Focal tunable liquid lens integrated with an electromagnetic actuator

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In this letter, a focal tunable liquid lens using a large deformable polydimethylsiloxane (PDMS) membrane is integrated with an electromagnetic microactuator for uniform pressure on the membrane by a fabrication process of PDMS compatible with conventional micromachining processes. The fabricated device is characterized by surface profiling and optical observations. A rectangular PDMS membrane of 3 mm in width for actuation shows that the maximum displacement is 51.4 $\mu$m when the current is 30 mA. In the optical observations, the image is blurred when the applied current is varied. From the result, it was found that the device changes the focal length. © 2007 American Institute of Physics. [DOI: 10.1063/1.2716213]

A focal tunable liquid lens has a variety of applications in miniaturized optical devices, such as in a minicamera module, in a display, and in an endoscope.\textsuperscript{1,2} One type of focal tuning mechanism is hydropressure on a large deformable elastomer membrane containing transparent liquid.\textsuperscript{3,4} One of these large deformable elastomers is polydimethylsiloxane (PDMS).\textsuperscript{5} PDMS is a thermocurable elastomer whose Young’s modulus is 750 kPa, only 1/250 times that of silicon. Thus, its membrane can be deformed more compared to other conventional membranes such as silicon oxide and silicon nitride.

In this letter, a focal tunable liquid lens using a large deformable PDMS membrane is integrated with an electromagnetic microactuator for uniform pressure on the membrane by a fabrication process of PDMS compatible with conventional micromachining processes. The fabricated device is characterized by surface profiling and optical observations. Figure 1(a) shows a schematic view of the device, which consists of a PDMS membrane for a lens and an actuating PDMS membrane containing electrical components to generate the Lorentz force formed on a bulk-etched Si wafer. On these membranes, liquid media, in order to transfer pressure induced on the actuating membrane to the membrane for the lens, is contained in a closed transparent chamber. The actuating part consists of a PDMS membrane and electrical paths transversing the membrane. The directions of the currents on the membrane are identical, as a part of the coil-shaped electrical path placed on the membrane, as shown in the figure. When current is applied to the electrical paths in the direction normal to the figure, the membrane is deformed by the Lorentz force induced by the external magnetic field and current on the membrane. Following this, the PDMS membrane for the lens is deformed by hydropressure in incompressible closed liquid media, which offsets the volume change induced by the deformation of the actuating PDMS membrane [see Fig. 1(b)]. The meniscus of the liquid contacted with the deformed membrane becomes a lens, the curvature of which is followed by the curvature of the membrane. The PDMS membrane was designed with a rectangular shape following the direction of a single silicon crystal with a width of 3 mm and a thickness of 11 $\mu$m. The number of electric paths across the membrane is 30 for the 3 mm membrane.

Figure 2 shows the fabrication process of the device. The electrical component of the coil-shaped electrical path and insulation layer generating the Lorentz force were fabricated by a conventional micromachining process. The PDMS membrane was fabricated by spin coating of uncured PDMS, in which the viscosity is reduced by dilution on the substrate onto which electric components were previously fabricated. After this process, the PDMS membrane including the electric components is opened by a bulk micromachining process. Finally, the device is completed by the bonding of the transparent chamber containing the liquid. The thickness of the membrane, 11.0 $\mu$m is determined by the PDMS viscosity and spin-coating speed.

Figure 3(a) shows the experimental setup and an optical image of the PDMS membrane. The completed actuating device is bonded onto a printed circuit board (PCB) plate by epoxy adhesive and electrically connected by a ball bonder. The device is located in a magnetic field between two pairs of electric paths.
of NdFeB magnets. The dimension of the magnet is $50 \times 10 \times 3$ mm$^3$. The density of the magnetic field $B$ in the middle of the magnets is 90 G (Gaussmeter, Lakeshore 421, Lake Shore Cryotronics, Inc.). The device has a rectangular PDMS membrane for the lens and a rectangular actuating membrane with a width of 3 mm. A detailed optical image shows the 3 mm width PDMS membrane for the lens and actuating membrane [see Fig. 3(b)]. The image of the PCB plate can be seen through the transparent PDMS membrane. 30 electrical paths, each with a width of 50 $\mu$m pass through the actuating membrane. These electric paths on the PDMS membrane are not electroplated to maintain the flexibility of the membrane, so their color appears darker compared to the other coil parts.

Figures 3(c) and 3(d) are scanning electron microscope (SEM) images of the fabricated device. Figure 3(c) shows cross-sectional views of the gold coil on the silicon membrane before PDMS was spin coated. There are two elements of the membrane for the lens and the actuator. The patterns of the gold coil are passed across the actuating membrane. Figure 3(d) shows a completed PDMS membrane with the gold coil. In order to obtain a cross-sectional image of the PDMS membrane, it was broken manually. The PDMS membrane with the gold coil was successfully completed. However, it was found that the surface of the membrane was attacked by a tetramethylammonium hydroxide (TMAH) solution of the silicon bulk micromachining etchant.

In the experiment, the static deformation of the actuating membrane was measured when the dc current was applied. An optical three-dimensional (3D) surface profiler ($\mu$-Surf, Nanofocus, Co.) visualizes a 3D profile of the deformed ac-
tuating membrane. The field of view of the profiler is 1.54 \times 1.60 \text{ mm}^2, thus, it can measure a quarter of 3 mm membrane width. Figure 4(a) shows surface profiles of the deformed actuating PDMS membranes with 3 mm widths when the applied current is 30 mA. The deformation profile is similar to the deformation of the rectangular membrane for a uniform pressure, except the fact that the difference of the profile in the vertical and horizontal directions is affected by the mechanical structure of the gold electrical paths. Their maximum displacement is 51.4 \mu m for 3 mm. The strip patterns across the membrane are a measuring error of the optical profiler induced by the severe difference of the reflectivity of the transparent PDMS membrane and the gold electric paths. Figure 4(b) shows the deformation profile of cross section \textit{a-a'} in Fig. 4(a), denoting the central line of the membranes for various currents. Following the plate model, the slope of the deformed membrane at the boundary must be 0, as a boundary condition is “fixed.” However, the slope of the boundary shown in the experimental result does not follow the regime of a fixed boundary, as the PDMS membrane is an elastomer. Figure 5(a) shows the completed device with the liquid (99.0\% Glycerol) chamber on the PDMS membranes as well as a schematic view of its optical experiment setup. This device is fixed above the 10\times lens of the inverted optical microscope, and the film mask for photolithography with micropatterns is placed on the object table [see Fig. 5(b)]. When the applied current was increased from 40 to 40 mA, it was found that the focal length changes, as shown in Fig. 5(c). As the current increases, the image of the micropattern is blurred so that the line disappears.

From the result, it can be confirmed that the electromagnetic actuator on the elastomer membrane performed as a working mechanism for a focal variable liquid lens. However, it is found that the actuator is heated up by the current in the electrode for Lorentz force. In spite of the heat problem, the concept of a countermembrane which offsets the deformation of the membrane for the lens in the incompressible fluidic media can be applied to various working mechanisms for focal variable liquid lens, such as those in electrophoresis.

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