Magnetically Tunable Optical Metamaterials and Diffractive Robotics

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Primary CNF Tools Used: Oxford FlexAL ALD, ASML DUV Stepper, JEOL 6300, CVC E-Beam Evaporators, Oxford 81/82/100 Etchers, PT770/PT740 Etchers, Anatech Asher, Zeiss SEMs, Veeco AFM, Tencor P7 Profilometer, Filmetrics UV, AJA Sputterer

Abstract:

We integrate ultra-flexible, five nanometer thick atomic layer deposition glass hinges with rigid magnetically programmed panels to create untethered, magnetically tunable optical metamaterials and robots at the diffraction limit. We first present a simple walking magnetic microbot consisting of two panels that form a simple mountain-valley fold in an external magnetic field. Next, we fabricate several larger optical metamaterials with magnetically tunable periodicities using this same mountain-valley motif. These structures form the basis for a new class of untethered, microscale optical robots that dynamically interact with the local surroundings (locomotion) and incident light (diffraction).

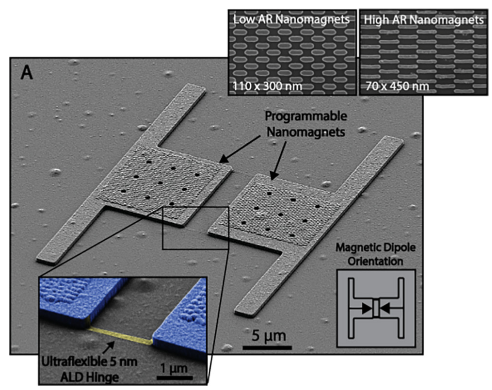


Figure 1: (A) SEM of magnetic microbot. (top-right inset). Arrays of low/high AR nanomagnets used to program the microbot. (bottom-right inset) Final magnetization of the microbot (lower-left zoom). False-color SEM of ALD hinge.

Summary of Research:

Figure 1 shows a microbot at the diffraction limit capable of magnetically controlled locomotion. We first fabricate arrays of single-domain cobalt nanomagnets (top inset) ~ 100 nm on a side with varying aspect ratios (ARs) that form magnetic dipoles along the long axis of the magnets. The coercive fields and magnetic dipole directions of these nanomagnet arrays are tied to the shape anisotropy; since moments prefer to align along the long axis of the magnet, higher shape anisotropy (higher AR) magnets require higher coercive fields. For example, the nanomagnets in Figure 1 (top inset) have coercive fields of 90 mT and 150 mT for the low AR and high AR magnets, respectively. We sequentially magnetize these arrays of nanomagnets with disparate coercive fields to program the magnetic control mechanism of the microbot [1]. The final magnetization directions of the microbot are shown in the bottom-right inset of Fig.1.

We embed these nanomagnets in rigid glass panels and connect the glass panels together with nanometer thick atomic layer deposition (ALD) glass hinges (lower left, Figure 1) that form a kind of fascia strong enough to hold together the body of the microbot but flexible enough to bend under an external torque [2]. We apply a uniform out-of-plane external field to torque both panels up or down, demonstrating the basic mountain-valley fold essential for origami-inspired metamaterials.

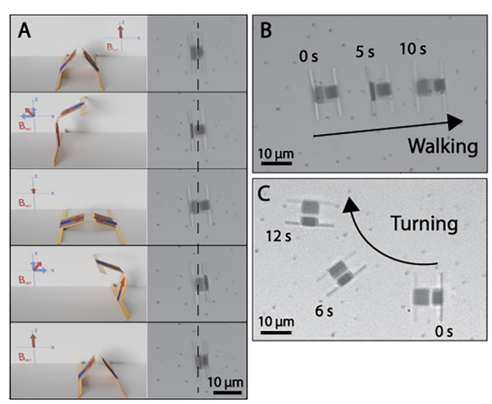
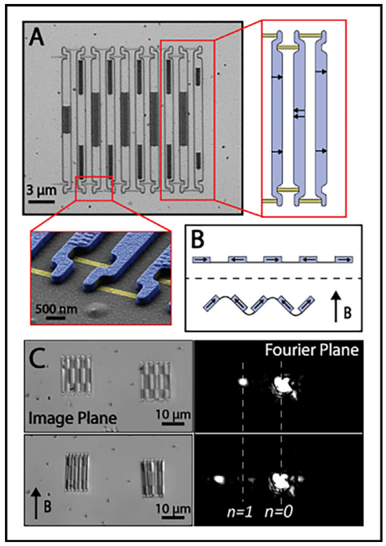


Figure 2: (A) Step motion of the magnetic microbot controlled by sinusoidal external magnetic torque. (B-C) Locomotion of the inchworm with a combination of a 1 Hz sinusoidal z-axis and x-axis magnetic field out-of-phase by 90 degrees. (C) Controlled turning locomotion.

Moreover, we demonstrate a crawling motion that mimics an inchworm by applying a combination of sinusoidal in-plane and out-of-plane magnetic fields out-of-phase by 90 degrees. The stepwise motion of the crawl is depicted in Figure 2A. The main mechanism of walking relies on the extension/contraction of the front/back armature as the microbot pivots out-of-plane. Each step moves the microbot about one-half body length; Figure 2B shows a timelapse of the microbot moving across the substrate with a 1 Hz sinusoidal field over 10 seconds moving at 0.5 body-lengths/second. Faster walking speeds are achieved by increasing the frequency of the control fields. Directional motion and turning (Figure 2C) of the microbot is achieved by adjusting the parity of the in-plane fields.



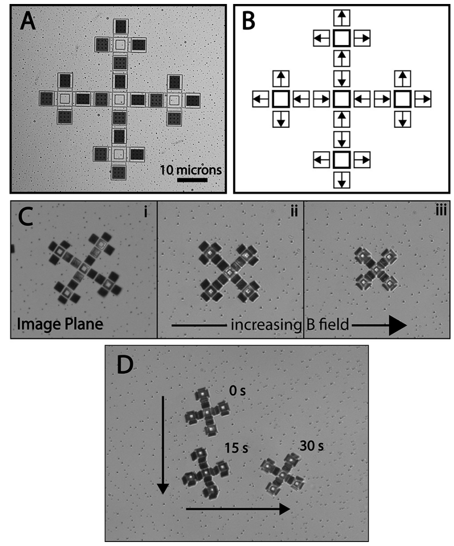


Figure 3, above left: (A) Diffraction grating with magnetically tunable periodicity. (B) Schematic of grating mountain-valley fold. (C) Image (left) and diffraction image (right) of the grating before and after actuation. Figure 4, abive right: (A) Micrograph of optical metamaterial with magnetic armature. (B) Programmed magnetic dipole directions. (C) Actuation of the microbot with an increasing out-of-plane external magnetic field from left to right, and (D) locomotion of the microbot, including a 90-degree change of direction.

The simple mountain-valley motif of the microbot is extended to an array of mountain-valley folds to create magnetically tunable optical metamaterials.

For example, Figure 3A shows a linear diffraction grating with a line spacing of 0.5 lines/micron that consists of an array of rigid panels with alternating magnetic dipole orientations (Figure 3A, top-right inset) held together by ALD hinges (Figure 3A, bottom inset). An external out-of-plane field of < 5 mT torques the panels out-of-plane (Figure 3B), and the ALD hinges bend elastically to accommodate this motion contracting and reducing the periodicity of the grating (Figure 3C, left). This contraction can be seen clearly by examining the diffraction peaks in the Fourier plane (Figure 3C, right) when illuminating the gratings with a laser. The first-order diffractive peak (n=1) moves away from the central peak as the periodicity of the grating decreases when compressed.

Finally, we apply this same mountain-valley motif to larger, less periodic structures. Figure 4A shows a micrograph of a microbot 50 µm on a side consisting of 25 panels, 20 magnetized panels, 4 magnetization directions, all held together by nanometer-thick ALD hinges [3]. The armature structure consists of four arms extending outward from a central panel, with three panels at the end of each arm forming a claw. The dipole orientations are shown in Figure 4B. An external out-of-plane field torques the panels out-of-plane, and the entire structure contracts in two-dimensions (Figure 4C). Finally, we can walk the microbot along the surface using the same crawling motion depicted in Figure 2A. Figure 4D shows a time lapse of the microbot walking along the surface, including a 90-degree turn.

Conclusions and Future Steps:

The combination of magnetic tunability and ultra-flexible hinges enable a new class of optical metamaterials and microbots at the diffraction limit that provide a new method to actively shape and control incident light using external magnetic fields. Future designs of these optical metamaterials will take the control of light a step further by fabricating optical meta-atoms, subwavelength dielectric optical elements that form the basis of metasurfaces, onto the surface of the microbots. We anticipate incredible potential in numerous fields from local Raman spectroscopy to medical imaging.

Acknowledgements:

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References:

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