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Design of a Magnetostrictive Bimorph for Micromanipulation

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Abstract— Micromanipulation within a lab-on-a-chip (LOC) device enables precise manipulation of cells, paving the way to diverse biomedical applications. In this research, the design of a magnetostrictive microactuator for micromanipulation is presented. The proposed microactuator is a cantilever-type bimorph consisting of a Poly-methyl methacrylate (PMMA) layer between a Terfenol-D and Samfenol-D layer, which have high magnetostrictive properties, and a Silicon probe tip at the free end. The microactuator characteristics were evaluated through numerical simulations. The designed microactuator can operate under frequencies up to 146.12 kHz. The sensitivity range of the microactuator is 77.6-11323.6 nm/T, while it can exert pressures up to 15.55 MPa for magnetic fields from up to 800 kA/m, demonstrating that it is capable of micromanipulation of cells in LOC devices.

Keywords: ***lab-on-a-chip, magnetostriction, MEMS, microactuators, microrobotics***

I. INTRODUCTION

A lab-on-a-chip (LOC) is a micro-electro-mechanical system (MEMS) device that integrates one or several laboratory functions onto a single chip. These are often microfluidic devices consisting of microfluidic channels, pumps, droplet generators and reservoirs. When it comes to LOCs in genomics and proteomics, it is essential to manipulate biological particles to observe, analyze and enumerate components at cellular level. Using microrobots for manipulation increases the throughput and repeatability of processes outperforming human manipulation.

In literature, there are basically two types of micromanipulators in terms of interaction: contact and non-contact. Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM) have been promising contact type micro/nano manipulation methods since 1990s (Pavliček & Gross 2017; Sitti 2001; Sitti & Hashimoto 1999). STM probes use electric pulses to manipulate particles, whereas AFM probes can perform more mechanical tasks such as pushing/pulling, cutting, touching, and indenting. The AFM probe is a cantilever/tip assembly which interacts with the sample. Usually, a separate mechanism controls the up and down and lateral motions of the probe. On the contrary, optical tweezers is a non-contact manipulator which uses a highly focused laser beam to create an optical trap (Xie et al. 2019). Existing approaches of LOCs for cell manipulation are different from AFM and STM. In most of the cases, they are polarizing particles using electric fields for cell manipulation (Medoro et al. 2003; Medoro et al. 2007). In addition, LOCs incorporate mechanical structures such as microgrippers to manipulate cells (Somà et al. 2017).

Magnetostriction effect is the phenomenon where a ferromagnetic material expands or contracts in response to an external magnetic field, as illustrated in Figure 1. Hence, utilizing this phenomenon in an actuator paves the way for wireless actuation and control. Researchers have created magnetostrictive bimorphs in millimeter scale and were able to achieve displacements up to 4 mm with static magnetic fields (Arai & Honda 1996). Despite their nonlinear material properties, magnetostrictive materials are deemed to perform better than piezoelectric and shape memory alloys due to inherent characteristics: fast response time, relatively large strokes, high resolution and bandwidth (Zhao & Lu 2018; Niu et al. 2017).

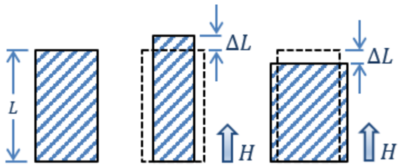

Figure 1. Schematic illustrating the positive and negative magnetostrictive effects.

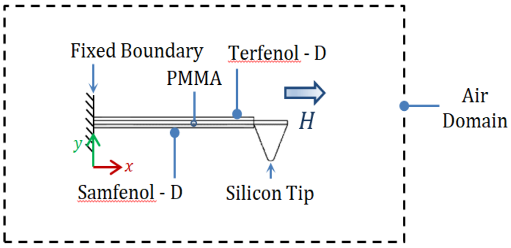

Figure 2. Layout of the proposed magnetic microactuator. The bimorph is 100 µm in length. *H* is the spatially uniform external magnetic field in the x-

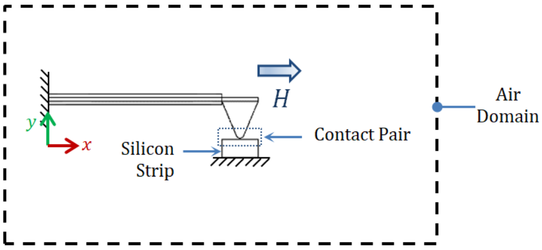

Figure 3. Schematic diagram of the contact simulation.

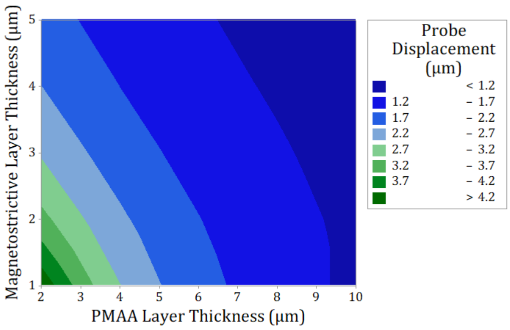

Figure 4. Variation of bimorph tip displacement with PMMA and magnetostrictive material layer thicknesses.

In this research, the design of a magnetostriction based micron-scale bimorph for micromanipulation is presented. The basic mechanical structure was inspired from the AFM probe. Through analyzing the characteristics of the microactuator, the capability of using magnetostriction based microactuators in micromanipulation is investigated. Significant design parameters such as accuracy, range of motion, and linearity were evaluated using numerical simulations to this effect. The abstract introduces the proposed magnetostrictive microactuator and describes the methodology of investigating microactuator characteristics. The microactuator characteristics obtained through numerical simulations are discussed, along with the conclusions.

II. MATERIALS AND METHODS

The conceptualized single degree of freedom (DOF) magnetostriction based cantilever-type microactuator is shown in Figure 2. It consists of a Poly-methyl methacrylate (PMMA) layer sandwiched between a Terfenol-D and Samfenol-D layer. Here, PMMA was selected due to its flexibility as a result of the low Young's modulus, the value of which is 3 GPa. From this, the stiffness of the bimorph is reduced. At the free end of the cantilever is the probe tip. In terms of magnetostriction, Terfenol-D and Samfenol-D have significant positive and negative magnetostrictive properties respectively. Hence, when an external magnetic field *H* is applied, the beam acts as a bimorph due to the strain difference of the two magnetostrictive elements. The saturation magnetization of Terfenol-D is 800 kA/m while for Samfenol-D it is 560 kA/m. Saturation magnetostriction of Terfenol-D and Samfenol-D are 820 ppm and -1258 ppm respectively. The initial magnetic susceptibility of both the materials were taken as 14. By selecting one magnetostrictive layer to have positive magnetostriction and other to have negative magnetostriction, the tip displacement of the bimorph can be increased.

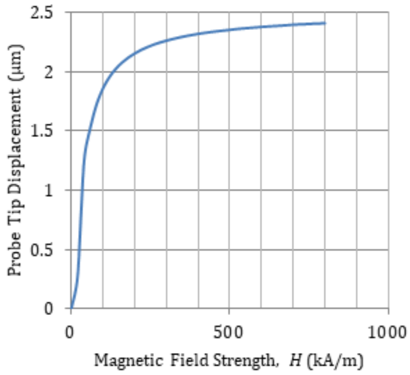

Figure 5. Probe tip displacement in the y-direction with varying magnetic field strength.

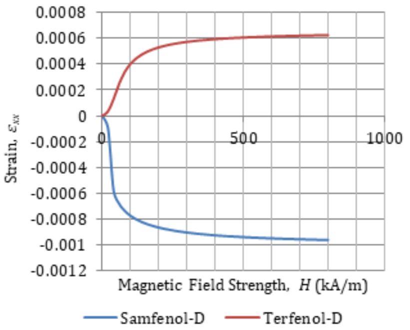

Figure 6. Direct strain of the magnetostrictive materials in the x-direction (ε_{xx}) variation with magnetic field strength.

The behaviour of the proposed microactuator was analyzed through 2-dimensional numerical simulations using COMSOL Multiphysics. The length of the bimorph is set as 100 µm. First, a parametric study was carried out without the probe tip to select the layer thicknesses of the bimorph by analyzing the probe displacement variation with the thicknesses of the PMMA and magnetostrictive element layers. The thickness of the PMMA layer was varied in the range 2-10 µm, while thickness of the magnetostrictive layers was varied in the range 1-5 µm. The applied uniform magnetic field in the x-direction for this study is the saturation magnetization of Terfenol-D, i.e. 800 kA/m.

After selecting suitable material layer thicknesses for the bimorph, a modal analysis using numerical simulations was conducted to find the first mode frequency and shape. Furthermore, numerical simulations were done to obtain the range of motion and sensitivity of the microactuator. For this, the uniform external magnetic field was varied in the range 0-800 kA/m and resulting probe tip displacement in the y-direction was computed. The pressure exerted by the actuator on an object was analyzed for different magnetic field strengths through computing the contact pressure between a Silicon strip and the probe tip using the penalty contact algorithm (see Figure 3). The initial gap between the probe tip and the strip is zero. The material of the probe tip is also Silicon. The applied external magnetic field strength was varied up to 800 kA/m in the aforementioned study.

III. RESULTS AND DISCUSSION

For any actuator, the range of motion is an important parameter that exhibits the capabilities and limitation of the actuator. The layer thicknesses of both the PMMA layer and magnetostrictive layers affect the bending of the bimorph. Therefore, it is desirable to analyze the behaviour of bimorphs with different layer thickness and select suitable values. From Figure 4, it is observable that the bimorph tip displacement in y-direction is high at low PMMA and magnetostrictive layer thicknesses. Therefore, to obtain a maximum probe tip displacement above 2 µm, both the PMMA and magnetostrictive layer thicknesses were selected as 2 µm.

The first mode frequency of the microactuator is 146.12 kHz. Hence, the excitation frequency should be less than 146.12 kHz in order to obtain the expected bending mode shape. The range of motion of the microactuator, which is the probe displacement in the y-direction, can be defined as 0-2.41 µm for applied magnetic field strengths in the x-direction up to 800 kA/m (see Figure 5). The sensitivity of the microactuator can be obtained by computing the gradient of the relationship between probe tip displacement and magnetic field strength. Overall, the microactuator shows a nonlinear relationship between probe tip displacement and applied magnetic field strength, where the sensitivity gradually decreases. However, in the considered magnetic field strength range are 77.6 nm/T and 11323.6 nm/T respectively. This sensitivity is more than sufficient for cell manipulation since the average human cell size is around 100 µm in diameter (the minimum of which is red blood cells with 8 µm diameter). Furthermore, it was observed that the Samfenol-D layer has a higher direct strain in the x-direction ε_{xx} than the Terfenol-D layer for a given magnetic field strength (see Figure 6).

The maximum contact pressure between the Silicon strip and probe tip is shown in Figure 7. Overall, it is observable that the exerted pressure increases nonlinearly with the magnetic field strength. This behaviour exhibits a saturation of the contact pressure. However, in the range 0-80 kA/m, this relationship is approximately linear. Hence, if the operating region is within this range, one can obtain linear actuator force characteristics. Consequently, the force controlling would be relatively easier in this region. The microactuator can exert a maximum pressure of 15.55 MPa at 800 kA/m and 11.82 MPa at 100 kA/m. Thus, the microactuator is able to manipulate a payload of 1 ng, which is the average weight of a human cell (assuming a 100 µm

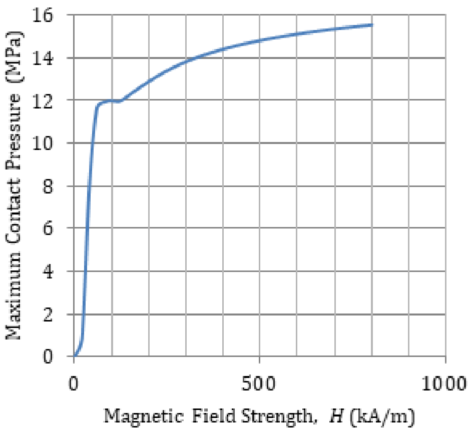

Figure 7. Maximum contact pressure variation with magnetic field strength.

diameter circular cell area). Furthermore, since the bimorph deflects in the y-direction, no additional mechanism is required to control the movement of the probe in the y-direction unlike in the AFM probe.

IV. CONCLUSION

A cantilever-type magnetic microactuator based on the magnetostriction effect is proposed for micromanipulation. The actuator consists of a bimorph that deflects due to magnetostriction and a probe tip at its free end. The probe tip interacts with the objects inside a lab-on-a-chip (LOC) device. The microactuator has sensitivity in the range between 77.6-11323.6 nm/T for magnetic fields up to 800 kA/m. The microactuator is able to operate up to 146.12 kHz, which is the first mode frequency of the system. Furthermore, contact pressures up to 15.55 MPa can be exerted using the proposed microactuator. Therefore, the nanometer sensitivity with higher force output verifies the possibility of magnetostrictive bimorph to be used for micromanipulation of cells in LOC applications.

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