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Variable-focus lens with 30 mm optical aperture based on liquid–membrane–liquid structure

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We report a liquid lens with a liquid–membrane–liquid structure in order to realize a variable-focus lens with a large optical aperture. We studied a typical liquid lens with a liquid–liquid structure and examined its physical limitation, namely, the capillary length, restricting the design of a larger-aperture liquid lens. We propose using elastic force instead of surface tension to acquire a much longer capillary length. We demonstrated that this approach can achieve sufficiently long capillary length when external pressure is loaded. A prototype lens with 30 mm aperture was constructed, and a resolution of 8.00 lp/mm was realized. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4800603]

Variable-focus lenses have been studied for decades, and many prototypes have been constructed, showing remarkable achievements. Examples include liquid crystal lenses,[1–3] pressure-actuated liquid lenses,[4–7] electrowetting lenses,[8,9] dielectric liquid lenses,[10–14] and microlens arrays.[15,16] In addition to their high-speed response and high optical performance, potential applications to a high-speed vision system,[17–19] camera lenses of mobile phones,[20] and spectacles[21] have been reported. However, there is no perfect liquid lens that possesses all of the desired features. For instance, a liquid lens with a liquid–liquid (LL) interface can achieve high resolution but the optical aperture is small; a liquid–membrane lens always suffers from the effects of gravity, which destroys the shape of the lens' meniscus curvature, and a liquid crystal lens is not adequate to be designed into a large aperture, because a large cell gap and a high refractive index anisotropy are required to realize a short focal length, which in turn will lead to a longer response time. Hence, a liquid-infused lens with a large optical aperture is still an unsolved problem. In the work reported in this letter, we studied a typical liquid lens with a liquid–liquid interface structure, and based on our findings, we propose a liquid–membrane–liquid structure (LML) allowing a liquid lens with a 30 mm aperture to be designed.

In the case of a liquid–liquid lens, two immiscible liquids are infused into two chambers, and an interface is formed between the two liquids. Because of the liquids' different refractive indexes, this interface works as a refractive surface. Since the shape of the liquid–liquid interface can be arbitrarily controlled and the lens power depends on the curvature of the refractive surface and the contrast of index of refraction, a variable-focus lens can be realized.[6,22]

The liquid-liquid interface is preferred to form a good parabolic meniscus shape in order to achieve good optical performance and meanwhile suppress its spherical aberration. Two immiscible liquids with high transparency, equal density, and high refractive index difference are considered to be ideal candidates. However, even though a density difference can be compensated for by using certain additives, it will appear again due to volume thermal expansion. Because of the unavoidable density difference between the two liquids, when the liquid lens is placed vertically, gravity is statically distributed on the interface. When the size of aperture is sufficiently shorter than capillary length,[6,23] the surface tension will become the dominant force and the effect of gravity is negligible. Hence, to avoid gravity destroying the shape of the meniscus curvature, it is recommended to set the lens aperture much smaller than the capillary length, l_c. The capillary length is a characteristic length scale for a fluid subjected to gravity and surface tension and is given by

$$l_c = \sqrt{\frac{\sigma}{|\rho_{liquid1} - \rho_{liquid2}|g}}, \tag{1}$$

where σ is surface tension, $\rho_{liquid1}$ and $\rho_{liquid2}$ are the liquid densities, and g is the gravitational constant. When the lens aperture diameter, d, is sufficiently smaller than the capillary length ($d < l_c$), gravity will be negligible. This is a key reason why a liquid–liquid lens can achieve a good spherical meniscus and optical performance.

Therefore, the capillary length is a physical limitation that restricts the aperture size. If we want to design a liquid lens having a large optical aperture without deteriorating its optical performance, a much longer capillary length is essential. According to Eq. (1), the liquid densities and gravity are constants, so the only possible solution is to increase the surface tension σ.

To design a variable-focus liquid lens with a large optical aperture, first we considered the benefits of a liquid–membrane lens and a liquid–liquid lens. If a piece of elastic membrane is inserted between two liquids, when the membrane is deformed, an elastic force is produced to resist the deformation. Normally, the surface tension between the two liquids is on the order of 10^{-3} N/m. For example, between ultra-pure water (0.997 g/cm^3) and poly-dimethylsiloxane (PDMS) (0.975 g/cm^3), the surface tension is only 34.8×10^{-3} N/m. Hence, the capillary length is calculated as 12.7 mm, and the lens aperture is set as 3 mm in one reported example.[6] Compared with surface tension, the elastic force should be able to provide a much stronger force. Therefore, the capillary length could become longer, making it possible to realize a large-aperture liquid lens. Based on this concept, we propose a liquid lens with a LML structure, shown in Figure 1.

Unlike surface tension, the elastic force is not a constant value but increases with increasing external pressure. Because the membrane is clamped at its boundary, the elastic force shows different values at different places when a certain external pressure is loaded on the membrane.[24,25] The meridional elastic force is considered as a substitute for surface tension. The elastic membrane used had a Young's modulus of 1.8 MPa, a Poisson's ratio of 0.45,[26] a thickness of 0.1 mm, and a diameter of 30 mm (with the boundary clamped). The capillary length was calculated assuming ultra-pure water (0.997 g/cm^3) and PDMS liquid (0.975 g/cm^3). The same values were adopted in other calculations. The average value of the meridional elastic force versus external pressure is shown in Figure 2 (black-circle-dotted line). Furthermore, according to Eq. (1), a given surface tension occurs as a result of the elastic force; therefore, the capillary length is re-calculated theoretically and is shown in Figure 2 (blue-triangle-dotted line). The capillary length becomes greater than 30 mm when an external pressure of 3 Pa is loaded. When the external pressure is increased to 130 Pa, the capillary length becomes 129.1 mm, which is sufficiently long to design a liquid lens with a 30 mm aperture. We also examined the case where the same elastic force acts on a liquid-membrane structure lens and this is shown in Figure 2 (red square-dotted line). The maximum value of the capillary length is less than 30 mm, making a liquid–membrane lens impractical for achieving a large aperture. In contrast, the LML structure is a possible solution for designing a liquid lens with a large optical aperture.

We examined spherical and symmetry deformation in the following two ways: (A) An LML model lens was compared with a liquid–liquid lens, both lenses having a 3 mm optical aperture, to examine the shapes of the interfaces. (B) The locations of the points of maximum deformation were observed in different simulations with a 30 mm optical aperture. The results are explained in detail below.

A. Because LML structure can provide stronger force during its deformation, there would be an improvement on the interface deflection. To compare the LL lens and the LML model lens, we used data from Ref. 6 for the liquid–liquid lens. For the LML lens, on the other hand, the data were acquired from the following simulation procedure: A 3 mm-diameter silicone membrane model was built, which is the same size as LL lens.[6] The difference in gravitational force between water and PDMS liquid was loaded on the membrane beforehand so as to be statically distributed over the membrane. Different uniform external pressures were applied to the membrane, and the 3D surface deformation was simulated using the finite element method (FEM). The optical path lengths (OPLs) of the deformed surface were calculated based on the shape of the 3D deformation and the refractive indices of liquids. Then, the wavefront surface defined by the OPLs was fitted to a spherical surface, and the peak-to-valley (PV) and root mean square error (RMSE) were acquired from the fitting results. Figure 3 (top and middle) shows the comparison result. The LML model lens showed great improvement in terms of spherical deformation, with smaller PV and RMSE values.

B. Symmetry deformation was examined, as another critical factor for evaluating the membrane deformation. We conducted several simulations on a membrane with a 30 mm diameter by using an FEM model. The FEM simulation involved thousands of nodes, and the nodes were fitted with a parabolic surface. The distance between the position of maximum deformation of the parabolic surface and the lens geometric center for different external pressures was observed and is shown in Figure 3 (bottom). Due to the accuracy of fitting and the minimum size of the mesh elements in the FEM model, a value of less than 0.15 mm was accepted as a symmetric shape. As a result, it was demonstrated that with increasing external pressure, the deformed shape of the elastic membrane became closer to a symmetric shape.

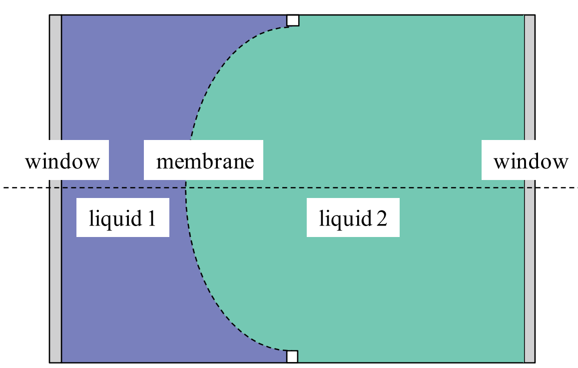

FIG. 1. Liquid–membrane–liquid structure.

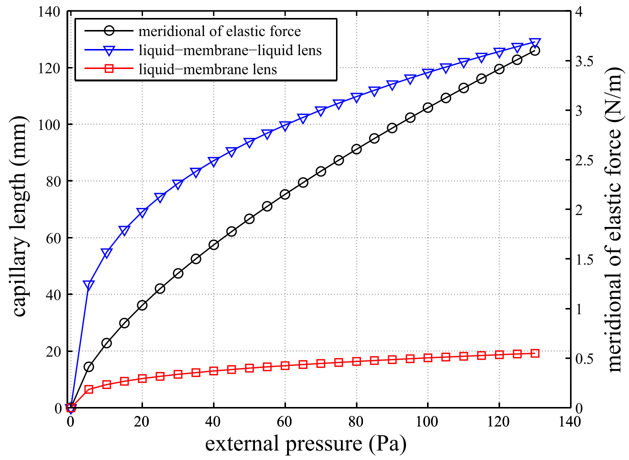

FIG. 2. Capillary length and meridional elastic force versus external pressure.

Figure 4 (left) shows a prototype based on the proposed liquid–membrane–liquid structure. A silicone membrane with a thickness of 0.1 mm was prepared and was mounted and clamped by a stainless-steel frame with a 30 mm inner diameter to ensure that it was deformed while maintaining a circular boundary. The two chambers were infused with two different liquids. If one of the liquids can be made to freely flow into and out of its chamber by means of a syringe, while the end of tube of the other chamber is locked, the lens can

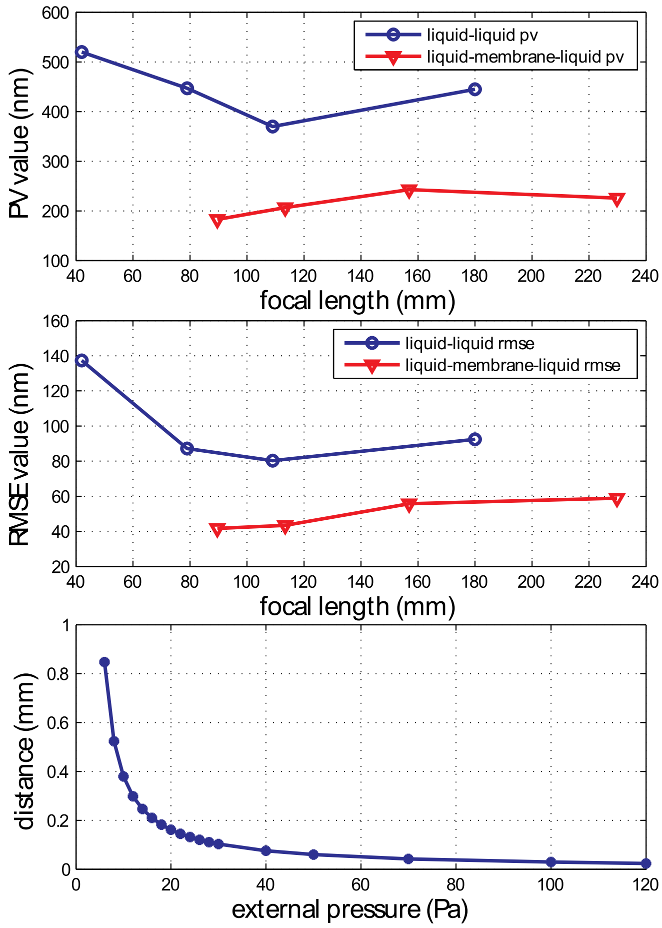

FIG. 3. Comparison of PV and RMSE between liquid–liquid model and liquid–membrane–liquid model with 3 mm aperture (top and middle). Distance between the point of maximum deformation and the lens center (bottom).

shift its power dynamically from positive to negative by pushing or pulling the syringe. In the prototype, glycerin (density of 1.25 g/cm^3, refractive index of 1.4732) and SantoLight5267 liquid (density of 1.26 g/cm^3, refractive index of 1.6737) were adopted as the two liquids[7,16] because we found incompatibility between the silicone membrane and the PDMS liquid during our experiments. The range of available focal length was examined between [−150 150] mm, and the minimize F/5 is attainable. An object was placed at a typical reading distance (300 mm) from the lens, and a set of images was taken by changing the liquid lens between convex and concave (Figure 4, right).

The resolution of the prototype lens was measured using a USAF 1951 Chart.[27,28] The setup was conducted by placing the chart and image sensor on either side of the liquid lens. Glycerin and SantoLight5267 were infused. Because the image was magnified by a factor of two, the resolution limit of the captured image should be divided by two. Figure 5 shows an image taken when the focal length was 150 mm. A resolution of 16.00 lp/mm (Group 4, Element 1) was achieved; therefore, the resolution of our prototype was determined to be 8.00 lp/mm. An identical model with the LML structure but with a spherical interface having a 150 mm focal length was constructed in Zemax optical design software. A resolution of 11.60 lp/mm was confirmed when the modulus of the optical transfer function was 0.1 in the Huygens MTF chart. Therefore, compared with a spherical surface lens, our proposed lens showed comparable optical performance.

In summary, we studied a typical liquid lens with a liquid–liquid interface and examined its physical limitation, namely, the capillary length, which restricts the design of a large-aperture liquid lens. We found that it is advantageous to insert a membrane at the interface to achieve a much longer capillary length. This proposed structure was examined by mechanical analysis of the membrane's elastic deformation, and spherical and symmetry deformations were modeled by finite element simulations. A prototype liquid lens with a 30 mm aperture based on a liquid–membrane–liquid structure was constructed, and experiments showed that a resolution of 8.00 lp/mm could be achieved. It should be possible to make the proposed liquid lens thinner for use in eyeglasses for vision correction. In addition, the lens has potential applications in vision systems for accomplishing zooming or focusing without the use of mechanically moving lens units.

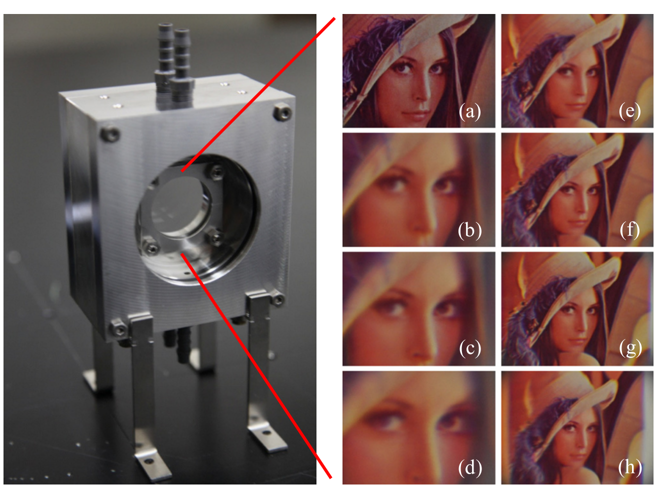

FIG. 4. Prototype liquid–membrane–liquid lens with aperture size of 30 mm (left). Image (a) is the original one captured without liquids infused; images (b) and (c) were taken with a convex lens and images (e)–(h) were taken with a concave lens.

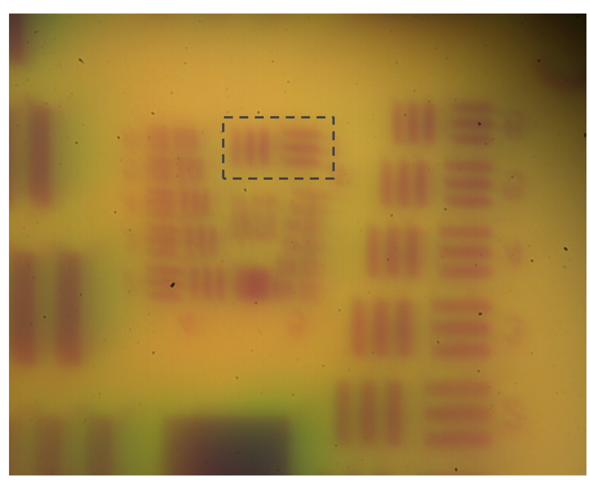

FIG. 5. An image of a USAF 1951 Chart was captured with focal length of 150 mm. The resolution value of the image should be divided by the system magnification of 2×. The image has a yellow tinge because Santolight5267 liquid is slightly yellow.

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