# Thermal Actuated Solid Tunable Lens

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

*Abstract*—**In this letter, the concept of driving tunable solid lens using microthermal actuator is presented. This microoptical device is composed of a flexible polydimethylsiloxane (PDMS) lens, silicon conducting ring, and silicon heater. The mismatching of coefficient of thermal expansion and stiffness between PDMS and silicon will lead to the deformation of polymer lens during heating, so as to further change its focal length. To demonstrate the feasibility of this approach, a microfabrication processes have been established to monolithically fabricate the present microoptical device. The typical experiment results show that the tunable focal length was up to 834 $\mu$m with an input current of 70 mA.**

*Index Terms*—**Microoptoelectromechanical system (MOEMS), polydimethylsiloxane (PDMS), thermal actuator, tunable lens.**

## I. INTRODUCTION

THE microoptoelectromechanical system (MOEMS) has been widely applied in the field of communication, imaging, display, and biodetection. Microlens is regarded as one of the key components in microoptical system. Presently, the focal length tunable microlens attracts attention and is extensively studied. In addition to the optical performance of the microlens, the fabrication and assembly processes are also major considerations in view of its small size. Typical tunable microlenses in existing works are composed of materials with different states (e.g., solid structures and liquid lens), and can be categorized as three types. For instance, the first category is electrowetting tunable lenses [1]–[3]. After applying large electric field at the interface of liquid lens and solid structure, the contact angle as well as the surface profile of the liquid lens is changed. The interface friction and evaporation of liquid problems cannot be ignored. The second category is the liquid-filled lens approach [4]–[10]. The main idea is to deform a liquid-filled chamber, which acts as a lens, via external pressure source. This approach provides large tuning ranges. However, an additional pressure source could be required [4]–[9], and the self-weight of liquid may introduce unwanted deformation. The third category is a liquid crystal immersed approach [11]. This method directly changes refraction index of liquid crystal to modify the focal length, yet it is difficult to realize an MOEMS due to the severe optical aberration induced by fringe effect.

The fabrication and packaging processes have been employed to improve the performance of the tunable liquid lens. For instance, the evaporation problem can be prevented using the packaging approach [3]. A built-in heating system can integrate with the microlens using the microfabrication processes to replace the pressure source [10]. In this study, the concept of tuning the focal length by means of a solid deformable polymer lens is presented. It is easy to tune the microlens by means of joule heat generated from a built-in microheater. Thus, the problems resulted from the liquid-state lens are prevented. Moreover, simple planar fabrication processes are also established to fabricate and integrate the tunable solid lens with various MOEMS components. The experiment results demonstrate the feasibility of the present design.

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Color versions of Figs. 1, 2, and 4–7 are available at http://ieeexplore.ieee.org.

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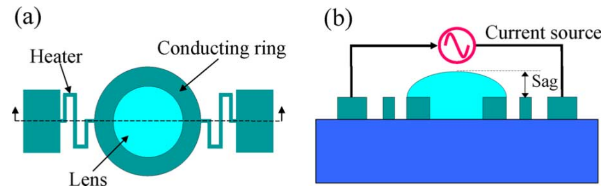


Fig. 1. Schematics of the present design; (a) top view and (b) side view.

## II. DESIGN AND SIMULATION

The present design concept is schematically illustrated in Fig. 1. The device consists of a polymer lens, a conducting ring, and a pair of heaters. When current is applied to the device, as illustrated in Fig. 1(b), the temperature of the conducting ring is increased by the heater. The heat also conducts to the microlens via the conducting ring. The temperature distributions of the conducting ring and microlens are ignored for these microscale components. Thus, the conducting ring and the microlens have the same temperature at the steady state. According to the difference of thermal expansion and stiffness between the conducting ring and microlens, the expansion of the lens is confined by the conducting ring in the edge. This will result in surface deformation of the microlens, so as to further change the radius of curvature $R$ as well as the focal length of the microlens. The present study employs this concept to tune the focal length of the microlens by temperature, which is easily controlled via managing the current input of the heater. In summary, this device has only simple and reliable thermal expansion of solid material, and the phase transition is not required during operation.

For a given temperature variation $\Delta T$, the lens with a higher coefficient of thermal expansion (CTE) leads to a larger variation of $R$. The rising temperature can be reduced if the microlens has a larger CTE and a smaller stiffness, as compare with the conducting ring. Moreover, the materials for lens and conducting ring are also influenced by the microfabrication processes. In this study, the polymer [polydimethylsiloxane (PDMS)] with low Young's modulus and large CTE is selected as the material for the lens. The PDMS has Young's modulus of about several MPa; CTE is $3 \times 10^{-4}$. In addition, the transparency of PDMS for visible light is even up to 95%, which makes it widely used as optical material. On the other hand, the

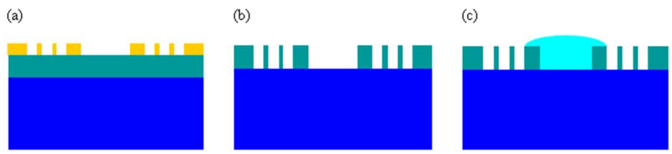


Fig. 2. Schematics of fabrication process flow, (a) photolithography on an SOG wafer, (b) patterned the device silicon layer by DRIE, and (c) dispense polymer on silicon.

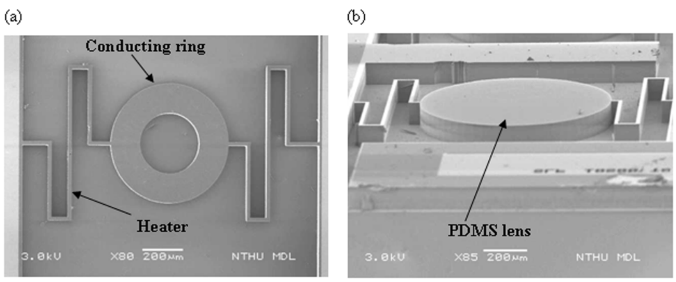


Fig. 3. SEM photos of typical fabricated devices, (a) before PDMS dispensing, and (b) after PDMS dispensing.

single crystal silicon (SCS) with a larger Young's modulus and a smaller CTE is selected as the material for conducting ring and heater. The Young's module and CTE of SCS are 165 GPa and $2.6 \times 10^{-6}$, respectively. Those characteristics make silicon comparably rigid and temperature invariant in dimension. The commercial finite element software (ANSYS) is employed to predict the variation of lens deformation with respect to the increasing temperature. Typical simulation results show linear relation between sag deflection and temperature increasing.

## III. Experiment and Results

The fabrication process steps are schematically illustrated in Fig. 2. The process starts on a silicon-on-glass (SOG) wafer. The glass wafer is chosen for its optical transparency and electrical isolation. The microcomponents are made of the silicon layer. The characteristics of the tunable lens are influenced by the thickness and resistivity of the silicon device layer. To reduce the driving voltage of the heater, the low resistance silicon layer was employed in this study. As shown in Fig. 2(a), the in-plane patterns of microcomponents were defined using the photolithography process. After that, the silicon layer was etched by deep reactive ion etching (DRIE). Thus, the microcomponents such as heater and conducting ring were formed, as shown in Fig. 2(b). After removing the photoresist, the PDMS polymer was dispensed into the space enclosed by conducting ring. As shown in Fig. 2(c), a perfect lens surface is automatically formed due to the surface tension of PDMS. The final step is curing the PDMS (Daw Corning SYLGARD184 PDMS, with a Young's modulus of 1.32 MPa and a refraction index of 1.43) in 150 °C for 15 min. Fig. 3 shows the SEM photos of typical fabrication results before and after PDMS lens dispensing. The heater and conducting ring are clearly observed in Fig. 3(a). The conducting ring has an inner radius of 150 $\mu$m and a width of 150 $\mu$m; the heater has a length of 2000 $\mu$m and a width of 10 $\mu$m. Fig. 3(b) shows the PDMS lens on conducting ring right after the process, its initial sag is 34.6 $\mu$m.

There were three test setups established, as shown in Fig. 4, to characterize the performance of the fabricated tunable lens. The optical interferometer in Fig. 4(a) was employed to measure deformation of surface profile of PDMS lens with resolution of

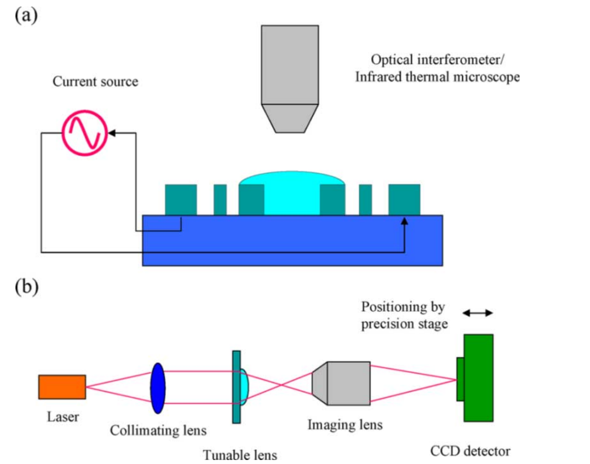


Fig. 4. Test setups for the measurement of (a) input current versus sag, as well as temperature (b) input current versus focal length.

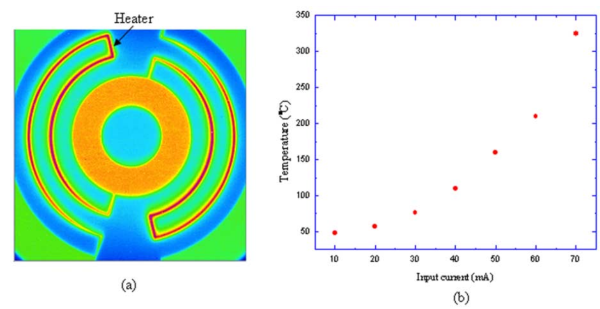


Fig. 5. Measurement results of (a) temperature distribution over conducting ring and heaters, and (b) input current versus polymer lens temperature.

nanometer. The infrared thermal microscope was used to measure the temperature distribution over device under heating, its spatial resolution is ranging from 3 to 60 $\mu$m and temperature resolution is 0.1 °C. To measure focal length of microlens, an optical system was setup as shown in Fig. 4(b). In this experiment, the focal length of tunable lens was determined by observing the image of charged coupled device camera.

Fig. 5(a) shows a typical temperature distribution of the present device measured by the infrared microscope in Fig. 4(a). The measured temperature distribution was originally displayed by colors, and the heater indicated in the figure had the highest temperature. According to the symmetric design, the temperature over the conducting ring is uniform, in that a homogenous temperature distribution over PDMS lens can be expected. For the lens on a conducting ring with an inner radius of 150 $\mu$m and a width of 150 $\mu$m; the variation of lens temperature with the input current measured by the infrared microscope is shown in Fig. 5(b). The lens temperature is rising while increasing the input current. Fig. 6 shows typical surface profiles of the microlens (on a conducting ring with an inner radius of 80 $\mu$m and a width of 100 $\mu$m) measured by the optical interferometer in Fig. 4(a). It clearly demonstrates that the lens surface profile deformed according to the temperature variation at different input currents.

The measurement results in Fig. 7(a) indicate that the lens sag of PDMS lens (on a conducting ring with an inner radius of 150 $\mu$m and a width of 150 $\mu$m) varies linearly with the rising temperature. This characteristic agrees with the simulation results. The test results in Fig. 7(b) shows sag of PDMS lens (on a conducting ring with an inner radius of 150 $\mu$m and a width of

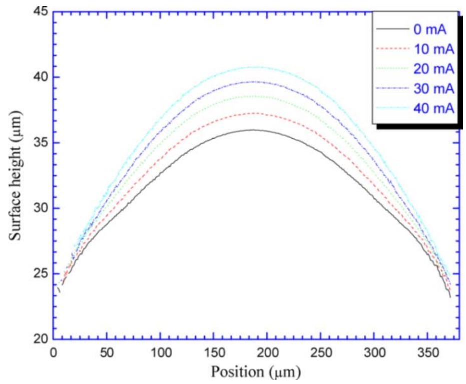


Fig. 6. Measured polymer lens surface profiles at different input currents.

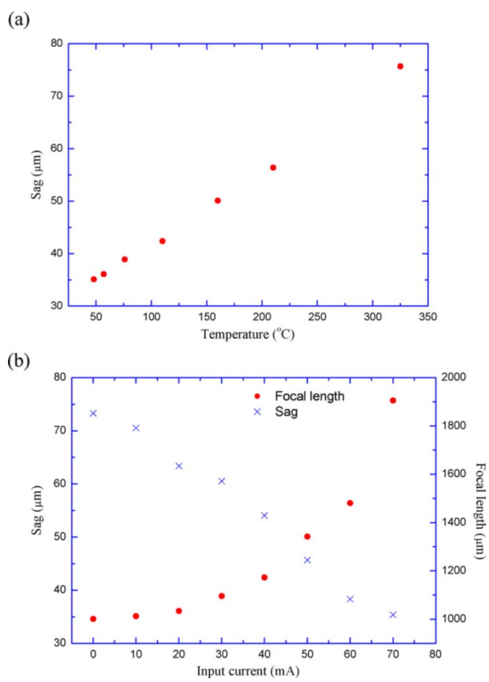


Fig. 7. Measurement results of (a) lens sag versus lens temperature, and (b) lens sag and focal length versus input current.

150 $\mu$m) with respect to the input current. According to Joule's law, the thermal energy produced by the resistor varies quadratically with the input current. In short, the simulated results agree well with the experimental data in Fig. 7(b) qualitatively. For the present design, a larger lens sag leads to a smaller radius of curvature of lens profile as well as a shorter effective focal length. Accordingly, the focal length can be successfully tuned by manipulating the input current. The variation of focal length with the input current of the present device was characterized by the test setup in Fig. 4(b). Fig. 7(b) shows the typical measurement results. In this case, the focal length of polymer lens varied from 1852 to 1018 $\mu$m after the applying current increased from 0 to 70 mA. To demonstrate the optical modulation capability of the presented device, the polymer lens was placed under a microscope to assist the focusing of a microgrid array. The microgrid array contained square targets with in-plane dimensions of 10 $\mu$m $\times$ 10 $\mu$m. The photos in Fig. 8 show the variation of images during focusing. At the beginning, the image containing the microgrid array is out-of-focus, as shown in Fig. 8(a). After adjusting the input current from 20 to 50 mA, the focal point

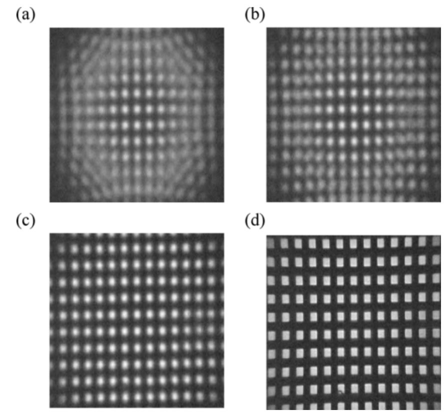


Fig. 8. Succeeding images under focal length changing.

moved closer to the target such that the image became in focus, as shown in Fig. 8(b)–(d).

## IV. Conclusion

In this letter, the design of the thermal actuated tunable lens has been demonstrated. It provides a simple and reliable mechanism to adjust the focal length of the microlens. A typical example demonstrated in this study showing that the tunable focal length was up to 834 $\mu$m with an input current of 70 mA. In comparison with other tunable microlens systems, the present device has the following characteristics. First, the tunable lens is composed of only solid-state polymer material, and no phase transition is required during operation. Second, the fabrication process is easy and has a very high yield rate. Third, the device requires no extra pumping system, like in liquid filled lens, so as to enable a stand-alone microtunable lens. These characteristics make the device suitable to be integrated with microoptics system. The driving current could be reduced and the tunable range could be increased through the optimizing design of conducting ring and heater.

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