Published in final edited form as:

Conf Proc IEEE Eng Med Biol Soc. 2016 August ; 2016: 4212–4215. doi:10.1109/EMBC.2016.7591656.

Low-Cost Rapid Prototyping of Liquid Crystal Polymer Based Magnetic Microactuators for Glaucoma Drainage Devices

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Abstract

Glaucoma is one of the leading causes of blindness in the world. Although there is no cure for glaucoma, pharmaceutical or surgical interventions are known to delay the progression of this debilitating disease. In recent years, implantation of glaucoma drainage devices (GDD) have increased due to their ability to manage IOP better than other therapeutic approaches. However, only 50% of the implanted devices remain functional after 5 years often due to biofouling. Here, we report our latest progress towards developing self-clearing GDDs using integrated magnetic microactuators. Our hypothesis is that these magnetic microdevices can provide local mechanical perturbations to prophylactically remove biological accumulation. To reduce the cost and increase the throughput of fabrication, we utilize a maskless photolithography setup and commercially available liquid crystal polymer foils to create prototype devices. The mechanical response of the devices is reported and compared with the theoretical values.

Keywords

Magnetic microactuators; thin-film device; implantable microdevice; BioMEMS; glaucoma drainage device

I. Introduction

Glaucoma is a common eye disease caused by an elevated intraocular pressure (IOP) that leads to optic nerve damage and visual field loss [1]. It is one of the leading causes of blindness in the world and affects more than 2 million people in the United States [2]. Unfortunately, there is no cure for glaucoma and the management of IOP is considered to be the gold standard in curtailing the progression of this debilitating disease [3]. Patients with glaucoma are often treated with aqueous humor secretion-reducing drugs to regulate IOP. However, more patients are undergoing surgical interventions such as trabecular filtration or glaucoma drain device (GDD) implantation to manage IOP. In recent years, implantation of GDD has increased from 7% to 22% due to better IOP control, minimum postoperative complications, and ease to use [4]. GDDs are typically comprised of a tube that diverts excess aqueous humor from inside the eye to an end plate reservoir placed at the equatorial region outside of the eyeball [5]. While the GDDs effectively reduce IOP and delay glaucoma progression, only 80% of implanted devices remain operational after 1 year,

decreasing to 50% after 5 years [6]. One of the main causes of this failure is protein adsorption, bacterial infection, and inflammation leading to shunt obstruction. Polydimethylsiloxane (PDMS), polypropylene, and polymethylmethacrylate (PMMA) are commonly used materials in GDD, however, these hydrophobic polymers have a high binding affinity for proteins. Protein adsorption on implant surface can lead to a cascade of inflammatory responses including cellular adhesion and chronic inflammation [7] that ultimately result in device failure. Although GDDs have been on the market since 1960's, none of the existing GDD designs have the capability to combat the issues related to biofouling. In order to combat protein adsorption, cellular adhesion, and subsequent shunt obstruction, we seek to develop a microfabricated smart self-clearing GDD. By leveraging our previous experience in designing and fabricating magnetic microactuators for combatting biofouling on implantable catheters [8]–[11], we propose to integrate an array of microscale magnetic actuators within microchannels of a GDD (Fig.1). The magnetic microactuators may serve dual purposes to (1) combat biofouling and (2) control the flow resistances to address a wide range of IOP pressure in patients. With a variable flow resistance, clinicians may be able to provide a more personalized treatment for each patient with a smarter adaptable device [12].

In this work, we demonstrate proof-of-concept magnetic microactuators to be integrated into self-clearing GDD. We designed, fabricated, and tested an array of magnetic microactuators using maskless photolithography on low-cost commercial copper-cladded liquid crystal polymer (LCP) sheets. The simple and novel process flow allows for rapid prototyping of various designs and arrangements. The mechanical responses of these prototype devices are examined.

II. Theory

A. Static response of magnetic microactuator

When the magnetic microactuator is placed in a static magnetic field, a magnetic moment is induced due to interaction between the soft ferromagnetic element and the applied magnetic field. If the applied magnetic field is normal to the surface of the magnetic element, the device can deflect out of plane. The resulting angle of deflection is a function of beam stiffness as the mechanical torque opposes the magnetic moment. The deflection angle of magnetic microactuator can be described by [13]

$$\phi = \frac{\nu \cdot (\vec{M} \times \vec{H})}{k_{\phi}}$$

with the angular deflection ϕ , magnet volume ν , magnetization M , applied magnetic field H , and the flexure stiffness k_{ϕ} . The beam geometry and the material property dictate the mechanical stiffness of the flexure with following equation:

$$k_{\phi} = \frac{E_c w t^3}{12l}$$

with the elastic modulus E_c , beam width w , beam thickness t , and beam length l .

B. Dynamic responses

The dynamic response of a microactuator can be estimated using a simple spring-mass system with following equation:

$$\omega = \sqrt{\frac{k_{\phi}}{M_{\text{eff}}}}$$

where ω is the resonant frequency of cantilever, and M_{eff} is the effective mass.

III. Methods

A. Maskless Photolithography setup

The cantilever and the magnetic element patterns were made using a maskless photolithography as described in [14](Fig.2). The computer is connected to a projector (HD 141X, Optoma, Fremont, CA, USA) with a digital micromirror device (DMD) to project and expose a desired pattern. Projector was vertically fixed on a stereo-microscope using a custom machined bracket. To improve the resolution and reduce the size of the image, lens and microscope were aligned between the sample stage and the projector. The mask pattern was designed using Microsoft PowerPoint. The exposure intensity was optimized by adjusting the pattern color in the software.

B. Device Fabrication

Fig. 3 illustrates overall process flow for the device fabrication. The magnetic microactuator was fabricated on commercial Cu-cladded LCP sheets (Rogers Ultralam 3850 HT, Rogers, CT, USA). We started the process by reducing the LCP thickness from 25 μm to 14 μm . We then laminated a dry film photoresist (FX-515, Dupont, Durham, NC, USA) on one side of LCP sheet and removed Cu from the other side using a Cu etchant (CE-200, Transene, Danvers, MA, USA). Next, the single-clad LCP laminate was attached on a 100-mm, 500- μm -thick silicon wafer (Silicon Quest, San Jose, CA) using PMMA (950 A10, MicroChem, Newton, MA, USA) as an adhesive. PMMA was spin coated at 4000 rpm for 30 s to obtain a film thickness of 1.8 μm . The single-clad LCP was placed on the PMMA layer and gently pressed down to remove the bubble between PMMA and the substrate using a glass slide. This was followed by baking at 150 $^{\circ}\text{C}$ for 2 min. The exposed LCP was etching a reactive ion etcher (RIE) with 17 sccm of O_2 and 3 sccm of SF_6 at 200 W in 150 mTorr for 30 min. After RIE, the sample was detached from the silicon wafer with an ultrasonication in acetone for 5 min.

The 14 μm -thick single clad LCP sheet was then remounted onto a carrier wafer using PMMA with the Cu on top. The top Cu layer was used as the etch mask for subsequent processes. First, an adhesion promoter (hexamethyldisilazane) 1.5- μm -thick layer of positive photoresist (AZ1518) was spin coated on the Cu surface and soft baked. The device pattern was exposed using the maskless photolithography and developed using 0.5 wt % sodium hydroxide. Next, the Cu layer was etched using CE-200 at 40 °C for 1 min. The exposed LCP surface was then etched with RIE as described above. The Cu mask was also used as the conduction layer for the nickel (Ni) electroplating. Ni was electroplated globally using a solution of 1 M nickel sulfamate, 0.4 M boric acid, and 10 g of sodium dodecyl sulfate with a constant current density of 20 mA cm⁻² for 50 min to achieve a final thickness of 14 μm . Next, the dry film photoresist was laminated on the Ni layer and patterned using the maskless photolithography. The dry film photoresist was used as a mask to pattern ferromagnetic.

C. Magnetic Microactuator Characterization

To quantify the functional capabilities of our prototype magnetic microactuators, the static mechanical responses of the fabricated devices were evaluated. The magnitudes of angular deflections were measured for a range of applied magnetic fields. The magnetic field was generated using a bespoke iron core solenoid electromagnet. The strength of magnetic field was quantified using a gaussmeter (Model 8010, Pacific Scientific, Chandler, AZ, USA). The sample was then placed on top of the solenoid and the magnetic field was applied. The vertical position of the magnet elements was measured using a digital microscope (KH8700, Hirox, Hackensack, NJ). Deflection angle of the device was calculated by measuring two vertical positions on the magnetic microactuator (i.e., tip of the device and end of flexure) for a given magnetic field strength. The dynamic response of the magnetic microactuators were measured using a scanning laser-doppler vibrometer (MSA-400, Polytec, Irvine, CA). The alternating magnetic field from a signal generator was swept from 500 to 4000 Hz at constant voltages to obtain the frequency response of microactuator through software (Polytec Scanning Virometer software, Polytec, Irvine, CA).

IV. Results

A. Fabrication results

Fig. 4 and 5 highlight fabrication results. The dual-beam microactuator patterns were well defined using maskless photolithography. However, the exposed patterns differed from the original design by approximately 5-10 μm due to variation in light exposure across the sample. A device pattern placed at a higher light intensity was overexposed compared to other parts of the exposed surface. The isotropic etching processes due to wet etching (Cu) and the RIE process (LCP) yielded approximately 10 μm of total undercut. The ferromagnetic Ni element was electroplated for 40 minutes to achieve 14 μm in thickness as expected. However, the isotropic etching of Ni produced inconsistent and imprecise ferromagnetic geometries (Fig. 5).

B. Static deflection and dynamic responses of magnetic microactuator

Fig. 6 shows the static response of prototype magnetic microactuators. The z-axis deflection in response to increasing static magnetic field was measured and converted into the deflection angle. The device deflection corresponded with the expected values in general. The dynamic responses of a magnetic microactuator are shown in Fig. 7. The primary mode resonant frequency showed at 1762 Hz in air on average ($n = 3$), which has errors from different beam widths and magnet volumes of each device [Table I].

V. Conclusions and Discussion

Here we reported on the rapid prototyping of LCP-based magnetic microactuator arrays as a part of our ongoing efforts to create a smart self-clearing glaucoma drainage device. We expect to integrate these devices within silicone-based microchannels to combat biofouling and to control flow resistance. The static response of these microdevices indicate good control of angular deflection in a customizable magnetic field range although it is may be possible to obtain larger deflections with a thinner LCP (Fig. 7). Without question, the process still requires additional optimization to improve resolution, minimize exposure variations, and reduce undercut to create more consistent and accurate microscale devices. Additional mechanical evaluations as well as *in vitro* and *in vivo* experiments are also needed to confirm functionality of these devices. However, our results illustrate the possibility of rapidly creating an array of microscale devices with varying shapes and sizes using readily available LCP laminate and a maskless photolithography setup. We hope that this low cost evaluation approach will expedite the development toward a smarter GDD with multiple functionalities.

Acknowledgments

The authors would like to thank Qi Yang and Chunan Liu for fabricating the electromagnet, Professor Jeffrey F. Rhoads for letting us use laser-doppler vibrometer, and the Rogers Corporation for providing LCP samples.

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Fig. 1. 3D images of magnetic micro actuators

(A) 3D illustrations of prototype array of magnetic microactuators in a magnetic field. Scale bar = 300 μm . (B) By integrating within microchannels, microactuators may be opened or closed to control flow resistance to keep constant IOP. The device is 1.5 mm wide, 7.8 mm in length, and 0.5 mm thick.

Fig. 2. Maskless photolithography setup

Digitized pattern designed on Microsoft PowerPoint is sent to a commercial DMD projector. The screen image is projected through an inverted projection lens and a microscope. XYZ controllable stage enable proper alignment of the image to the sample.

Fig. 3. Fabrication process for the double beam magnetic microactuator

(a) Making the cantilever pattern on the copper clad laminate of LCP substrate. (b) Wet etching for copper layer and RIE for LCP layer (c) Nickel electroplating and dry film photoresist lamination and patterning (k) Wet etching for Ni and Cu layer, which is followed by stripping the dry film photoresist.

Fig. 4. Fabrication results of magnetic microactuator

(A) Flexure patterns from maskless photolithography. (B) Copper etched patterns (C) RIE for removing exposed LCP layer. (D) Nickel patterned magnetic microactuators on LCP layer. Scale bar = 500 μm .

Fig. 5. Deflection of magnetic microactuator in static magnetic field

Compare to the microactuator without magnetic field (A), cantilever plane was deflected into out of plane in magnetic field with 54 kA m^{-1} (B). (Scale bar = $250 \text{ }\mu\text{m}$)

Fig. 6. Theoretical (solid and dotted line) and measured angular deflection (circle) in an increasing static magnetic field

The theoretical value was calculated with actual average value of cantilever dimensions (width = $27.66 \mu\text{m}$, length = $212.7 \mu\text{m}$, and thickness = $14 \mu\text{m}$) and average magnet volume ($= 10.13 \times 10^6 \mu\text{m}^3$). The results ($n = 4$) are expressed as average $\pm$ s.d.

Fig. 7. Dynamic responses of a magnetic microactuator in air
The magnetic fields were generated by applying constant voltage in air.

Table I
The device dimensions and resonant frequency

Device [number]	1	2	3
Beam Width [μm]	32.2 ± 3.4	28.6 ± 3.2	29.4 ± 4.1
Magnet Volume [mm^3]	10.7×10^{-3}	10.4×10^{-3}	9.29×10^{-3}
Resonant Frequency [Hz]	1723	1779	1785