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A LATCHING, BISTABLE OPTICAL FIBER SWITCH COMBINING LIGA TECHNOLOGY WITH MICROMACHINED PERMANENT MAGNETS

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SUMMARY

A bi-directional, latching microactuator which combines the use of micromachined permanent magnets and electromagnets has been developed. The device is fabricated primarily from Ni/Fe permalloy using LIGA technology, whereas the permanent magnets are cut from NdFeB using micro-electro discharge machining. The permanent magnets allow the actuator to operate with zero standby power. The device offers very high throw and high force output with sub-micron positioning accuracy. It latches in both directions, achieves a minimum switching speed of 2.1 ms, and requires drive currents of only 5.88-8.83 mA. Power dissipated by the switch within this operating regime is as low as 11 mW. Switching energy is as low as 25 μJ.

A 1×2 optical fiber switch was constructed using the latching magnetic switch. The mechanical load of the fiber did not measurably affect the switch performance. Optical insertion loss was measured at 0.5 dB for the latching switch. The loss did not change when the switch was powered off.

Keywords: LIGA, permanent magnets, optical switch

I. INTRODUCTION

Linear microactuators and micro motors have numerous applications in the areas of switches, relays, valves, and rotational drives. Specifically, there is a need for switches which can send a signal on an incoming optical fiber to one of two output fibers (a 1×2 switch). These devices are required as network elements in optical communication systems, subscriber loop networks, fiber to the home applications, optical cross-connects for redundant or protective switching, and factory testing of optical elements and equipment testing [1].

There are two general methods of accomplishing this switching with the use of passive optical techniques (i.e., no optical amplifiers). One method is to actuate the actual fiber by moving it into alignment with one of two outgoing fibers (moving fiber switch). The other method involves fixing the fibers in place and moving something else that routes the light to one of two outgoing fibers (fixed fiber switch). Of these two methods the moving fiber switch has the potential to obtain a lower insertion loss because the fixed fiber switches introduce additional losses by using additional elements within the switch such as a mirror or waveguide. Switch losses originate from the fiber misalignment and the Fresnel reflection loss at the glass-air interface. This makes the moving fiber type switch attractive for low loss applications.

For all the applications mentioned it is desirable to switch a single mode optical fiber because it has less optical power lost per unit length when compared to a multi-mode fiber [2-4]. This task, however, is more challenging because the core of a single mode fiber is smaller (9 μm in diameter) and this makes the alignment of the fibers within the switch extremely critical. Low loss switching (less than 1dB optical power loss) requires alignment on the order of tenths of microns. The ability to properly align the fibers is the most critical issue affecting optical performance.

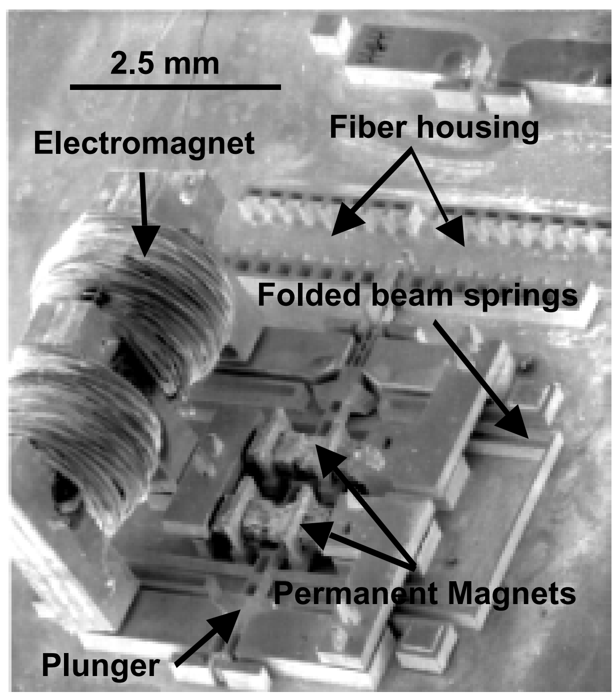

Fig. 1: SEM of the bi-directional linear actuator. The length of the permanent magnets is 1.5 mm.

Moving fiber switches have been fabricated using several techniques. Since the throw requirement is a little over one fiber diameter (~125 μm) the switches which have been implemented generally use thermal and magnetic actuators. Surface micromachining techniques

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have been used to successfully fabricate an optical fiber switch and latching was obtained by using two actuators [5]. As is inherent in thermal actuators the power dissipated is relatively large (in the order of several hundred milliwatts). This can be troublesome when a large number of switches are being employed. In contrast, magnetic switches have been used to produce excellent low power switches [6]. Additionally, the availability of permanent magnet materials provides a mechanism for latching the displacement and eliminating the standby power.

The LIGA microfabrication process [7,8] produces parts which have not only precision tolerances but extremely low run-out as well. This means parts made using the technology have virtually perfect vertical sidewalls. Typical runout for LIGA parts is less than 0.1 µm per 100 µm of height [9], which makes it attractive for fabricating alignment fixtures for the optical fiber switch. LIGA can be used to make durable metal parts as well as soft magnetic materials [10], which are needed for magnetic latching.

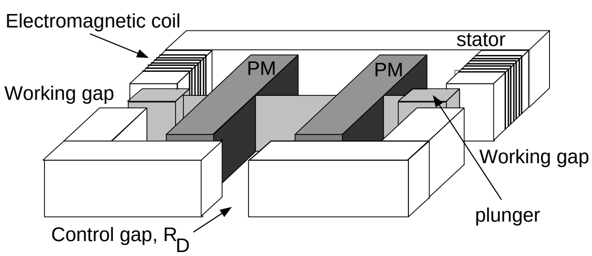

Fig. 2: Concept drawing of the bi-directional magnetic actuator. All material in the core and the plunger are high permeability.

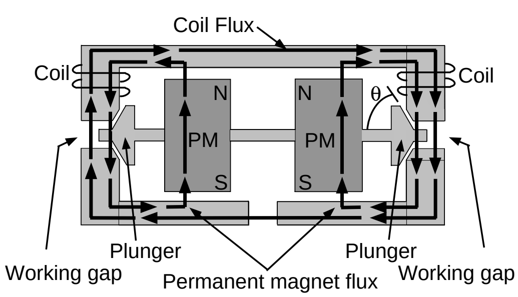

Fig. 3: Flux paths of the magnetic actuator showing the various important components.

The optical performance of all the moving fiber switches is based almost entirely on the fiber alignment. This alignment is done almost exclusively through the use of some kind of V-groove technique. The precision of the V-groove therefore determines the quality of the switch. Earlier models of the LIGA optical fiber switch produced excellent optical performance [11] (0.5 dB insertion loss in air) because the technology produces excellent alignment flats for the fibers. This performance was achieved even without the use of matching fluids. Avoiding the use of matching fluid is attractive because fewer packaging and reliability issues are introduced. However, when matching fluid was used, the insertion loss reduced to on. 0.1-0.2 dB.

A limitation of the earlier versions of LIGA optical fiber switches lay in the inability to latch. They required two coils and continuous power to hold the fiber aligned with an output fiber. A new switch has been designed which, in addition to the excellent performance, can now latch in the off state with the help of permanent magnets (Fig. 1). The design, fabrication, and testing of this device are described in the following sections.

II. LINEAR ACTUATOR DESIGN

The design of the bi-directional actuator is illustrated by the conceptual drawing in Fig. 2. The actuator uses a varying total reluctance provided by the high permeability plungers to produce a force. The device switches when current is driven into the coil of the device. The coil current produces magnetic flux that interacts with the constant flux produced by the pair of permanent magnets (Fig. 3). The flux from each permanent magnet feeds one side of the total loop while the coil directs flux through the high μ_r perimeter. To operate the switch the coil is energized. The coil flux will increase the total flux in the working gap on one side and reduce the total flux in the working gap of the other side. When sufficient current is used the flux in one working gap will be nearly zero and the other working gap will have a flux density nearly equal to the saturation flux density of the core. This causes the actuator to switch to the side with the largest flux density in the working gap. This arrangement also avoids demagnetization of the permanent magnets because the coil flux is never driven through the permanent magnets.

The latching action is produced by engineering the force profile through the use of a shaped plunger (Fig. 3). When the switch is closed and the coil is de-energized the shaped plungers and the flux provided by the permanent magnets provide a closure force that keeps the actuator in place even when powered down.

The theoretical force profile of the actuator as a function of position along travel path is shown in Fig. 4. The theoretical results were determined using a reluctance model which determines the forces by an energy method [12]. The force produced by the actuator is determined by its position and the applied current in the coil. The calculations assume 250 µm height for the flux path, 200 µm height for the permanent magnet, 10 µm plunger gaps, 60° angle for the plunger wedge, and a 2000 turn coil. The latching forces are evident from the force profile for zero applied current at the two ends of travel position. When the actuator is at one end of the device's travel it will hold there without applied current and with a set amount of latching force. The actuator is switched by applying current to the coil. The theory indicates it should be able to generate forces in the 100 mN range. An in depth discussion of the theory is presented in [12] and will not be presented here due to space limitations.

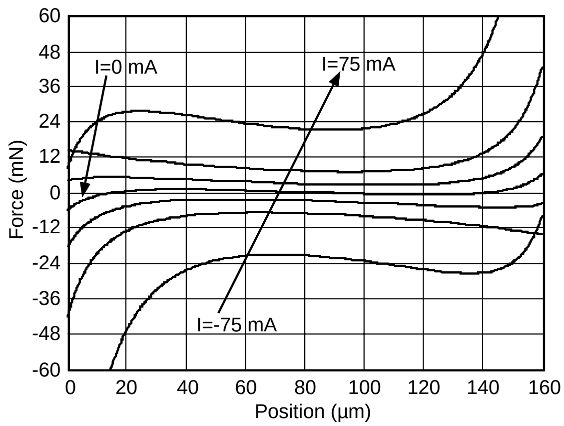

Fig. 4: Theoretical force profiles for the actuator with a 60 degree wedge. The zero current curve shows the latching force when the coils are de-energized.

III. CONSTRUCTION

The University of Wisconsin version of the LIGA process [8], a deep x-ray lithography process, was utilized to fabricate the device. The actuator components were made from electroplated permalloy (NiFe 78/22). The permalloy has a high permeability (μ_r=2000) and is an excellent mechanical material. The parts were made separately and assembled to construct the final device. Fixed parts were fabricated which remain attached to the substrate. Free parts for assembly used the same process for fabrication, however the plating base was etched as a final step to release the pieces. A precision slot and peg technique was used to put the device together [13].

The completed and assembled device is shown in Fig. 1. The total size of the actuator is roughly 6mm by 6mm. The coils have 2000 turns with L=24 mH. The permanent magnets are fabricated using an electro discharge machining technique [14] which allows the precise cutting of parts from any electrically conductive material. The magnets used were NdFeB rare earth permanent magnets. The magnets ride on the mobile actuator which is suspended off the substrate using folded beam springs. Assembled core pieces shunt the magnetic flux over the spring elements and interface with the permanent magnets.

Attachments allow for the actuator to drive an optical fiber. Figure 5a shows the end of the actuator shaft with the assembled extension which holds the single mode optical fiber. The V-grooved alignment tube aligns the fibers on precision LIGA defined sidewalls and fiber clips hold the two fixed fibers against the alignment flats through a spring force. Figure 5b shows a similar mechanism with fibers in place.

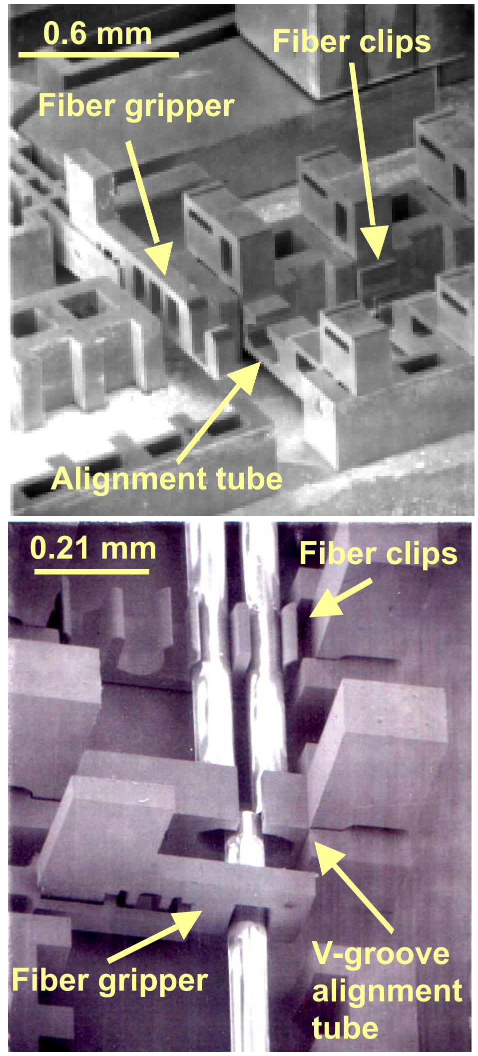

Fig. 5: (a-upper) Alignment tubes and fiber clips without optical fibers; (b-lower) Similar mechanism with optical fibers included.

IV. MEASUREMENTS AND RESULTS

Several actuators were assembled and tested. Two different angled wedge designs were used: 45 and 60 degrees. In addition, spring beam widths of 10 µm and 15 µm were used to test the effect of the spring constant on actuator performance. The design with the thicker springs and 60 degree wedge was found to switch the fastest and this device will be discussed here.

Figure 6 shows the switching speed of the actuator as a function of drive current. There are two operating regimes indicated, the subthreshold region and the normal operating region. The dividing line is defined as the threshold current. Due to the energy stored in the springs, the device can switch from a latched state using less current than if the device is switching from an unlatched state at the center position. The normal operating region is the current range over which the device will always switch, regardless of the starting position. The subthreshold region is the current range over which the device will switch from a latched position. The threshold current, the minimum current for the normal operating region, is 5.88 mA. If the device is switched from a latched position only 3.37 mA is required.

As indicated earlier, the switching occurs when the flux from the coil opposes the flux from the permanent magnet in the working gap that is not favored while it strengthens the flux in the gap that is favored. As the current in the coil is increased, the flux in the gap that is not favored first decreases to zero and then begins to increase again with a reversed polarity. This flux provides an undesired attractive force that can keep the plunger from switching. The shape of the plunger, and the possibility that the flux in the favored working gap can be saturated, can both serve to enhance this effect. The maximum drive current for which the device functions is 8.83 mA. Thus, the operating window is 5.88-8.83 mA, which is sufficiently wide for reliable operation.

The minimum switching time was found to be 2.21 ms when operated at 7.4 mA. The device operates most efficiently at the switching current of 5.88 mA, which lies at the threshold between the normal and subthreshold regions. In this case, the minimum power dissipated is as low as 11 mW. The minimum energy required is as low as 25 J.

Single mode optical fiber insertion losses were determined using a 1550 nm light source. Measured insertion losses were as low as 0.5 dB. When matching fluid is added the insertion loss drops to between 0.1 and 0.2 dB. This loss was measured and determined to be equal in the energized and de-energized states.

V. CONCLUSIONS

An energy-efficient bi-directional electromagnetic actuator capable of >150 m displacement and >10 mN force has been designed and fabricated using a combination of permanent magnets and electromagnets. The components were fabricated primarily by the LIGA process using NiFe. The permanent magnets were micromachined from NdFeB using micro-electro discharge machining. The actuator was applied to an optical fiber switch which physically guides the fiber ends and positions them with 0.1 m accuracy. Switching times were measured to be in the 2 ms range, while optical losses were only 0.5 dB in air and 0.1-0.2 dB in matching fluid. The actuator required only 5.88 mA to switch, which represents an energy of just 25 J. The device requires zero standby power, and consumes energy only while switching.

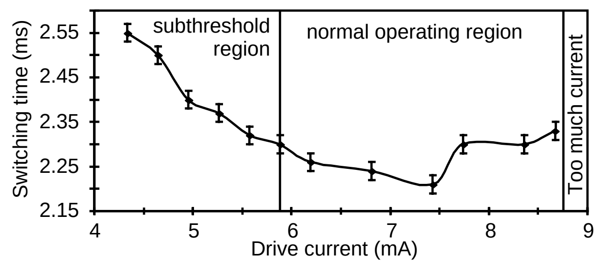

Fig. 6: Measured switching time of actuator.

REFERENCES

[1] Jones-Bey H, "Optical Switches Pursue Crossconnect Markets," *Laser Focus World,* p. 153-62, May 1998.

[2] Neumann EG, *Single Mode Fibers*, Springer, NY, 1988

[3] Allard F, *Fiber Optics Handbook*, McGraw-Hill, New York, 1990.

[4] Hiroshi M, *Handbook of Optical Fibers and Cables*, Dekker, New York, 1996.

[5] Hoffmann M, Kopka P, Groß T, Voges E, "Optical Fiber Switches Based on Full Wafer Silicon Michromachining," *J. Micromechanics. & Microengineering,* vol. 9, p. 151-5, 1999

[6] Tabat N, Guckel H, "Single Flux-Path Bidirectional Linear Actuators," HARMST '97, Madison, WI, June 1997.

[7] Becker EW, Ehrfeld W, Hagmann P, Maner A, Münchmeyer D, "Fabrication of Microstructures with High Aspect Ratios and Great Structural Heights by Synchrotron Radiation Lithography, Galvanoforming, and Plastic Moulding (LIGA Process)," *Microelectronic Engineering*, vol 4, pp. 35-56, 1986.

[8] Guckel H, Mangat P, Emmerich H, Massoud-Ansari S, Klein J, Earles T, "Advances in Photoresist Based Processing Tools For 3-Dimensional Precision and Micro Mechanics," *Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, June 1996.

[9] Siddons DP, Johnson ED, Guckel H, "Precision Machining Using Hard X-rays," Synchrotron Radiation News, 7(2), p. 16-18, 1994.

[10] Christenson TR, Garino TJ, Venturini EL, Berry DM, "Application of Deep X-Ray Lithography Fabricated Rare-Earth Permanent Magnets to Multi-Pole Magnetic Microactuators," *Transducers '99*, June 1999.

[11] Guckel H, Fischer K, Chaudhuri B, Stiers E, McNamara S, "Single Mode Optical Fiber Switch," *HARMST'99*, Tokyo, Japan, June 1999.

[12] Fischer KJ, *A LIGA Fabricated Latching, Bistable Magnetic Micro Actuator For Optical Fiber Switching and Other Applications*, Ph.D. Dissertation, University of Wisconsin-Madison, 2000.

[13] Fischer K, Klein J, Chaudhuri B, Guckel H, "Design and Fabrication of One Millimeter High Structures," *Microsystem Technologies*, Springer-Verlag, 4(4), pp 176-80, July 1998.

[14] Takahata K, Shibaike N, Guckel H, "High-Aspect-Ratio WC-Co Microstructure Produced by the Combination of LIGA and Micro-EDM," *HARMST '99*, Tokyo, June 1999