical shape with a radius of 135 μm and height of 65 μm. The inset of Fig. 2(b) shows an SEM photograph of the conventional 2-D planar microlens with a straight sidewall profile.

III. Results and Discussion

A charge-coupled-device (CCD) image of the focal spot of the 3-D planar microlens is shown in Fig. 3. Light from a laser source was focused by the PDMS planar microlens with a refractive index of 1.43, and the focal spot was observed through a microscope. It was 1.5 μm in width and 3 μm in height, while the 2-D planar microlens has a focal line with a height of 37 μm, as shown in the inset of Fig. 3. Although the slight spatial variation of the focal length resulted in an elliptical focal spot instead of a circular one, the size of the focal spot was small enough for the 3-D planar microlens to allow for an effective collection of the incident signal into the output SMF. The SMF had a core diameter of 10 μm and a numerical aperture of 0.12.

To measure the fiber-to-fiber coupling efficiency of the 3-D planar microlens, the input and output SMFs were fixed on the ultraprecision xyz-translation stages. The light from a laser diode with a wavelength of 1550 nm was coupled to the input fiber. After a prealignment of the fibers with the microlens to achieve the maximum coupling efficiency, the output fiber was scanned in both horizontal (x) and vertical (y) directions to observe the coupling efficiency with respect to the fiber displacement.

The measured coupling efficiency profiles of the proposed 3-D planar microlens and those of a conventional 2-D planar microlens were compared, together with the output fiber displacements in the x- and y-directions, as shown in Fig. 4(a) and (b), respectively.

The 3-D planar microlens showed a maximum coupling efficiency of 71%, which was more than two times the efficiency of the 2-D planar microlens (34%). The broad profile of the 2-D planar microlens with respect to the y-direction displacement

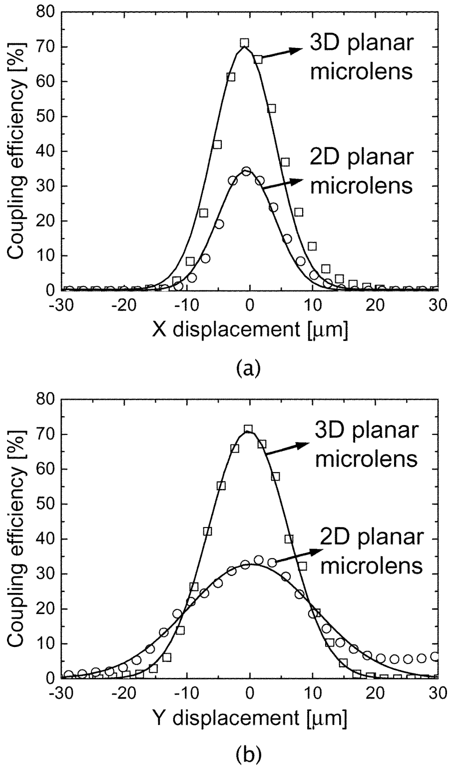

Fig. 4. Measured fiber-to-fiber coupling efficiency with the (a) x-direction and (b) y-direction displacements. The 3-D planar microlens shows more than two times the coupling efficiency (71%) compared to the 2-D planar microlens (34%).

(standard deviation $\sigma = 10.2~\mu$m) represents its inferior focusing characteristics in the vertical direction to the 3-D planar microlens ($\sigma = 6.3~\mu$m).

We consider four factors can contribute the 29% coupling loss of the 3-D planar microlens. They are surface roughness of the 3-D planar microlens, optical loss in PDMS, signal reflection at the air-PDMS interfaces, and the aberrations, where the first two seem to be negligible since the surface roughness is within a few nanometer [15] and the 3-D planar microlenses with narrower width of 80 and 120 μm (therefore, having a biconvex shape) showed the same coupling efficiency of 71% regardless of their width.

Finally, the process sensitivity of the 3-D planar microlens was examined. Because the radius of the sidewall curvature and the focusing characteristic in the vertical direction are mainly determined during the 3-D diffuser lithography procedure of the photoresist mold fabrication, it is very important to observe the effect of variations of the process conditions on the coupling efficiency. The sensitivity of the coupling efficiency with the UV exposure time in the 3-D diffuser lithography step was examined. To within ±3.7% (±6 s) variation of the UV exposure, it was confirmed that the coupling efficiency was over 65%.

IV. Conclusion

A 3-D planar microlens fabricated by novel 3-D diffuser lithography and plastic replication methods was reported, and showed as high as a 71% fiber-to-fiber coupling efficiency, while a 2-D planar microlens coupled only 34% of the incident optical signal into the output fiber. The excellent coupling characteristic of the 3-D planar microlens resulted from a well-designed curved sidewall profile. It displayed a superior focusing characteristic in the vertical direction compared to a conventional 2-D planar microlens. In addition, the curvature of the 3-D planar microlens sidewall can be adjusted by using appropriate diffusers during the 3-D diffuser lithography.

The developed 3-D planar microlens is expected to be directly applied for various optical interconnections in optoelectronic circuits. Additionally, a highly effective fiber-based optical detection system in a biochip can be realized using a proper combination of the PDMS microfluidic channel and these 3-D planar microlenses.

Acknowledgment

The authors would like to thank Y. B. Cho and Prof. S. Y. Shin for their supports in the optical measurements.

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