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Electromagnetically driven liquid lens☆

Sang Hoon Oh, Kyehan Rhee*, Sang Kug Chung*

Department of Mechanical Engineering, Myongji University, Yongin, South Korea

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ABSTRACT

This paper presents a new design of tunable liquid lens. The lens was operated by electromagnetic actuation for autofocusing (AF) in miniature cameras and its optical performance was experimentally verified. An electrical voltage was applied to an electric coil inside an electromagnetic system beneath the liquid lens to generate a magnetic field around the electromagnetic system according to Faraday's law of induction. The magnetic field was used to actuate a ring-type neodymium magnet placed on the top of an elastic membrane in the liquid lens. The sag (sagittal) height of the liquid lens was measured as a function of the applied voltage. The sag height of the lens increased linearly from −1 mm to 0.8 mm when the applied voltage was changed from 0 V to 50 V at 5 V increments. The average variation of the sag height per volt was about 32 μm. The focal length was also measured with respect to the applied voltage by using a custom-built testing system consisting of a laser, mirror, liquid lens, and detection screen. The measured focal length values were compared with the theoretical ones. For imaging tests, a single-object focusing test was first performed by using a sheet of paper with a check pattern. Furthermore, the ability of the liquid lens to distinguish two objects positioned at different distances by changing its focal plane was successfully tested. Finally, the response times of the liquid lens for actuation and relaxation were measured by a high-speed camera and were found to be about 900 ms.

1. Introduction

The demands for miniature cameras in various industries such as electronics and automotive companies are increasing. Therefore, liquid lenses have attracted the attention of the optics and microelectromechanical systems (MEMS) communities owing to their compact size and fast actuation speed [1–5]. A lens is typically used for focusing light to form an image by refraction. However, it has a fixed single focal length and no tunable optical elements. Hence, most of the imaging systems have external actuators to control the position of lenses mechanically [6,7]. Thus, their focuses are variable. However, these actuators often make the imaging systems bulky and expensive [4,8,9].

In order to address these challenges, various liquid-based tunable optical elements have been developed such as a liquid lens for the focal length control and a liquid iris for light regulation [10–13]. According to the operation mechanism, a liquid lens based on a liquid-liquid interface can be classified into two different types. The first type is an electrowetting-on-dielectric (EWOD) driven liquid lens [14–17]. Berge and Peseux developed the incipient EWOD driven liquid lens by using two immiscible liquids [18]. This lens was intended for use in imaging systems requiring fast focus and zoom. Then, a variety of liquid lenses with different designs have been developed. Kuiper and Hendriks designed a miniature camera module based on the EWOD driven liquid lens and demonstrated various optical properties of the liquid lens [19]. The EWOD driven liquid lens has outstanding advantages such as miniaturization and fast actuation. However, it has several limitations such as use of relatively high voltages and the system's unreliability in high and low temperatures [20–22].

The second type is a deformable-membrane-based liquid lens [23–29]. To develop most of the liquid lenses, deformable transparent membranes with liquid chambers have been used. These lenses change their focal length when the liquid is pumped in or out of the lens chamber by the deformable membrane that is operated by various actuators [30–33]. Pouydebasque et al. designed a compact varifocal liquid lens based on a deformable membrane actuated by electrostatic parallel plates and demonstrated its optical performances in terms of optical power and wave front [34].

In this paper, a new design of the liquid lens is presented and its performance is experimentally verified based on the prototype of the envisioned liquid lens. An electrical voltage is applied to an electric coil inside an electromagnetic system beneath the liquid lens to generate a magnetic field around the electromagnetic system

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* Corresponding authors.
E-mail addresses: khanrhee@mju.ac.kr (K. Rhee), skchung@mju.ac.kr (S.K. Chung).

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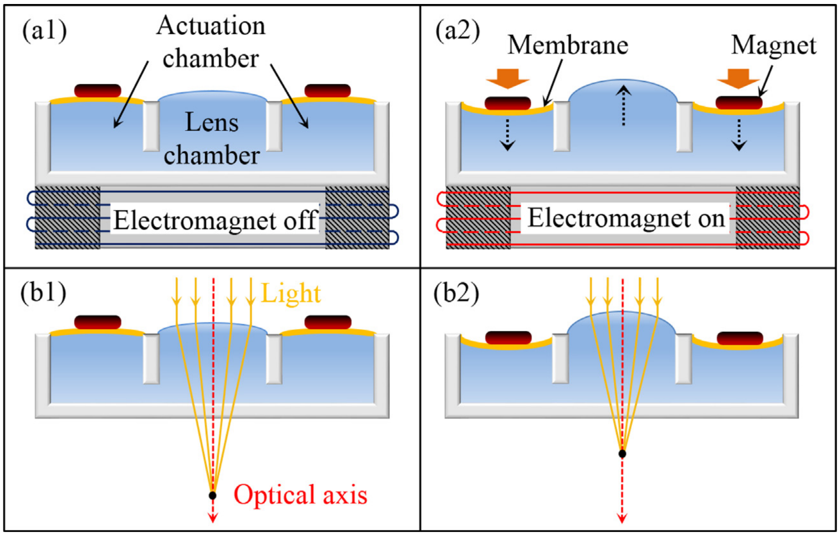

Fig. 1. Schematic diagram of a tunable liquid lens operated by electromagnetic actuation.

according to Faraday's law of induction. In this work, the magnetic field is used to actuate a ring-type neodymium magnet placed on the top of an elastic membrane in the liquid lens, as shown in Fig. 1. When the membrane actuated by the electromagnetic system is deformed, the liquid inside an actuation chamber flows into a lens chamber through open walls. This results in the change of the surface profile and focal length of the liquid lens. A preliminary report on this work was presented at the 18th International Conference on Solid-State Sensors, Actuators and Microsystems held in Anchorage, Alaska, U.S.A. [35].

2. Electromagnetic system design and experimental setup

Fig. 1 shows the schematic of the proposed liquid lens operated by electromagnetic actuation. According to Faraday's law of electromagnetic induction, when electric current flows in an electric coil, a magnetic field is generated in its surroundings [36,37]. In this work, the magnetic field is used to actuate or pull the ring-shaped neodymium magnet (outer and inner diameters, and thickness are 13 mm, 9 mm, and 2 mm, respectively, Magnetpark Co.) placed on the top of an elastic polydimethylsiloxane (PDMS) membrane in the liquid lens. The force $\vec{F}$ acting on the ring-shaped magnet as a result of the magnetic field is [37].

$$\vec{F} = \int_V \left(\vec{M} \cdot \nabla\right) \vec{B} dV \quad (1)$$

where $\vec{M}$ is the magnetization of the ring-shaped magnet in amperes per meter (Am^{-1}), $\vec{B}$ is the flux density of the applied magnetic field in Tesla (T), and V is the volume of the ring-shaped magnet (m^3).

Fig. 2 shows the schematic exploded diagram of the liquid lens as well as the images of its prototype. The prototype of the liquid lens consists of an acrylic circular lens body, an acrylic supporting frame, a PDMS membrane, polyimide silicone spacers, a ring-type neodymium magnet, and a glass substrate, as shown in Fig. 2. The lens body and supporting frame were manufactured by using a laser cutter (IS-640, Innosta Co). The first and second spacers made of polyimide silicone double-sided adhesive tapes (PIT-10050S-D50S-FL50, Isoflex) were used for attaching the lens body with the glass substrate and the PDMS membrane, respectively. The supporting frame was also glued on the glass substrate; however, the liquid inside the actuation and lens chambers still could flow back and forth through the open walls of the supporting frame, as shown

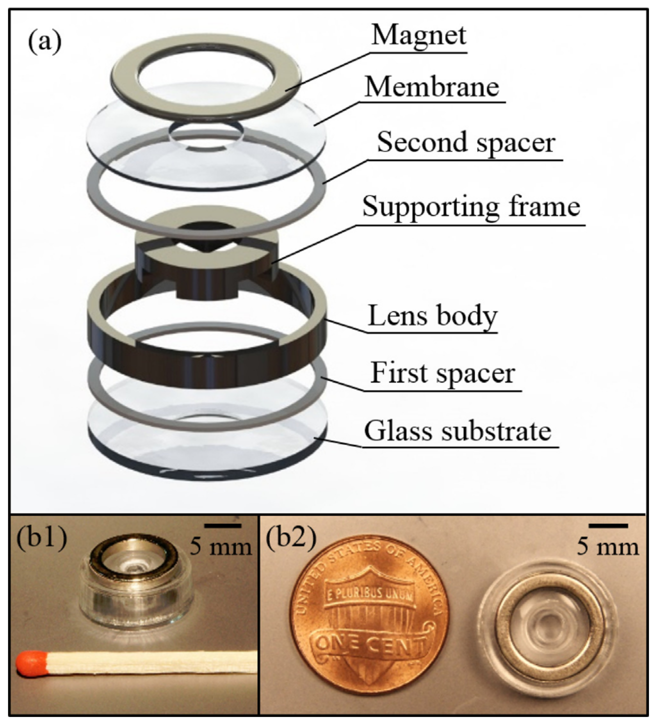

Fig. 2. Schematic exploded diagram of the proposed liquid lens and the prototype of the liquid lens. Note that the supporting frame has open walls for liquid passage between the lens chamber and the actuation chamber.

in Fig. 2. The PDMS membrane was obtained by the following processes [38,39]. First, a chemical mixture (Sylgard 184 silicone elastomer base and curing agent at the ratio of 10 to 1) was degassed in a thermal vacuum chamber (SH-VDO-30NG, Samheung Energy Co.) for about 30 min until no bubbles appeared. Then, the degassed mixture was poured into a prepared mold (outer and inner diameters and thickness: 20 mm, 5 mm, and 500 μm, respectively) and cured in the thermal vacuum chamber at 60 °C for 4 h. Finally, the 500-μm-thick PDMS membrane with a Young's modulus of about 2.63 MPa was obtained by carefully detaching it from the mold by using tweezers. Note that the prototype of the liquid lens does not have any membrane in the lens chamber; so, the liquid interface is open, which is similar to the other liquid lenses [10,40].