Microlens With Tunable Astigmatism

Sz-Yuan Lee, Wen-Chih Chen, Hsi-Wen Tung, and Weileun Fang

***Abstract*—A novel astigmatism-tunable microlens is reported in this letter. This device is based on a thermal-actuated current-controlled tunable polymer lens. The thermal deformation as well as surface profile of polymer lens is tuned by temperature using the current induced Joule heating. The asymmetric boundary condition is further applied on the silicon conducting ring of the lens to invoke asymmetric deformation of the polymer lens as well as astigmatic change of the polymer lens. To prove the concept, the astigmatism-tunable polydimethylsiloxane lens has been fabricated on the silicon-on-glass wafer. Astigmatism tuning was demonstrated by change of astigmatic focal distance, from 1590 to 44 μm, as input current increased from 0 to 30 mA. In addition, aspect ratios of focal spot shape were varied from −20 to −1.3 and 16 to 1.22 with respect to anterior and posterior focal points. This device provides a feasible solution to the dilemma of astigmatic tuning capability and miniaturization. In summary, the present device has the potential to act as a key component for microelectromechanical systems-based aberration corrector or laser focus-spot shaper.**

***Index Terms*—Astigmatism, microelectromechanical systems, polydimethylsiloxane (PDMS), polymer lens, tunable lens.**

I. Introduction

ASTIGMATISM is a common aberration existing in most optical systems. In most cases, the astigmatism of optical systems can be fully compensated by adding a cylindrical lens [1]–[3]. The cylindrical lens can be easily miniaturized, however, its astigmatism cannot be tuned; and thus, customized optical surface design or artificial refraction-index distribution is required. Adaptive optics is a new approach to reduce astigmatism [4]–[6]. The adaptive optics corrector is not only reconfigurable, but also eliminates other aberrations simultaneously. However, the complicated fabrication process and complex control requirements significantly limit the potential applications of adaptive-optical devices. Furthermore, it is difficult to miniaturize the conventional adaptive optical devices to millimeter scale or even smaller.

The compactness requirement in a modern optical system leads to emerging needs of microoptical astigmatism generator/compensator. For example, in the application of a semiconductor laser (670–680 nm) de-astigmatism, typical microlens provides 40-μm astigmatic focal distance (AFD) [7]. Similar application for diode laser with a wavelength of 774 nm requires a correction lens of 83-μm AFD [8]. For the applications of optical communication, a correction microlens is presented with focal lengths of 127 and 606 μm for an unstable-resonator laser (wavelength 980 nm) [9]. In [10], commercial polymer-material microastigmatic lenses, designed for accommodating diode laser, optical fiber, and waveguide, are fabricated with a focal length of 218 and 921 μm (wavelength 1550 nm).

Manuscript received May 9, 2007; revised June 4, 2007. This work was supported in part by NSC (NSC-95-2221-E-007-158) and in part by MOE (95-EC-17-A-07-S1-011).

S.-Y. Lee is with the Institute of Microelectromechanical System, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C. (e-mail: d929206@oz.nthu.edu.tw).

W.-C. Chen and H.-W. Tung are with the Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C. (e-mail: d927713@oz.nthu.edu.tw; g923762@alumni.nthu.edu.tw).

W. Fang is with the Institute of Microelectromechanical System, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C., and also with the Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013, R.O.C. (e-mail: fang@pme.nthu.edu.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2007.903010

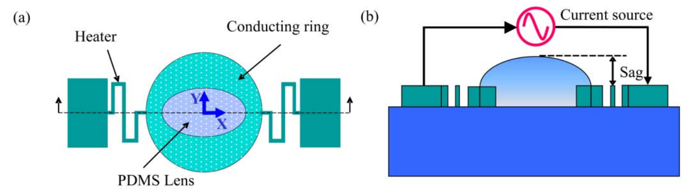

Fig. 1. Schematic of thermal tunable microlens. (a) Top view and (b) side view.

Presently, none of the existing astigmatism compensation scheme can simultaneously meet the requirements of miniaturization and tuning capability. This study reports a new type of micromachined polymer microlens having the two features. The asymmetrical deformation of the polymer lens caused by joule heating is employed to invoke tunable astigmatism. The astigmatism control is simply via input current. Compared to conventional astigmatic lenses, this design has advantages in several aspects. 1) To our knowledge, it is the first microlens with tunable astigmatism. 2) The device presented here provides AFD from 1590 to 44 μm (at wavelength 632.8 nm). The wide range of AFD covering needs of versatile applications, which is fulfilled by fix-AFD microlens presently. 3) It is a pure solid structure and employs simple actuating principle. It is the first tunable microlens relates to only a single state of matter. This makes the device robust and reliable. Its control is as easy as tuning input current. 4) The simple structure makes the fabrication relatively easy and low cost. Further more, it implies the device is suitable to integrate with other microopticalelectromechanical systems devices.

II. Design and Simulation

The new device inherits operation principle and fabrication processes from thermal-actuated focal-length tunable microlens in [11]. Fig. 1(a) illustrates the design concept. The device consists of polymer-lens [the discussions in this study were focused on the polymer material of polydimethylsiloxane (PDMS)], silicon conducting ring, and silicon heaters. The asymmetry aperture in the new design is the main difference from the pure focal-length tunable device. In Fig. 1(b), the applied current heats the conducting ring and PDMS lens. Thus, the thermal expansion of PDMS confined by the silicon conducting ring will lead to the deformation of PDMS-lens surface profile. In the

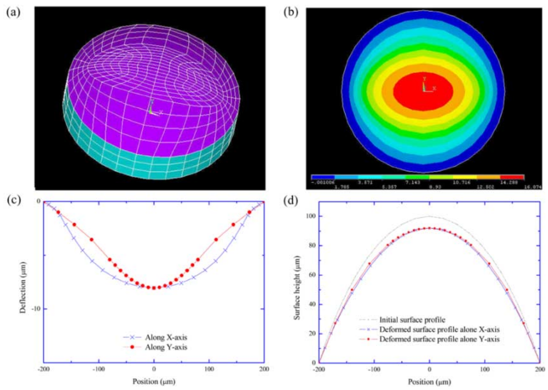

Fig. 2. Simulation of lens profile change under temperature change of 100 °C. (a) FEM model of PDMS lens and conducting ring; (b) contour plot of asymmetric surface deflection; (c) deflection along x- and y-direction; and (d) lens surface profiles before and after temperature change.

present design, the elliptical shape of the conducting-ring aperture raises asymmetric boundary constraints on the PDMS lens. Consequently, the deflection of the lens surface profile due to thermal deformation is different along the x- and y-axes, and meanwhile leads to different variations in radius of curvature (ROC) of the lens surface profile along the x- and y-axes. As a result, the astigmatism of the polymer lens can be easily tuned by joule heating using the input current.

The thermal mechanical behavior of the device depicted in Fig. 1 can be predicted by finite-element analysis. Fig. 2(a) shows a typical finite-element method (FEM) model in this study. To compare with the experiment results, the FEM model established a silicon conducting ring with an outer radius of 200 μm and an elliptical aperture 150 μm long in semimajor axis and 100 μm long in semiminor axis. In addition, the radius and sag of the modeled PDMS lens were 200 and 100 μm, respectively. Fig. 2(b) shows a typical deformation contour of lens surface (in the z-axis direction) while changing temperature. It indicates that the thermal deformation of the lens surface is strongly affected by the aperture shape of the conducting ring. Fig. 2(c) quantitatively shows the deflection of lens surface profiles along the x- and y-axes with a temperature decrease of 100 °C. It resembles the case that a PDMS lens was cured at 130 °C and cooled to room temperature. On the other hand, as this lens heats from room temperature to curing temperature, its surface profile will be deformed to the initial curing condition. As indicated in Fig. 2(d), the lens surface profiles along the x- and y-axes are initially identical at the curing temperature, which means no astigmatism exists on-axis incident light. As the temperature is decreased, the lens profile along the x-axis has a larger deformation compared to that of the y-axis. Hence, the ROC of the PDMS lens along the x-axis is smaller than that along the y-axis, and further leads to the occurrence of an astigmatism. Since the PDMS lens is operated within its rubbery plateau region, the simulated process is reversible. Therefore, the cooled lens depicted above can be heated up again from ambient temperature to 130 °C; the lens surface would restore to identical profile along the x- and y-axes. Meanwhile, the astigmatism of the lens would decrease to zero as temperature is increased.

A ray tracing optical software is employed to model the focusing effect of the astigmatic lens. The modeled lens contains an elliptical clear aperture of 150 μm $\times$ 100 μm. Astigmatism is simulated by shorting the ROC of the lens along the the x-axis. Since the modeled lens has a shorter ROC along the X-direction, the vertical-shaped focal spot appears first (i.e., anterior focus) and then the horizontal-shaped focal spot (i.e., posterior focus). The AFD is defined as the distance between these two orthogonal focuses. Figs. 3(a) and (b), respectively, show the simulated anterior and posterior focal spot shapes for different AFD. The aspect ratio of focal spot shape is defined as the quotient of focal spot length along the x- and y-axes. The positive sign indicates a length along the x-axis larger than the y-axis, and the negative sign represents the reverse case. It shows that a larger astigmatism results in a higher aspect ratio (absolute value) of the focal spot shape.

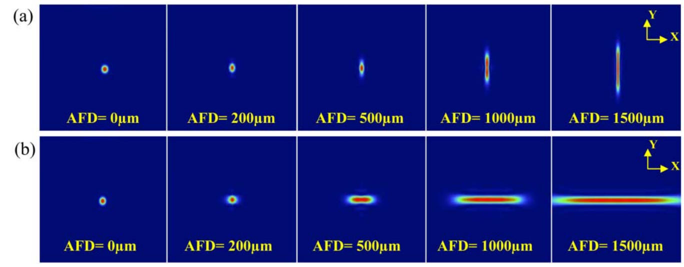

Fig. 3. Simulated (a) anterior and (b) posterior focal spots with increasing astigmatism for aperture radius of $X/Y = 3/2$. The AFD from left to right are 0, 200, 500, 1000, and 1500 μm, respectively. (Wavelength $= 632.8$ nm).

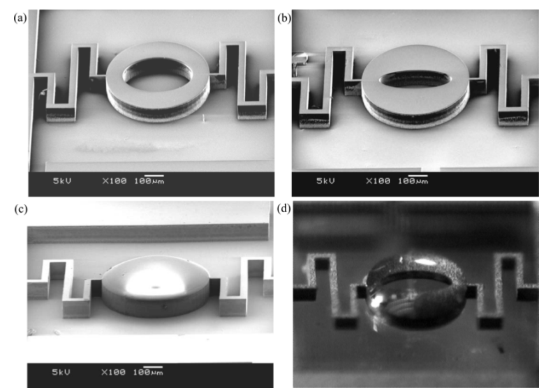

Fig. 4. Typical fabricated devices. Asymmetric type tunable lens with aperture radius of (a) $X/Y = 200\ \mu\text{m}/150\ \mu\text{m}$, (b) $X/Y = 200\ \mu\text{m}/75\ \mu\text{m}$. (c), (d) Side view and top view of lens after PDMS dispensing.

In summary, the simulations in Figs. 2 and 3 clearly show that the joule heating by input current can change the PDMS lens profile so as to further tune the AFD and aspect ratio of focus spots. Hence, the lens can be used to adding astigmatism to microoptical systems or adding counter-astigmatism to compensate existing astigmatism of a microoptical system.

III. Experiment and Results

This study employed the process in [11] to fabricate the present devices. Fig. 4 shows the typical fabrication results. The scanning electron microscope (SEM) micrographs in Fig. 4(a) and (b) clearly show the heaters and conducting ring made of single crystal silicon. The heater has a length of 2000 μm and a width of 20 μm. The outer radius of the conducting ring is 300 μm, and the elliptical apertures are

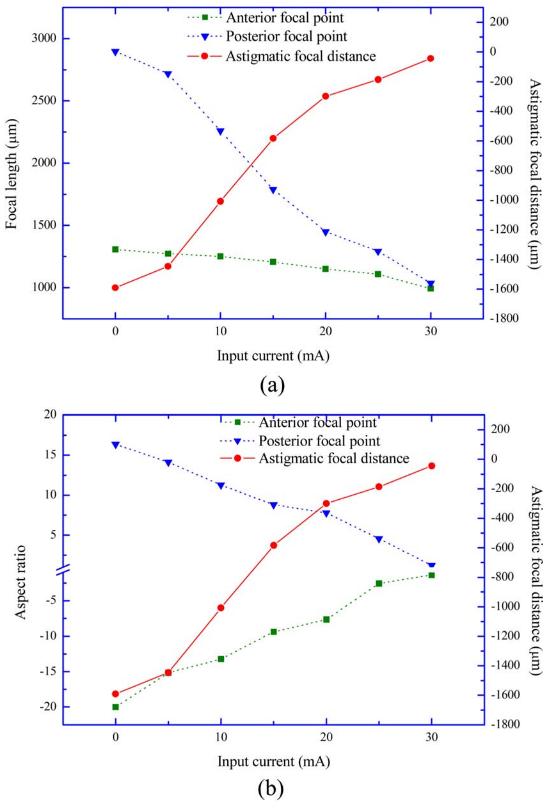

Fig. 5. Measurement results of astigmatism versus input current at wavelength $= 632.8$ nm. (a) Focal length of two focuses and AFD (negative sign indicates that the anterior focal spot is vertical-shaped), and (b) aspect ratio of focal spots changes with input current.

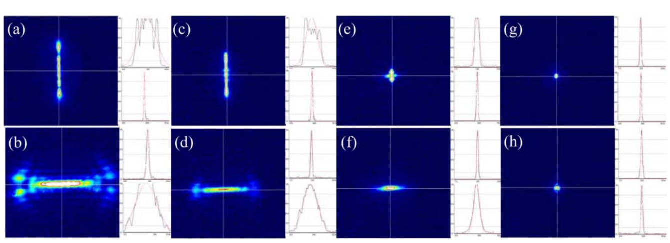

Fig. 6 Measured anterior and posterior focal spots at different driving current of (a), (b) 0 mA, (c), (d) 15 mA, (d), (e) 25 mA, and (f), (g) 30 mA.

200 μm $\times$ 150 μm and 200 μm $\times$ 75 μm, respectively. Furthermore, the conducting rings of various outer radii and elliptical apertures have also been fabricated. The photos in Fig. 4(c) and (d) show the SEM and optical micrographs of the complete astigmatism tunable lens after PDMS dispensing.

The same optical measurement system in [11] was applied to characterize the focal length of the microlens, and to observe the focal spots as well. The tested device has a conducting ring of 200-μm outer radius with an elliptical aperture of 150μm $\times$ 100μm. In this experiment, the astigmatism variation is characterized by AFD and the aspect ratio of the focal spot shape. The measurement results in Fig. 5(a) show the variation of focal length (at wavelength $= 632.8$ nm) with the input current. As the current increases from 0 to 30 mA, the anterior focal length (square dots) varies from 1307 to 993 μm; the posterior focal length (triangle dots) varies from 2897 to 1037 μm. Thus, as indicated by the circle dots in Fig. 5(a), the absolute value of AFD is 1590 μm at 0-mA input current. Since the PDMS lens was curing at 130 °C, the lens has an astigmatism at ambient temperature (20 °C). As the input current increases from 0 to 30 mA, the absolute value of AFD decreases gradually to 44 μm, and approaches nearly to 0 μm. This implies the operating condition is steadily approaching to curing temperature, and the astigmatism of PDMS-lens is gradually approaching zero. In addition, as the input current increases from 0 to 30 mA, the measurement results in Fig. 5(b) show the aspect ratio of anterior focus spots changes from -20 to -1.3, and that of posterior focus spots changes from 16 to 1.22. The measurement results agree with the simulation predicted in Fig. 3 that large astigmatism accompanies a higher aspect ratio (absolute value) focal spot shape. Fig. 6 shows the corresponding anterior and posterior focal spot shapes captured by the beam profiler in optical measurement system at 0, 5, 15, and 30 mA, respectively. Similar measurements were also performed on the light sources of different wavelengths. The AFD changes from 1576 to 43 μm at the wavelength of 532.18 nm, and from 1572 to 43 μm at the wavelength of 473.06 nm.

IV. Conclusion

Astigmatism is one of the most common aberrations in optical systems. It can be compensated for by adding counter-astigmatism. However, there was not much of a successful tunable astigmatism compensator, except the adaptive optical system. This study has demonstrated a new approach to successfully provide tunable astigmatism. The tuning of astigmatism due to input current is verified by corresponding variations of AFD and an aspect ratio of focal spot shape. Compared to the existing adaptive optics approaches, it has the following advantages: 1) easy fabrication and miniaturization; 2) easy integration with other microoptical components; 3) astigmatism tuning mechanism is simple and reliable; and 4) low cost.

References

[1] W. T. Foreman, "Lens correction of astigmatism in a Czerny-Turner spectrograph," *Appl. Opt.*, vol. 7, pp. 1053–1059, 1968.

[2] E. Acosta, C. Gomez-Reino, and R. M. Gonzalez, "Design of an anamorphic gradient-index lens to correct astigmatism in diode lasers," *Proc. SPIE*, vol. 1401, pp. 82–85, 1990.

[3] J. J. Snyder, "Cylindrical micro-optics," *Proc. SPIE*, vol. 1992, pp. 235–246, 1993.

[4] J. M. Spinhirne, D. Anafi, R. H. Freeman, and H. R. Garcia, "Intracavity adaptive optics. Correction performance 1: Astigmatism," *Appl. Opt.*, vol. 20, pp. 976–984, 1981.

[5] J. Liang, D. Williams, and D. Mille, "Supernormal vision and high-resolution retinal imaging through adaptive optics," *J. Opt. Soc. Amer. A*, vol. 14, pp. 2884–2892, 1997.

[6] E. J. Fernández and P. Artal, "Membrane deformable mirror for adaptive optics: Performance limits in visual optics," *Opt. Express*, vol. 11, pp. 1056–1069, 2003.

[7] X.-Q. Zhou, N. K. Ann, and K. S. Seong, "Single aspherical lens for deastigmatism, collimation, and circularization of a laser beam," *Appl. Opt.*, vol. 39, pp. 1148–1151, 2000.

[8] K. Tatsuno and A. Arimoto, "Measurement and analysis of diode laser wave fronts," *Appl. Opt.*, vol. 20, pp. 3520–3525, 1981.

[9] Z. L. Liau, J. N. Walpole, D. E. Mull, C. L. Dennis, and L. J. Missaggia, "Accurate fabrication of anamorphic microlenses and efficient collimation of tapered unstable-resonator diode lasers," *Appl. Phys. Lett.*, vol. 64, pp. 3368–3370, 1994.

[10] W. R. Cox, T. Chen, and D. J. Hayes, "Micro-optics fabrication by ink-jet printing," *Opt. Photo. News*, pp. 32–35, 2001.

[11] S.-Y. Lee, H.-W. Tung, W.-C. Chen, and W. Fang, "Thermal actuated solid tunable lens," *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2191–2193, Nov. 1, 2006.