Applied Physics Letters

Thermally actuated tunable liquid microlens with sub-second response time

Alireza Ousati Ashtiani and Hongrui Jiang

Citation: Appl. Phys. Lett. **103**, 111101 (2013); doi: 10.1063/1.4820772
View online: http://dx.doi.org/10.1063/1.4820772
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v103/i11
Published by the AIP Publishing LLC.

APPLIED PHYSICS LETTERS **103**, 111101 (2013)

Thermally actuated tunable liquid microlens with sub-second response time

Alireza Ousati Ashtiani[1] and Hongrui Jiang[1,2,3,4,a)]
[1]*Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[2]*Department of Biomedical Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[3]*Materials Science Program, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[4]*McPherson Eye Research Institute, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*

(Received 26 July 2013; accepted 12 August 2013; published online 9 September 2013)

This letter reports a thermally actuated liquid microlens. In this design, a thermoelectric device was brought into direct contact with water to alter the water temperature and drive the lens through the thermal expansion of water. The shape of a pinned water meniscus at an aperture was deformed in response to the net volume change in the water, creating a tunable lens with a fast thermal response time of 0.8 s. Focal length of the microlens varied continuously from −82 mm to −29 mm as the temperature was increased from 20 °C to 30 °C. *© 2013 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4820772]

Tunable liquid microlenses have many potential applications, ranging from small surveillance cameras to smartphones and laparoscopic devices.[1–4] Compared to solid microlenses, they provide the added flexibility of a controllable focal length that enables the lens to focus an image without mechanical lens movement that in turn empowers engineers to make cameras smaller, simpler, and even on flexible substrates.[2] Furthermore, the meniscus profile of a liquid microlens is defined via surface tension, which gives rise to an optically smooth surface, resulting in high optical quality lenses.[3]

In order to drive a liquid lens, various actuation mechanisms have been proposed. For instance, electrowetting is a widely studied driving mechanism for lens manipulation.[4] Very fast microlenses have been demonstrated via electrowetting.[5] Moreover, responsive arrays of microlenses with indirect electrowetting actuation that achieve a focal length modulation speed of 1 kHz, have been reported.[6] Further, among the several actuation mechanisms for a liquid lens, electrowetting also enjoys commercial production. Nonetheless, electrowetting usually shows hysteresis[7] and also requires an electrical circuit to supply relatively high voltages.[8] In other designs, deformable actuators have been used to create a pressure gradient inside a lens chamber to deform the meniscus, thus shaping the lens profile. Examples of such driving mechanisms include electroactive polymers[9] and piezoelectric bimorph actuators,[10] all of which generally use large area actuators, making their integration challenging in space limited applications. Furthermore, fast focusing using a pinned-contact oscillating liquid lens has been reported,[11] which is based on a harmonically driven liquid meniscus. Although such a type of liquid lens shows a very fast response time, it might be hard to maintain a specific focal length. An external pressure source can as well be used to vary the lens surface profile[12] in different types of liquid lenses. In a recent pressure driven lens, a liquid crystal actuator has been used to stimulate the lens.[13] This design, however, still needs a relatively high functional voltage (80 V). Yet another actuator that has been utilized to drive liquid lenses is the stimulus responsive hydrogel.[14] Thermally actuated hydrogels are used to induce a shape modification in a pinned water meniscus and thus change the focal length.[15] Previous experiments showed promising optical performance, yet they demonstrated a limited response time ranging from tens of seconds to a few seconds.[16]

Recently, focus tunable lenses based on thermopneumatic actuators were reported.[17,18] This approach exploits the thermal expansion of an encapsulated gas, to move the liquid inside the lens, thus inducing a change in the lens surface profile. The thermopneumatic lens has an inherent simplicity since only a resistive element is needed to actuate the device. However, these types of lenses typically show tens of seconds of response time. Moreover, they usually rely on natural heat dissipation to cool down, since the heat pump is effectively unidirectional, as the electrical resistor can only inject heat into the working fluid and cannot extract thermal energy out of it. Thus, the temperature alteration is not bi-directionally symmetric, meaning that the working fluid (gas) will need more time to cool down compared to the time it needs to warm up. In addition, an encapsulated working fluid incorporated in a thermopneumatically driven lens is inherently compressible. Therefore, it is sensitive to vibrations since the mass of the liquid of the lens would exert force on the working fluid when it is accelerated and as a result, it can change the net volume of the working fluid. Hence in practical application, vibration and movement of the device affect the focal length of the lens. In this paper, we present a thermoelectrically driven thermally actuated liquid lens that relies solely on liquid expansion to address aforementioned challenges.

Figure 1 shows the device cross section. A thermoelectric (TE) device is placed and sealed on top of a deionized (DI) water filled cavity that is made from poly(isobornyl acrylate) (poly-IBA). On top of the thermoelectric device, a heatsink is placed to dissipate the heat generated in the TE device. The water filled cavity beneath the TE is connected

---

[a)]Author to whom correspondence should be addressed. Tel.: 608-265-9418. Fax: 608-262-1267. Electronic mail: hongrui@engr.wisc.edu.

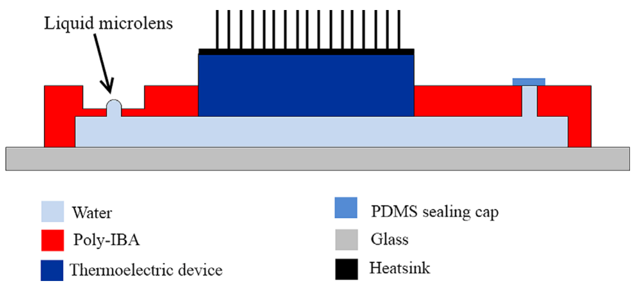
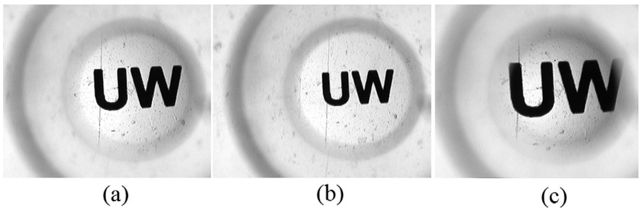


FIG. 1. Cross section of thermoelectrically driven tunable liquid microlens. On the left side, a small aperture would pin a water meniscus that forms the lens.



(a) (b) (c)

FIG. 2. Images of an object after passing through the curved water meniscus as observed via a microscope. (a) An initial image at the room temperature of 25 °C. (b) A demagnified image at 20 °C. (c) A magnified image at 30 °C.

via an opening to the air interface. This shallow water cavity constitutes the heat engine of the device. Surface of the poly-IBA inside the cavity and along the edges of the opening is made hydrophilic to pin the water meniscus at the opening (aperture) and form the lens at the interface of the water meniscus and the surrounding material which can either be air or in practical applications, a density matched, immiscible liquid with a reasonably different refractive index. By changing the temperature of water inside the cavity through the TE device, the density of water is altered and considering that its mass can be kept constant with proper sealing, this results in a net volume change of water. This volume change in turn would vary the radius of curvature of the spherical cap of the water meniscus, and hence the focal length of the microlens.

Replacing gas, used as a working fluid in previous designs,[11,17,18] with liquid results in a simpler device construction since there is no need to encapsulate the working fluid separately from the liquid used in the optical part of the device. Effectively, the working fluid of the heat engine and the liquid used in the optical system are the same. Furthermore, since the working fluid of the heat engine is a liquid, it will remain incompressible because of the very large bulk modulus of liquids. Consequently, the volume of the working fluid of the heat engine will not be affected by vibration and physical movement of the lens, resulting in a more stable lens.

The TE heat pump can be used to both increase and decrease the temperature of the working fluid incorporated into the lens. In order to stabilize the heat engine at a constant temperature, a closed-loop system with feedback is needed, in either a resistive heat pump or a TE based design. Yet owing to the bi-directional heat pumping capability of the TE device, one can implement a controller with a relatively large overshoot, which in turn results in a much faster system compared to a resistive based heat pump.[17,18]

In order to test the operation of the proposed design, a prototype was fabricated and placed on top of a printed object on a transparent film, while the resulting image was observed via a microscope. As the temperature of the water cavity varied from 20 °C to 30 °C, images acquired through the curved meniscus varied accordingly. As anticipated, a gradual volume expansion resulted in the variation in the radius of curvature of the water meniscus and thus a change in the focusing power of the meniscus, which was clearly evidenced by the change in the image compared to the initial condition (Figure 2).

The device assembly procedure consisted of two stages.[19] First, a poly-IBA bi-layer structure was fabricated on top of a glass substrate. Second, the device assembly was conducted on the fabricated structure. In the device assembly process, initially a type T thermocouple sensor (Omega Engineering Inc., Stamford, CT, USA) was put in a predefined recess and a small amount of thermally conductive epoxy (Arctic Alumina^{TM}, Arctic Silver Inc., Visalia, CA, USA) was applied on it. Then, lower edges of the TE device (TE-65-0.6-0.8, TE Technology, Inc., Traverse City, MI, USA) were coated with a thin layer of the epoxy glue and it was placed on top of the device structure, thus forming the device assembly, as can be seen in Figure 3. After water injection from the right aperture and forming a pinned water meniscus on the left aperture, the left water meniscus was covered by Dow Corning 550 silicone oil to prevent further water evaporation and a polydimethylsiloxane cap was also placed on top of the oil cavity to prevent oil from pouring in vertical orientations.

In order to assess the speed of microlens, a two-step approach was implemented. In the first step, the steady-state focal length measurement as a function of the device temperature was conducted in a manner similar to the methods previously used by our group.[2] In this method, the microlens was fixed on an optical bench and was illuminated by a collimated light source. Following the microlens, a charge-coupled device (CCD) sensor was placed on a translational stage normal to the optical axis and aligned with the microlens in a manner such that the focused beam would illuminate the sensor. By moving the CCD sensor and observing the image of the focused beam, the point at which the focused circular image on the CCD had the smallest possible size was found, and the focal length (the distance between the microlens and the CCD sensor) was thus determined. The procedure was conducted, while the temperature was scanned from 20 °C to 30 °C in steps of 1 °C to find the focal length as a function of temperature. In the next step, thermal response of the device, as a function of time, was logged. Since water has

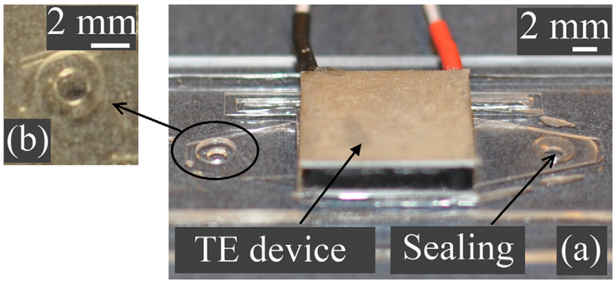


FIG. 3. (a) The fabricated device structure. It is shown without the heatsink, the thermocouple, water and oil for better visualization. (b) The water meniscus opening is shown as the inner aperture. This aperture would pin the water and forms the lens.

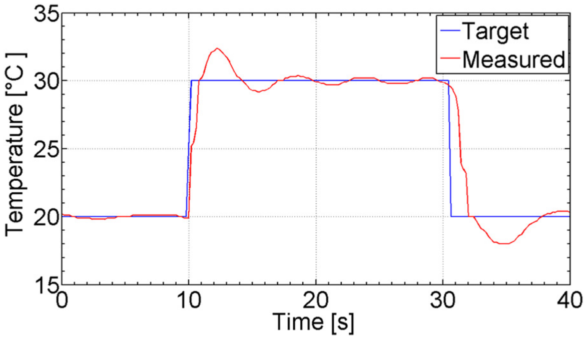


FIG. 4. Empirical time-domain temperature response of the device. A pulse function with an amplitude of 30 °C (an increment of 10 °C) is applied as the set-point value at time = 10 s to the system, which lasts until time = 30 s. Measured response times are 0.8 s for the rise time and 1.4 s for the fall time, respectively.

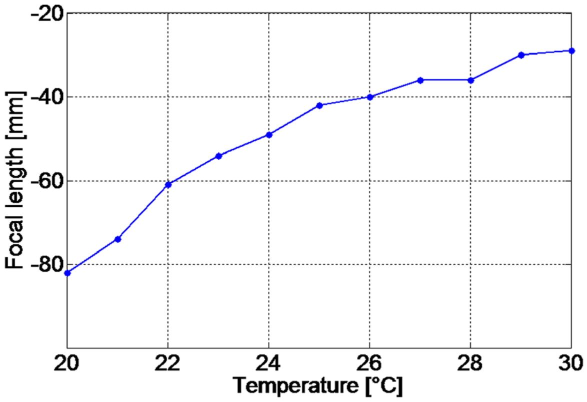


FIG. 5. Measured focal length of the device as a function of temperature. The lens remains divergent because water bulges into the silicone oil at the water-oil meniscus.

an enormous bulk modulus (2.2 GPa) and in most applications it can be considered incompressible fluid, it is safe to assume that the volume expansion of the water that is encapsulated in a rigid cavity would result in a rapid fluid transfer from relatively short and wide channel towards the water meniscus. Therefore, the temperature change in the water inside the cavity would quickly reflect itself onto a volume change in the pinned water meniscus. Accordingly one can assume that the time delay between a temperature change in the water cavity and a volume change in the meniscus is negligible and hence one can measure the time-domain thermal response and correlate it to the thermal-optical response in order to deduce a time-domain optical response.

To acquire the time-domain thermal response, a closed-loop feedback system was used to drive the TE device. The temperature feedback was provided to the TE controller (ATEC302NBM, Accuthermo Technology Corp., Fremont, CA, USA) via the thermocouple junction. First, the system was assembled and calibrated and then a time-domain response curve shown in Figure 4 was obtained. The temperature was varied from 20 °C to 30 °C and vice versa to observe the dynamics of the thermal response. A median temperature of 25 °C was chosen because it is close to room temperature; therefore the heat engine in its resting position would only need a fraction of energy to operate compared to extremum temperatures. During the experiment, maximum supplied voltage on the TE remained under 6 V and in the steady state, it stayed around 3 V which is very low compared to electrowetting-based microlenses. With regard to Figure 4 and by examining the rising edge of the measured temperature signal, a thermal rise time of 0.8 s was observed for the device, while going from 20 °C to 30 °C. This response time was defined as the time needed for the temperature difference to change from 10% to 90% of its final value of 10 °C. Likewise, the fall time was measured to be 1.4 s. Compared to previously reported thermopneumatically driven microlenses, both rise and fall times showed more than an order of magnitude of improvement.[14,15]

The results of the focal length measurement are shown in Figure 5. The focal length of the microlens changed continuously from −82 mm to −29 mm as the temperature was increased from 20 °C to 30 °C. As noted, the focal length of the sample used here remains negative throughout the temperature range that is used. This comes from the fact that the silicone oil used on top of the water meniscus has a higher refractive index (1.4935) compared to the water (1.33), and since the water remains bulged into the oil, the effective microlens becomes a divergent lens and thus shows a negative focal length. It is worth noting, however, that by adjusting the initial water meniscus volume, one can outline a wide range of the focal lengths. For instance, one can initially fabricate a microlens with a concave water meniscus, then via a positive net volume change by water thermal expansion, eventually make the meniscus convex by flattening it. Consequently, we can provide a range of positive and negative focal lengths.

In summary, integration of a thermoelectric device into a liquid chamber resulted in a more responsive tunable liquid microlens with a temperature response time of 0.8 s, an order of magnitude faster than previously reported thermopneumatic lenses. In future works, the device packaging will be further improved. Moreover, the thermal budget of the microlens will be reduced through making a smaller heat engine. This, in turn, will reduce the energy consumption of the lens. Future work also includes exploring other liquids with higher thermal expansion coefficients, dynamic measurement of the focal length, fine tuning the controller to obtain an oscillation free, critically damped system, and evaluating the effect of refractive index change on the optical performance of the microlens at different temperatures.

This work was supported by the U.S. National Science Foundation under Grant ECCS 0745000. The authors would like to thank Dr. B. Aldalali, A. Kanhere, and C. Li for technical discussions and help.

[1] X. Zeng, C. Smith, J. Gould, C. Heise, and H. Jiang, J. Microelectromech. Syst. **20**, 583 (2011).
[2] D. Zhu, X. Zeng, C. Li, and H. Jiang, J. Microelectromech. Syst. **20**, 389 (2011).
[3] A. Werber and H. Zappe, Appl. Opt. **44**, 3238 (2005).
[4] B. Berge, in *Proceedings of the 18th IEEE International Conference on Micro Electro Mechanical Systems (MEMS),* Miami, FL, 30 Jan–3 Feb, 2005, pp. 227–230.
[5] S. Kuiper and B. H. W. Hendriks, Appl. Phys. Lett. **85**, 1128 (2004).
[6] C. U. Murade, D. van der Ende, and F. Mugele, Opt. Express **20**, 18180 (2012).

[7] F. Li and F. Mugele, Appl. Phys. Lett. **92**, 244108 (2008).

[8] B. Berge and J. Peseux, Eur. Phys. J. E **3**, 159 (2000).

[9] S. T. Choi, J. Y. Lee, J. O. Kwon, S. Lee, and W. Kim, Proc. SPIE **7208**, 72080P (2009).

[10] T. Kaneko, T. Ohmi, N. Ohya, N. Kawahara, and T. Hattori, in *Proceedings of the IEEE International Conference on Solid-State Sensors Actuators,* Chicago, IL, 1997, pp. 63–66.

[11] C. A. López and A. H. Hirsa, Nature Photon. **2**, 610 (2008).

[12] P. M. Moran, S. Dharmatilleke, A. H. Khaw, K. W. Tan, M. L. Chan, and I. Rodriguez, Appl. Phys. Lett. **88**, 041120 (2006).

[13] H. Ren, S. Xu, and S. Wu, Lab Chip **13**, 100 (2013).

[14] L. Dong, A. K. Agarwal, D. J. Beebe, and H. Jiang, Nature (London) **442**, 551 (2006).

[15] L. Dong, A. K. Agarwal, D. J. Beebe, and H. Jiang, Adv. Mater. **19**, 401 (2007).

[16] D. Zhu, C. Lo, C. Li, and H. Jiang, J. Microelectromech. Syst. **21**, 1146 (2012).

[17] K. Lee, K. Park, G. Lim, H. Kim, and S. H. Kong, J. Opt. Soc. Korea **16**, 22 (2012).

[18] A. Werber and H. Zappe, J. Microelectromech. Syst. **17**, 1218 (2008).

[19] See supplementary material at http://dx.doi.org/10.1063/1.4820772 for the detailed device fabrication process flow.