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Electromagnetic Rotational Actuation

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Abstract

There are many applications that need a meso-scale rotational actuator. These applications have been left by the wayside because of the lack of actuation at this scale. Sandia National Laboratories has many unique fabrication technologies that could be used to create an electromagnetic actuator at this scale. There are also many designs to be explored. In this internship exploration of the designs and fabrications technologies to find an inexpensive design that can be used for prototyping the electromagnetic rotational actuator.

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NOMENCLATURE

AFRL	Air Force Research Labs
COTS	Commercial Off The Shelf
DOE	Department of Energy
ECD	Electro Chemical Deposition
FIB	Focused Ion Beam
LPCVD	Low-Pressure Chemical Vapor Deposition
MEMS	Micro Electro Mechanical Systems
PM	Polarization Maintaining
SNL	Sandia National Laboratories

1. INTRODUCTION

There is a need for a meso-scale actuator to bridge the capabilities of commercial off the shelf (COTS) small servo motors and micro electro mechanical systems (MEMS) actuators. Current COTS motors provide the force and displacement requirements but these motors are much larger than the meso-scale devices making the system much too bulky for their intended purpose. The MEMS actuator could be a solution to size issue but currently no MEMS actuator has both the force and displacement that is required by the meso-scale devices.

Many applications have been pursued to the point that this actuator is critical at which point they have been left by the wayside. These applications vary from optical laser systems to actuation of mechanical flaps. The first is an acousto-optic isolation of fiber high power laser system. This project is being developed by an Air Force Research Lab (AFRL) and would require 125 μm diameter polarizations maintaining optical. A second is an aerodynamic flap actuator to control a μUAV (micro-unmanned-air-vehicle) being developed by DARPA. A third is a biomimetic lens for use in miniature cameras being developed by the University of Utah. Not all of the application can be developed at the same time but once the actuator is developed only slight modifications will need to be made. For proof of concept design the application being focused on in this project is rotating a glass fiber. The glass fiber will have a diameter in the range of 100 μm – 1 mm with hopes of using a Polarization Maintaining (PM) optical fiber. The torque required to rotate a glass fiber of this size to the desired 10 degrees is between 10^{-6} to 10^{-4} N-m. Another challenge of this particular application is the need to drive the fiber from DC to 1 MHz. This force and variability in drive frequency can be created by using an electromagnetic coil.

2. POTENTIAL FABRICATION TECHNIQUES

Sandia National Laboratories (SNL) has many unique processes that can be utilized to aid in this project. With the current funding and time restraints of this project not all of these processes will be practical. Even though many of the processes are not practical at this point it is still important to discuss all of them for future work when more time and funding is available.

2.1 Patterning the Fiber

The most difficult obstacle to overcome in this design is patterning the glass fiber. Patterning fibers at this scale has not been successfully attempted in very many cases and requires specialized and modified equipment and processes. Ideally the fiber will have a uniform coating which can be achieved by rotating the fiber as it is sputter coated or by using a technique that would normally be used to get uniform side wall covering like Low Pressure Chemical Vapor Deposition (LPCVD). There are many options to doing this at Sandia as there are many deposition systems. Once the fiber is coated to the desired thickness with the appropriate material it can then be patterned using one of many possible processes.

2.1.1 Focused Ion Beam (FIB)

One process for patterning the material on a fiber has been done by David Adams in the Advanced Prototyping Lab, org. 1832. In this case a 500 um fiber was coated with Cr followed by Au. Then using a customized FIB system the metal was patterned with a 30keV Ga ion beam. This case demonstrated the ability to fabricate a radial coil which if it was used in this configuration it would yield a force parallel to the axis. This force may have applications for axial translation but is not the goal of this project.

This process could be modified and used to create a pattern that will generate a torque. Using the FIB to pattern the fiber is a very time consuming process because with every movement of the fiber is potential need for realignment and by nature the FIB is a slow milling process. Even with the specially modified system, the addition of an extra axis of rotation, in the advanced prototyping lab the process is still time consuming but allows for more precise patterns.

2.1.2 Laser Enhanced Chemical Etch

An alternate method to the FIB for etching with a beam is laser enhanced chemical etching. Laser enhanced chemical etching utilizes corrosive gas, like chlorine, to etch the metal with the laser used to locally heat the area of the sample to be etched making this method much faster. This is another capability of the Advanced Prototyping Lab but at this point the system would have to be modified to be able to rotate the fiber in the system. After talking to David Adams if funding became available this system could have a rotational axis added and become an automated system. Being able to upgrade this system would be a much better opposition then using the FIB because it would be a reproducible automated process that would provide the ability to pattern complex geometry.

2.1.3 Resist

Another way to pattern the fiber is to use photolithography; this is difficult do to the fiber being small and round making it hard to handle. Patterning the fiber in this way will limit the patterning to very simple designs. The Fiber must be coated by the photo-resist one possible way that has been talked about is using a spry resist either positive or negative. It could then be exposed using a contact aligner and simple mask. Another novel way to pattern the fiber would be using multiple exposures from different angles using the coated fiber as the mask so only the sections that had been exposed for long enough would be etched. Figure 1 Timed exposure pattern. In bottom right the dark blue represents the area that has only been exposed for 2 cycles and if it is timed right it will be left to mask the fibershows an example of the pattern, exposure times have been represented in colors. In the bottom right after timed exposure from 4 angles the dark blue is the region that was exposed twice and if the timing is correct then this region will be left. Over etching can be used to etch the thin sections on the sides. Patterning the resist could also be done using the FIB. Using ion milling allows for a more complex pattern to be made but would be very time consuming.

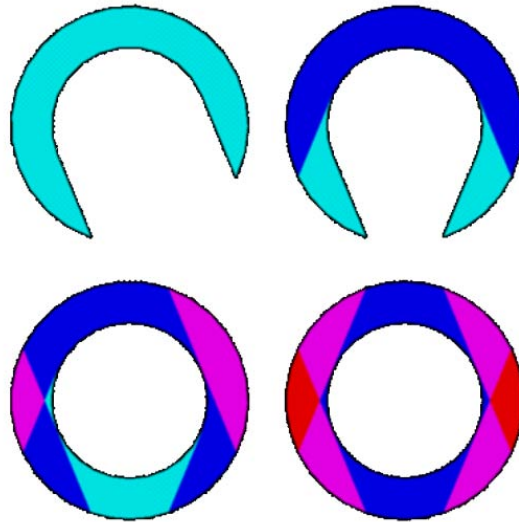


Figure 1 Timed exposure pattern. In bottom right the dark blue represents the area that has only been exposed for 2 cycles and if it is timed right it will be left to mask the fiber after development.

2.1.4 Assembling on the fiber

Patterning the fiber by deposition and etching, as has been discussed in the previous sections, is not the only way that it can be done. The fiber can also be attached to anything that will react to the external magnetic field. One example would be using a wire and wrapping it around fiber. Wrapping the wire radially around the fiber will provide an axial translation that may be useful but is not the goal of this project. If the wire is wrapped at a high angle close to being parallel to the axis it will give the desired rotation but wrapping at that angle is difficult so it may require the wire to be wound then attached to the fiber. Another option would be to use a permanent magnet. The permanent magnets of this size are commercially available as watch making parts from Audemars microtec. The magnet could also be fabricated through electroplating.

2.2 Electro Chemical Deposition

Once the Fiber has been patterned adding a soft magnetic material will help by increase the strength of the magnetic fields. Electro Chemical Deposition (ECD), also known as electroplating, of magnetic material can be used for this purpose. At SNL the Metal Micromachining group, 1725, has developed a process for depositing Ni-Fe 78/28 and 45/55 which are both soft magnetic materials. Depositing 78/22 is more a developed process but the 45/55 shows more desirable properties. The metal micromachining group has also demonstrated potential for plate Ni-Fe-Co, a hard magnetic material, but will require more funds to acquire a fully developed process. Either of these materials can be used to increase the thickness of the trace that has been patterned by any of the above techniques. Material cannot be deposited directly on to the fiber because it is necessary to have current on the area that is desired for patterning. ECD gives not only the ability to grow magnetic material on the fiber but could also be used to grow custom magnet for creating the external magnetic field. To make the magnets with high aspect ratios the LIGA process can be used to create the mask which would provide well defined and strait sidewalls.

2.3 Electromagnet to create the magnetic field

The magnetic field will be created using an electromagnet. An electromagnet consists of current carrying wire wrapped around a core.

$$B = \frac{\mu_0 \mu_r N I}{2 l} \quad (2.1)$$

Equation 2.1 calculates the magnetic field at the end of a solenoid that has a length much larger than the radius where μ_0 is the permeability in vacuum, μ_r is the relative permeability of the core material, N is the number of turns, I is the current, and l is the length. Using a core material with a high permittivity can greatly increase the field strength because μ_r can vary from 1 for vacuum to 10's of thousands for soft magnetic materials. Having a high permittivity often comes with the cost of being a conductive material. Using a conductive material will cause eddy currents leading to magnetic hysteresis which limits the frequency of which the electromagnet can be operated. Another factor to consider is the wire, smaller wire will increase the number of turns that will fit in an area but decrease the current carrying capacity. The wire size in the magnetic laboratory goes down to 50 μm and Audamers size ranges from 10 – 200 μm .

3. DESIGN

The designs of the electromagnetic actuator were evaluated in two main categories; first was the magnetic field that could be produced and the second was the cost of fabricating the device with technologies currently available at SNL. Of those factors the later is the more important at this point as this project is funded through summer internship funds. In all the designs the main focus is patterning the glass fiber assuming use of an electromagnetic coil to produce the external field.

3.1 Toroidal

This device is modeled after the toroid; although in a toroid the strongest fields are in the core which is impossible to use to actuate this device. This design came about because if the trace was to go up the fiber then come back down next to it opposing fields would be created and cancel each other out. One solution is to have the trace overlap so that the field on the outside dominates, Figure 2 Toroidal pattern on fiber with two conductive and an insulating layer. This configuration then becomes complex because it requires an insulating layer between two conductive layers. Each of the conductive layers would require complex patterning that would require either the FIB or laser enhanced chemical etch.

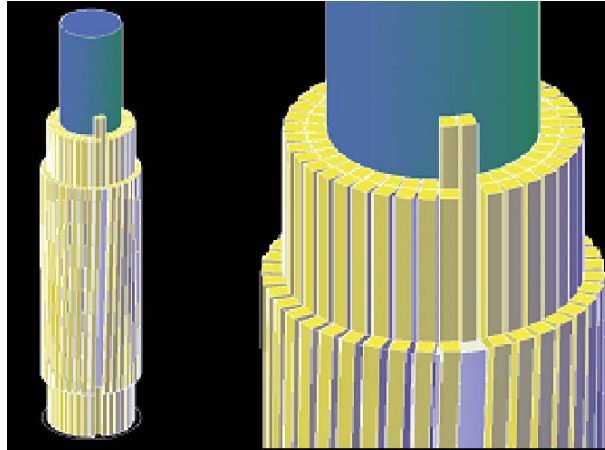


Figure 2 Toroidal pattern on fiber with two conductive and an insulating layer

3.2 Thick and Thin

This design takes advantage of the Biot-Savart law (3.1) focusing on the current density, J , which is equal to the current, I , over cross sectional area, A .

$$H = \frac{1}{4\pi} \int_v \frac{J \times \hat{R}}{R^2} dv \quad (3.1)$$

This shows that if the current is held steady then the wire with a larger area will have a smaller field. To utilize this effect the trace should go down the fiber with small width then when it goes back up next to it have a larger trace and continue alternating the width of the trace all the way around the fiber, Figure 3 Thick and thin patten to be wrapped around the fiber. If the fiber was patterned in this way most of the field would still be canceled out by the opposing fields because the distance between the centers of the traces is great enough that even the wider trace would dominate. If the trace was made thicker rather than wider this may be useful but would require more simulation to decide if it would provide forces required. This concept could be used in the previous design with the inner traces being wider to help the outside trace to be dominant.

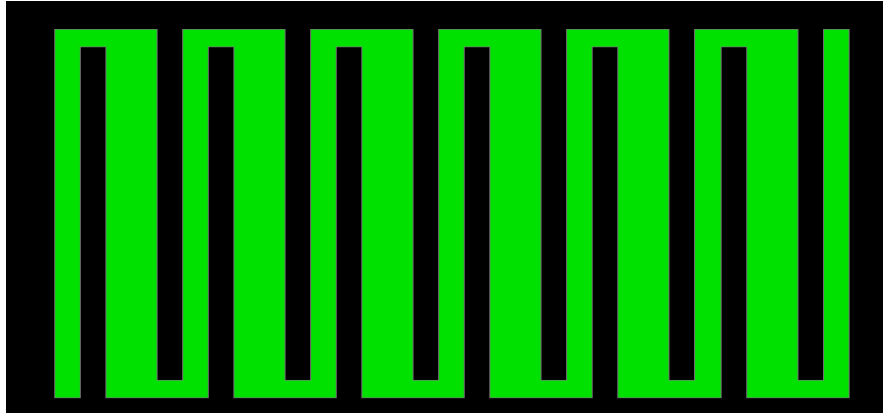


Figure 3 Thick and thin patten to be wrapped around the fiber

3.3 Single Loop

To simplify the patterning a single trace could go up one side and back down the opposite side, Figure 4 Single Loop pattern. Trace up one side and back down the other.. This pattern would create a field similar to dipole permanent magnet where there is a positive and negative side. Because this pattern is simpler it could be patterned using the photolithography process rather than the more complex beam etching techniques.

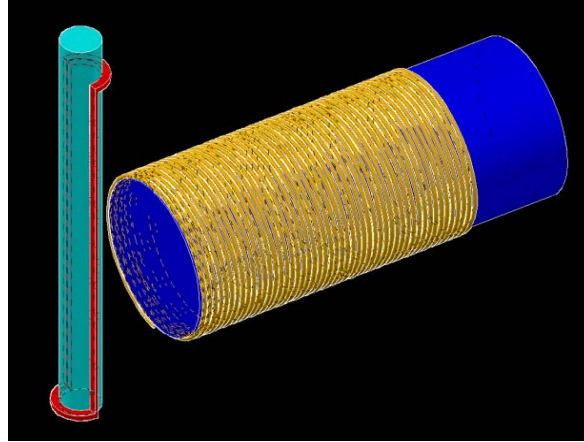


Figure 4 Single Loop pattern. Trace up one side and back down the other. Dark blue represents the electromagnet with wire wrapping.

3.4 High Angle Coil

An identical field could be created by wrapping or attaching coil at a high angle close to parallel to the axis as seen in Figure 5 High Angle Coil. Wire wrapped around the fiber to create electromagnetic field.. This altogether eliminates the need to patent the fiber but will bring up other issues of attaching the coil to the fiber. This design could eliminate the need for the external field to be created by an electromagnet by using the coil on the fiber to create the alternating magnetic field.

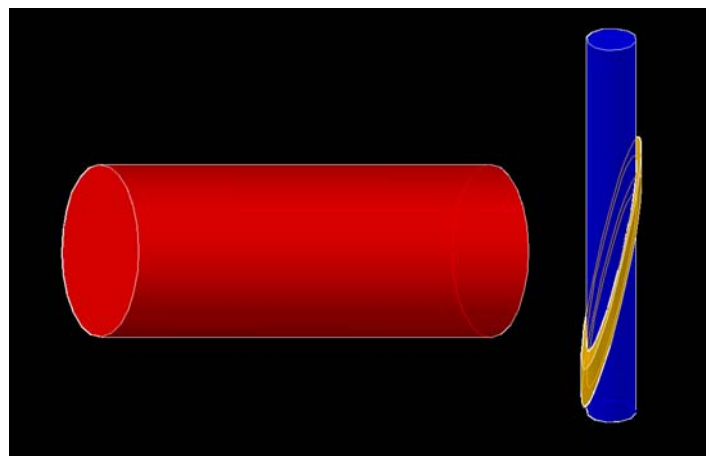


Figure 5 High Angle Coil. Wire wrapped around the fiber to create electromagnetic field.

3.5 Current in Single layer

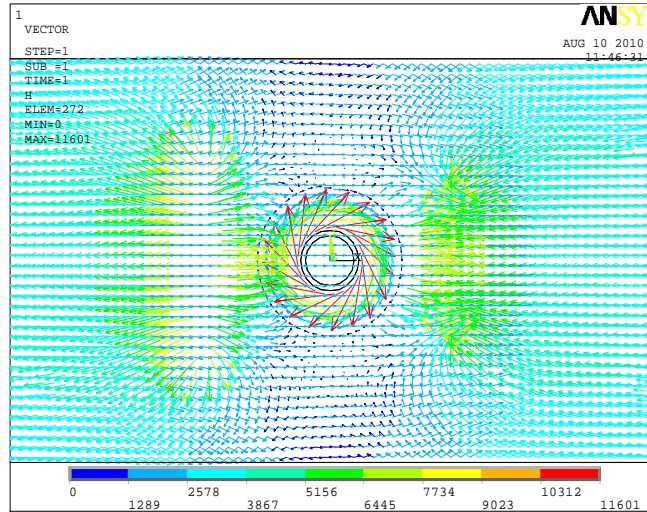


Figure 6 Ansys simulation showing the magnetic field of current in soft magnetic layer.

This design is by far the simplest because it requires no patterning. Using a wire to create an electromagnetic field is not optimal but provides an inexpensive way to prove the viability of creating a meso-scale electromagnetic rotational actuator. This simplified design also provides a platform for testing out many of the other fabrication techniques including depositing the seed layer and electroplating the fiber. Simulation of this design, Figure 6, shows a nearly uniform field causing the torque to be very low, 10^{-8} N-m, but this design can still be used to demonstrate rotational actuation.

3.6 Permanent Magnet

Using a permanent magnet on the fiber offers the main advantage of being the only design discussed that does not require electrical connection to the fiber. Permanent magnets of this size are commercially available through watch making companies like Audemars Microtec or it could be fabricated using micromachining or LIGA electroplating. The magnet could then be attached to the fiber or once the electroplating process for Fe/Ni/Co is completed then it can be grown directly onto the fiber. Simulation of the design, Figure 7, provided a torque of 10^{-5} N – m which is in the range required for the prototype design.

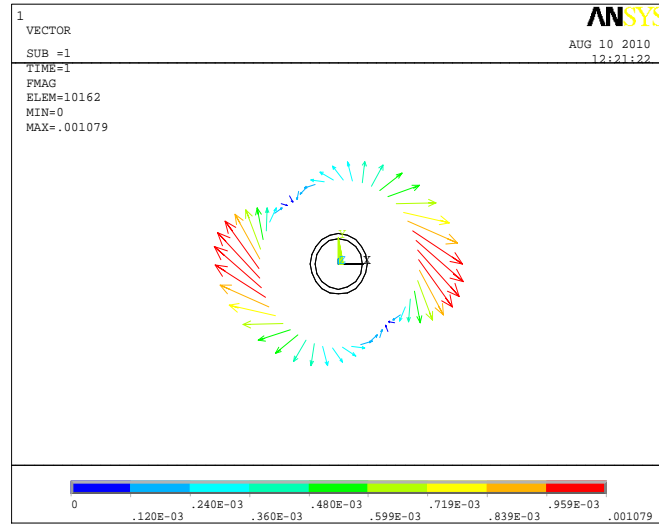


Figure 7 Ansys simulation showing force vectors in the permanent magnet case

3.7 Testing fixture

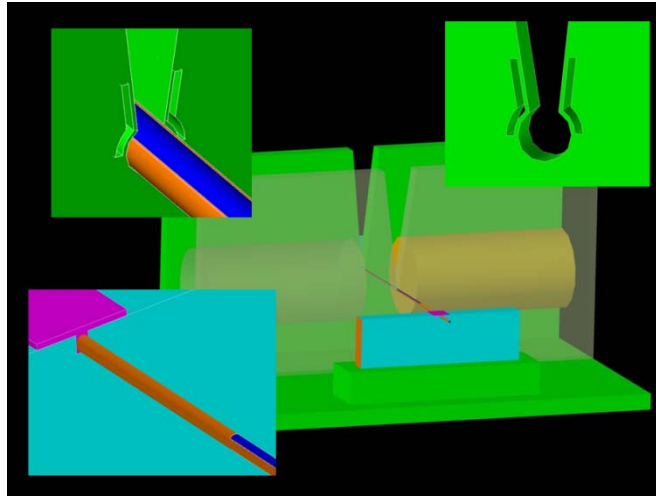


Figure 8 Testing fixture. Lower left fiber attachment point, upper right fiber snap point, upper left fiber snapped in.

Once the fiber is fabricated it will be tested in a test fixture, Figure 8, which will hold it in place. One end of the fiber will be attached perpendicular to a plate using epoxy, seen lower left of Figure 8. The plate is then held in place and the fiber is snapped into place to limit the fiber to moving in the axial rotation direction. In between the two points where the fiber is being held is where the electromagnets to create external field. It should then be possible to see the fiber rotate.

4. CONCLUSIONS

There is an apparent need for a meso-scale actuator with many applications waiting for this actuator. After review many fabrication technologies and designs that may be used for future work on this project the cheapest method currently available was proceeded with. Currently the fabrication is in process to be completed shortly. Multiple fibers are attached to a piece of a silicon wafer using a conductive epoxy. At that point the fibers are coated with Ti followed by Cu the fibers are continually rotated in the evaporator so all sides are coated. The fibers are then patterned with a simple photo resist pattern to grow a cylinder of Fe/Ni to use as the wire. This fabrication shows great potential for success although with more funding other techniques could be used to create an actuator with much high torque.

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