Magnetically actuated optical phase modulator

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Abstract. A magnetically actuated optical phase modulator is described. The phase of a reflected optical beam is modulated by deflecting a Mylar® membrane, coated with a magnetic iron/nickel film, with the field of an electromagnet. A phase change of π for light of wavelength 0.633 μm was achieved with a driving voltage of only 4 V, much smaller than the voltage required for comparable, electrostatically-actuated devices. The modulator can be scaled to micron dimensions for fabrication in arrays, scaled for even lower drive voltage, and operated at megahertz frequencies.
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1 Introduction

There continues to be interest in low-cost optical modulators for applications in information technology (e.g., optical communications and optical data storage). The most widely used modulators (e.g., LiNbO$_3$ electro-optic type) are expensive. Optical modulators that use reflective membranes that move under electrostatic or magnetostatic forces have potentially lower cost. The electrostatic type has received considerable attention, and experiments with electrostatically driven devices have shown that membrane type modulators can be driven at megahertz frequencies.[1,2] The electrostatic approach requires tens of volts and is not directly compatible with silicon very large scale integration (VLSI), which can supply about 1 V or less. This letter describes optical phase modulators with reflective membranes that are magnetically controlled and can be driven by lower voltages. The modulator can be constructed entirely on a semiconductor chip, scaled to micron dimensions to form arrays, and fabricated with conventional processes.

2 Theory

A schematic for a magnetically actuated optical phase modulator is shown in Fig. 1. The force per unit volume on the reflective magnetic film is

$$\vec{F} = (\vec{M} \cdot \nabla)\vec{B},$$

where $\vec{M}$ is the magnetization in the film and $\vec{B}$ is the applied magnetic inductance due to external sources alone. If the field and its gradient are perpendicular to the magnetic film, a direction we will label $\hat{z}$, the force can be written as

$$\vec{F} = M\frac{\partial B}{\partial z}\hat{z}.$$

For a moderately sized applied field the magnetization can be replaced with its saturated value M_S. If the magnetic film is thin, the field gradient can be taken to be constant along $\hat{z}$ in the film and the pressure on the film can be written
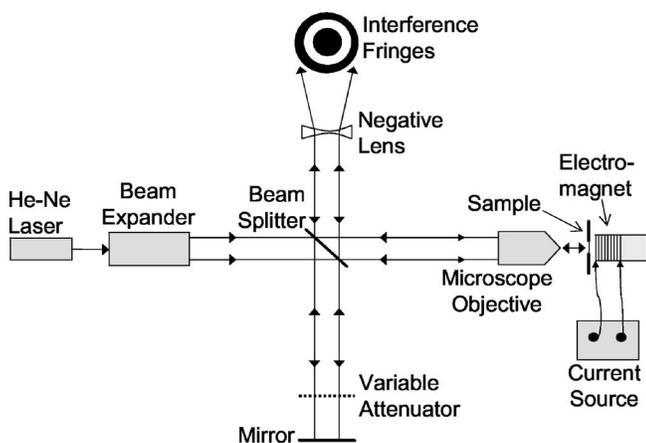
$$P = M_S\frac{\partial B}{\partial z}t$$

where t is the film thickness.

The deflection of a film is proportional to the applied pressure provided the deflection is small (i.e., less than or on the order of the thickness of the membrane). The maximum deflection, at the center of a circular magnetic membrane of radius R clamped at its edges, is
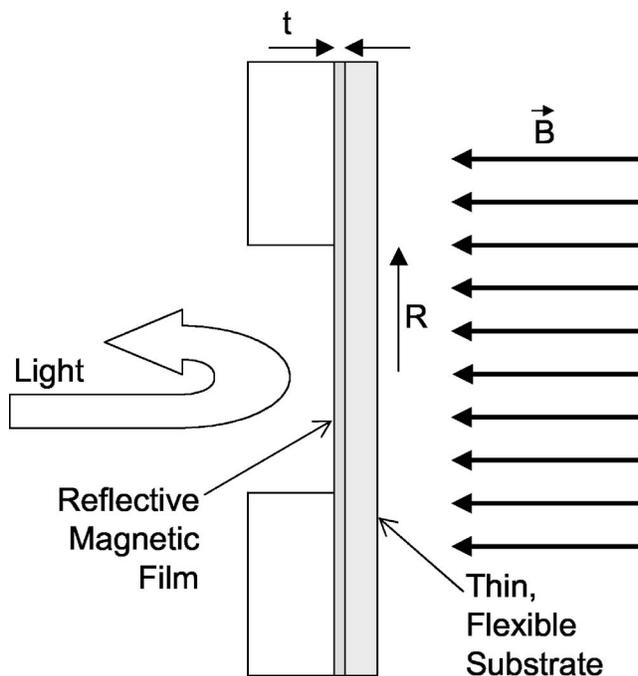
Fig. 1 Cross section of the flexible mirror, including Mylar® substrate and Fe$_{0.55}$Ni$_{0.45}$ reflective magnetic film.

Fig. 2 Experimental setup for measuring the deflection of a flexible mirror in the field of an electromagnet.

$$\Delta h = \frac{P}{64D}R^4 = \frac{M_S \frac{\partial B}{\partial z} t}{64D}R^4 \tag{1}$$

where D is a stiffness constant that depends on the thickness, Young's modulus, and Poisson's ratio for the membrane material.[3] An equivalent D can be found for a combination of magnetic film and underlying flexible support, which makes Eq. (1) approximately correct provided the two materials have approximately the same Poisson's ratio.[4] The deflection is always toward the electromagnet. Note that there is no membrane deflection in a uniform magnetic field.

## 3 Mirror Fabrication and Experimental Setup

For this study, electron beam evaporation with an Fe(55%)/Ni(45%) source was used to deposit a 70-nm-thick, reflective, magnetic film onto a 2.5-μm thick Mylar® substrate. Mylar® (polyethylene terephthalate) was chosen for its flexibility and ability to withstand heating (melting point=254°C) during the evaporation process. The Mylar-Fe/Ni composite film was glued to the surface of an aluminum plate over a hole of radius 4.1 mm.

The setup for measuring mirror deflection is pictured in Fig. 2. A 629-turn, 2-cm-long electromagnet was fabricated by wrapping copper wire around a wood post of diameter 12 mm. The resistance of the coil was 7.9 Ω. Magnetic field strength was measured by replacing the sample with a thin gaussmeter probe. A helium-neon laser with a wavelength of 0.633 μm and a Twyman-Green interferometer were used to measure the deflection of the reflective membrane when current was applied to the electromagnet. Figure 2 also shows how a phase modulator can be converted to an amplitude modulator using interference. The laser beam was tightly focused onto the center of the membrane so that the interferometer measured the maximum deflection.

## 4 Results and Analysis of Experiment

For small separations between the membrane and the electromagnet, a current of 0.5 A and a corresponding drive voltage of just 4 V deflected the membrane by an amount sufficient to change the optical phase of the helium neon
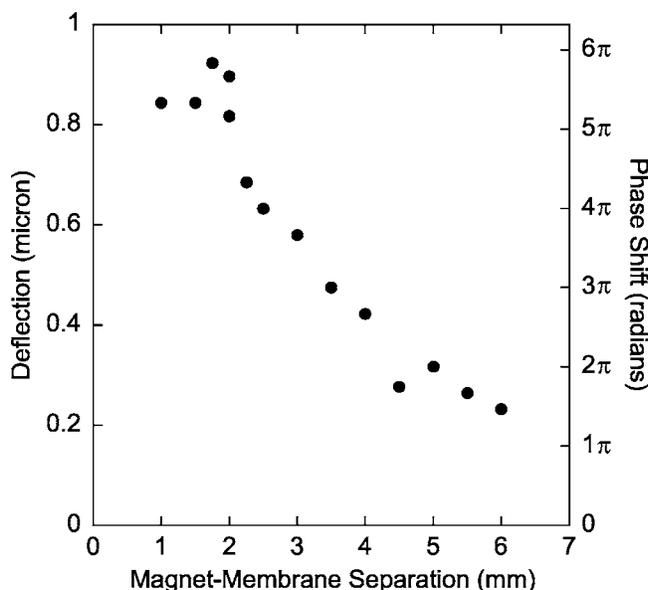
Fig. 3 Measured deflection of the flexible mirror and corresponding phase shift for the reflected optical beam.

beam by π. In order to better understand the operation of the modulator, membrane deflection was measured as the distance from the membrane to the front of the electromagnet (the plane of the first magnetic loop) was varied from 1.0 to 6.0 mm, as shown in Fig. 3. For these measurements, a coil current of 2 A was used to produce magnetic fields and the corresponding drive voltage was about 16 V. The optical phase shift for the reflected helium-neon beam is also shown in Fig. 3.

The magnitude of the magnetic field was measured for distances from the front of the electromagnet that ranged from 1.732 to 7.732 mm. It was not possible to bring the
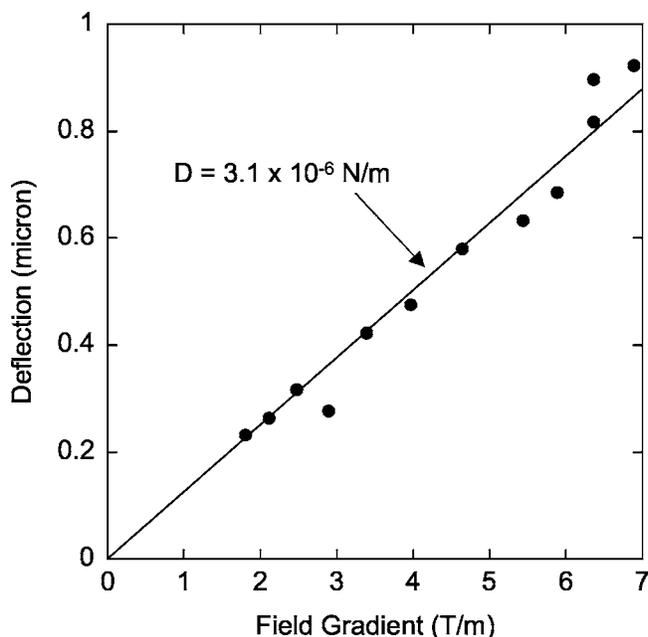
Fig. 4 Membrane deflection versus the magnitude of the gradient of the applied magnetic inductance.

center of the magnetic probe any closer to the electromagnet because of the finite thickness of the probe housing. The experimental values for the magnetic inductance were fit with a function that was the sum of a constant and an exponential. The function was analytically differentiated to produce an expression for the field gradient. Figure 4 shows the measured deflection as a function of the magnitude of the corresponding field gradient. The relation is nearly linear, as predicted by Eq. (1). Using the slope for the data in Fig. 4 and a value of 1.6 A/m for the saturated magnetization,[5] Eq. (1) gives a value for the stiffness D of the film of 3.1×10^{-6} N/m. The relatively large value for D suggests that the drive voltage for the modulator can be further reduced by decreasing the stiffness of the membrane, as discussed in the next section.

5 A Scaled, Optimized Optical Phase Modulator

The results presented in the previous sections include the information needed to predict the performance of an optimized phase modulator, scaled to smaller size for fabrication into arrays. We consider a highly flexible membrane made of Mylar®, with a small reflecting disk of Fe(55%)/Ni(45%) alloy deposited just on the center portion of the polymer. This geometry allows the membrane to be as flexible as possible, although a moderately sized magnetic disk will be required in order to produce sufficient force to deflect the membrane. The proposed device shares similarities with the mechanical aspects of an actuator described by de Bhailís et al.[6] We consider a 1.5-μm-thick polymer film with a radius of 100 μm and with a 2-μm-thick magnetic disk of 3 μm radius. A 15-turn electromagnet of radius 5 μm is positioned 2.5 μm from the center of the membrane. We estimate the current required to produce a π phase shift for a light at a wavelength of 1540 nm to be about 140 mA. The current could be supplied by a drive voltage of 1 V provided the resistance of the electromagnet is no greater than 7 Ω.

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