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Electromagnetically driven liquid iris

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ABSTRACT

This paper presents a tunable liquid iris based on electromagnetic actuation for miniature cameras in mobile devices such as smart phones and pads. To investigate the effect of a magnetic field on a ferrofluid, contact angle modification and transportation of a sessile ferrofluid droplet are tested using a neodymium magnet and an electric coil. The variation in the contact angle of the ferrofluid droplet is 21.3° for the neodymium magnet and 18.1° for the electric coil. In addition, transportation of the ferrofluid droplet is also demonstrated using the neodymium magnet and the electric coil. As a proof of concept, a pretest of a tunable iris operated by electromagnetic actuation is conducted by using a hollow cylinder cell. Initially, the ferrofluid is in a relaxed state, so the cylinder cell shows the largest aperture (4.06 mm). When an electric current is applied to an electric coil wound around the outside of the cylinder cell, the ferrofluid, which is initially placed in the hydrophobic sidewall inside the cylinder cell, is actuated and pulled to the center. The aperture diameter under the applied current is modified from 4.06 mm at 0 A to 3.21 mm at 2.0 A. Finally, a tunable iris, consisting of two connected circular microchannels, is realized using MEMS technology. The iris size is 9 mm × 9 mm × 2 mm, and the aperture diameter can be varied from 1.72 mm at 0 A to 1.09 mm at 2.6 A. The response times of the iris for actuation and relaxation are measured by a high-speed camera and found to be 250 ms and 450 ms, respectively.

1. Introduction

Development of a new type of optical element has become important to meet increased demand for miniature cameras for mobile devices such as smart phones and pads [1,2]. Liquid based tunable optical elements such as liquid lenses and irises have received substantial attention from optical and microelectromechanical systems (MEMS) societies owing to their compact size and fast response times [1–4]. Optical focus in optical devices can primarily be achieved in three ways: control of the position of a lens, the curvature of a lens, and the refractive index of a lens. Most optical systems have relied on the control of the position of lenses by external actuators for optical focus [4].

On the other hand, some optical systems based on a liquid lens have used a liquid–liquid interface as a lens and achieved optical focus by controlling the radius of the curvature of the interface [5,6]. Most of the liquid lenses have applied a deformable transparent membrane, and various external actuators have been used to control the radius of the curvature of the membrane for optical focus [7–9]. In particular, a liquid lens actuated on the basis of the electrowetting-on-dielectric (EWOD) principle uses electrical potentials to control the radius of the curvature of the liquid–liquid interface, resulting in the modification of the focal lengths [4,10–12]. It has outstanding advantages such as miniaturization, low power consumption, and fast response time without membranes or mechanical moving parts. Hence, some companies such as Varioptic and Philips developed an EWOD-driven liquid lens for autofocus in mobile devices [1,4].

Another important liquid based tunable optical element is the liquid iris [13–18]. In optics, an iris, or aperture stop, is placed in the light path of a lens or objective. The iris regulates the amount of light that passes through the lens by controlling the size of the aperture, which is an opening at its center. The iris not only controls light flux, field of view, and depth of field, but also blocks scattered light and improves image quality by limiting spherical aberration [19,20]. Hence, the iris is an indispensable element in most optical systems. However, the conventional mechanical iris, consisting of movable sliding blades, requires a complicated sliding rotary mechanism which must be operated by bulky motors, and is therefore difficult to miniaturize [21,22]. Hence, various types of liquid iris have been developed.

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Müller et al. developed and experimentally verified a tunable iris, which used an opaque liquid as a light absorber in combination with another transparent liquid for defining optical apertures of variable diameters [2]. The apertures are tuned by deforming a ring-shaped liquid–liquid interface using EWOD actuation. Chang et al. also developed a similar EWOD driven iris with fast response based on the application of a single opaque liquid and air in microchannel structures for optical coherence tomography (OCT) [19,23].

In this study, a new type of tunable liquid iris that uses a ferrofluid manipulated by electromagnetic actuation is developed and experimentally verified. Control of the aperture diameter in the iris is achieved by manipulating the size of the ring-shaped ferrofluid in the microchannels using magnetic fields generated by an electromagnetic system placed beneath the iris. Note that the ferrofluid is used as a shutter to exclude light. The electromagnetically driven liquid iris has advantages such as compact size, which is due to its simple design structures, and robust operation, which is due to the absence of mechanical moving parts. This allows simple fabrication processes for mass production. It can be applied to miniature cameras for smart devices and biomedical applications. Note that a preliminary report on this work was presented at the International Conference on Micro Electro Mechanical Systems held in San Francisco, USA [24].

2. Electromagnetic system design and experimental setup

Fig. 1 shows the schematic diagram of a tunable liquid iris controlled by electromagnetic actuation. According to Faraday's law of electromagnetic induction, when an electric current flows in an electric coil, a magnetic field is generated in its surroundings [25]. In this work, the magnetic field is used to actuate or pull magnetic microparticles (diameter: 10 nm) in an opaque ferrofluid with a viscosity of less than 5 mPa s at 27 °C (EMG 707, Ferro Tec). The ferrofluid initially fills the microfabricated channels inside the iris and is pulled by the magnetic field to the center of the main channel to control the size of the ring-shaped ferrofluid, as shown in Fig. 1. The

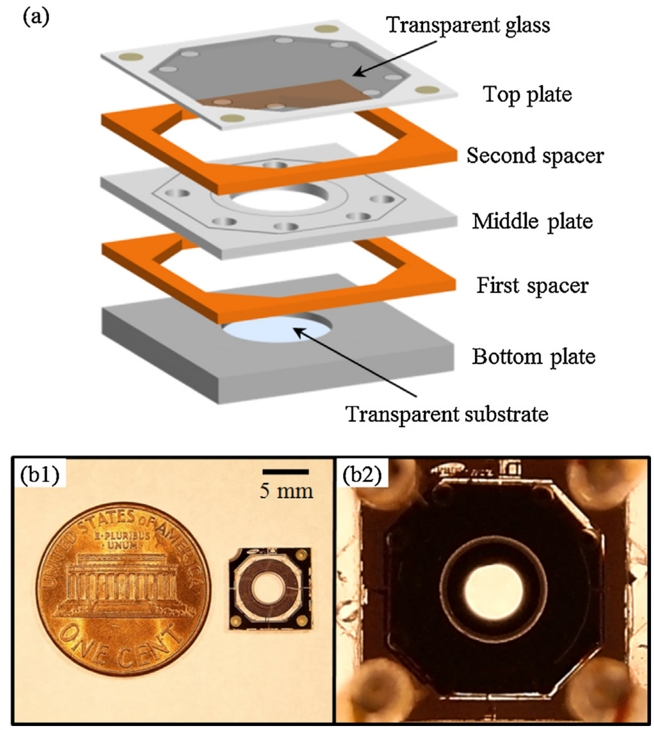

Fig. 2. (a) Schematic exploded diagram of the proposed optical iris and (b) a microfabricated iris and the testing setup.

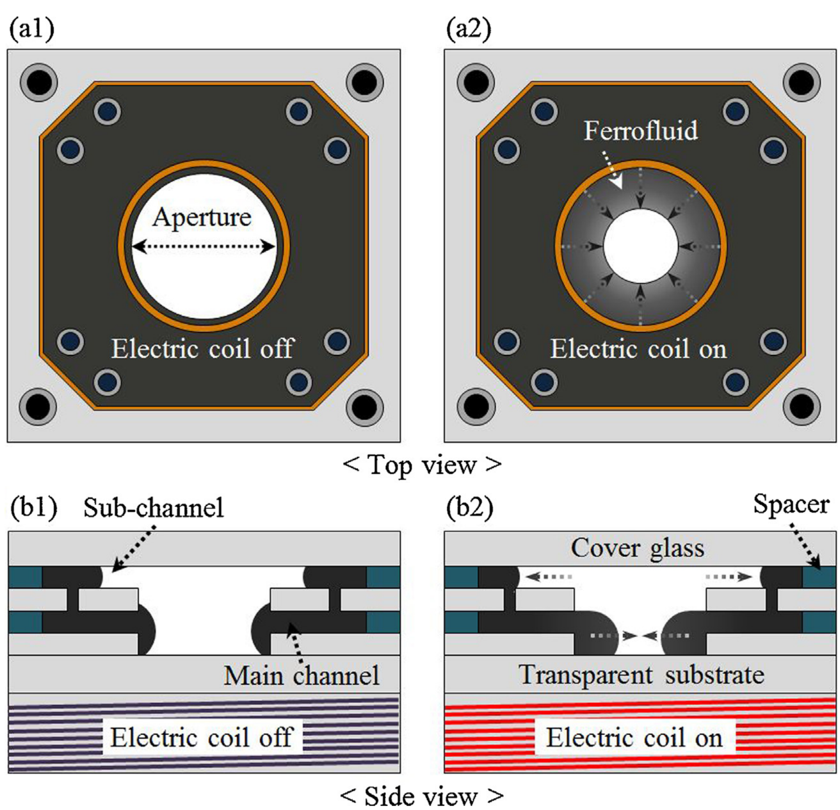

Fig. 1. Schematic diagram of a tunable optical iris operated by electromagnetic actuation: when an electrical current is applied to an electric coil, a ferrofluid initially inside the sub-channel of the iris is electromagnetically actuated and pulled to the center of the main channel, which results in changing the aperture of the iris. (a) Top view and (b) side view.