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Thermally-actuated reflection mode asymmetric Fabry–Perot modulator utilizing a thin transparent elastomeric film

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This letter describes a thermally-actuated reflection mode asymmetric Fabry–Perot modulator that consists of a thin transparent elastomeric film bounded by partially and highly reflecting metallic mirrors. The thickness of the transparent layer determines the intensity of light reflected from the modulator; changes in its thickness modulate the reflectivity. Electrical current flowing through the highly reflecting mirror provides a source of heat for controlling, by thermal expansion, the thickness of the elastomeric film. Modulators with this design show contrast ratios >15 dB and insertion losses <0.3 dB. © *1998 American Institute of Physics.* [S0003-6951(98)02116-0]

Modulators are important components of nearly all optical processing systems. The sensitivity of the optical properties of bulk materials to electric or magnetic fields, or to mechanical strains forms the basis of most conventional modulators.[1] More recently, several varieties of high performance micromechanical modulators—tilting micromirrors,[2] deformable diffraction gratings using silicon microbeams[3] or molded elastomers,[4] mechanically adjustable antireflection microswitches,[5] and tunable Fabry–Perot microcavities[6–8]—have been demonstrated. In this communication we describe micromechanical devices based on thermal control of the interference that occurs from multiple reflections in planar optical cavities that consist of thin transparent elastomeric films bounded by thin partially and highly reflecting metallic mirrors (Fig. 1). The phase that accumulates upon passage through the film determines how light reflected from the rear of the cavity interferes with light reflected from the surface of it. When the wavefronts associated with these reflections are in phase, the reflectivity of the structure is high; when they are out of phase, the reflectivity is low. Resistive heating induced by flowing current through one of the mirrors causes expansion of the transparent film, changes the path length for light passing through it, and modulates the reflectivity of the device.

The depth of modulation is determined by the reflectivity of the mirrors and by the loss in the cavity. It is straightforward to show that when phase shifts induced by the partial reflector are small,[9] the reflectivity of the modulator (R_m) is given by

$$R_m=\frac{(\sqrt{R_1}-\sqrt{(1-A)R_2})^2+4\sqrt{(1-A)R_1R_2}\,\sin^2\phi+A_1[(1-A)R_2(A_1-2)+2\sqrt{(1-A)R_1R_2}(1-2\sin^2\phi)]}{(1-\sqrt{(1-A)R_1R_2})^2+4\sqrt{(1-A)R_1R_2}\,\sin^2\phi},$$

where

$$\phi=\frac{2\pi nt}{\lambda}+\phi_0. \tag{1}$$

The phase, ϕ, due to passage through the cavity is determined by λ, the wavelength of the light, t, the thickness of the transparent layer, and n, its index of refraction; it also depends on ϕ_0, the phase shift due to reflection from the high reflector. The reflectivities of the partially and highly reflecting mirrors are R_1 and R_2, respectively, A_1 is the loss associated with passage through the partial reflector, and A is the loss associated with passage through the transparent layer twice, and reflection from the high reflector once. For values typical of the devices described here ($R_1=65\%$, $A_1=5\%$, $R_2=95\%$, and $A=15\%$), R_m varies between ~ 0.03 and ~ 0.93; the change in thickness (Δt) required to switch from states of maximum to minimum reflectivity is given by

$$\Delta t=\frac{\lambda}{4n}. \tag{2}$$

This change can be achieved through thermal expansion induced by resistive heating in the high reflector. When loss of heat from the device is proportional to the difference in temperature between a heat sink and the device itself, and when the change in phase is due entirely to a change in thickness, then the change in phase induced by passage of current i through the resistive heater/high reflector with resistance R and area a is given by

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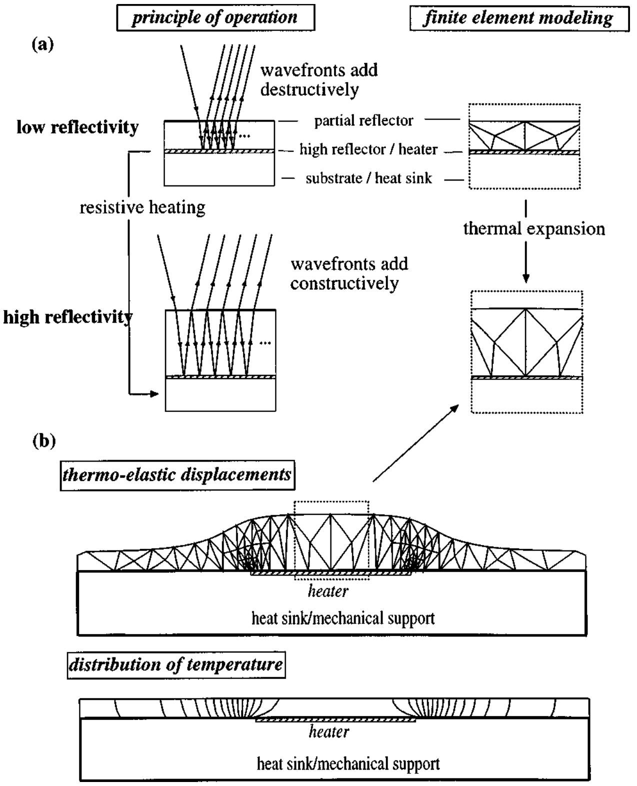

FIG. 1. (a) Schematic illustration of the operation of thermally-actuated reflection mode asymmetric Fabry–Perot optical modulators. A partial reflector on the front surface and a high reflector on the back surface of a thin transparent elastomeric film form a planar optical cavity. Changes in the thickness of the elastomer modulate the phases of multiple reflections through the cavity. The thickness is controlled through thermal expansion induced by resistive heating of the high reflector. (b) Distorted finite element meshes and temperature contours for a slab of material heated on part of its lower surface. Displacements are exaggerated for illustration. The difference in temperature between adjacent contours is constant; for this particular system, the temperatures near the outer contours are ~0.1 times the peak temperature. The portions of the lower surface not connected to the heater undergo heat loss to a sink held at constant temperature; the front surface is thermally insulated. Equations presented in the main text assume that the thermal expansion is uniform and does not misalign the optical cavity; experimental data validate these assumptions.

$$\Delta\varphi=\frac{2\pi}{\lambda}\,\Delta T\alpha_N nt=\frac{2\pi}{\lambda}\,\Delta T\left(\frac{1+\nu}{1-\nu}\right)\alpha_L nt$$

$$\propto\frac{2\pi}{\lambda}\,\frac{i^2R}{a}\left(\frac{1+\nu}{1-\nu}\right)\frac{\alpha_L nt}{C_p\rho ta}\propto\left(\frac{1+\nu}{1-\nu}\right)\frac{\alpha_L n}{C_p\rho}\equiv\mathfrak{J},\qquad(3)$$

where λ is the wavelength of light evaluated in vacuum and ΔT is the change in temperature. The index of refraction of the thin transparent layer is n, and t, ν, ρ, and C_p are its thickness, Poisson ratio, density, and heat capacity, respectively. The bulk linear coefficient of thermal expansion (CTE) is α_L, and α_N is the out-of-plane CTE for a thin film tightly bound to a rigid support.[10] $\mathfrak{J}$ is a figure of merit that characterizes the film; it determines, for a given λ, a, t, and rate of loss of heat from the film, how much electrical power is required to change the phase. $\mathfrak{J}$ is large when ν, n, and α_L are large and when ρ and C_p are small. Elastomeric materials have Poisson ratios near 0.5; they generally also have large α_L. The products of their densities and heat capacities are relatively small for solid transparent materials. Furthermore, although the indices of refraction of most transparent elastomers are near 1.5, many of them can be easily doped with dyes to increase this value. These characteristics, along with their ability to be deposited in thin uniform films by spin casting, make elastomers well suited for the transparent layer in the modulators described here.

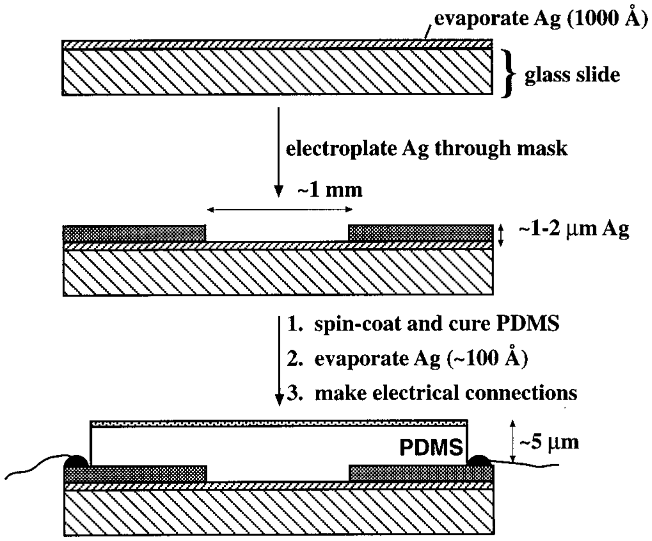

FIG. 2. Steps for fabricating thermally-actuated reflection mode asymmetric Fabry–Perot optical modulators. Electrodeposition of Ag through a mesh yields lines of Ag with thicknesses ~1–2 μm in all regions except those protected by the mesh. Spin coating and curing polydimethylsiloxane (PDMS) onto the patterned slides yields a thin transparent elastomeric film (~5.5 μm). Evaporation of Ag (~100 Å) onto the PDMS completes the planar optical cavity; no additional alignment is required. (The thickness of this film was optimized empirically to give the largest contrast.) Current applied to the Ag lines causes significant heating only in the regions with ~1000 Å thickness (i.e., the active areas of the device).

Figure 2 shows steps for fabricating devices like those described above. Electron-beam evaporation and simple

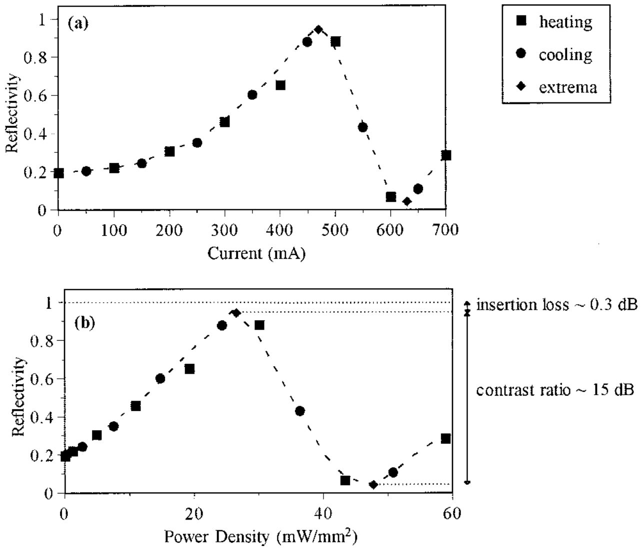

FIG. 3. Performance of a thermally-actuated reflection mode asymmetric Fabry–Perot optical modulator that incorporates a thin transparent elastomeric film. (a) Reflectivity of the device measured at 633 nm with a HeNe laser as a function of current passing through the resistive heater/high reflector. After data were collected during heating and cooling, the current was adjusted to locate the extrema in the reflectivity. (b) Intensity as a function of power density applied to the heater. The data indicate an insertion loss of ~0.3 dB, and a contrast ratio of ~15 dB. (In both frames, the dashed lines are guides for the eye.)

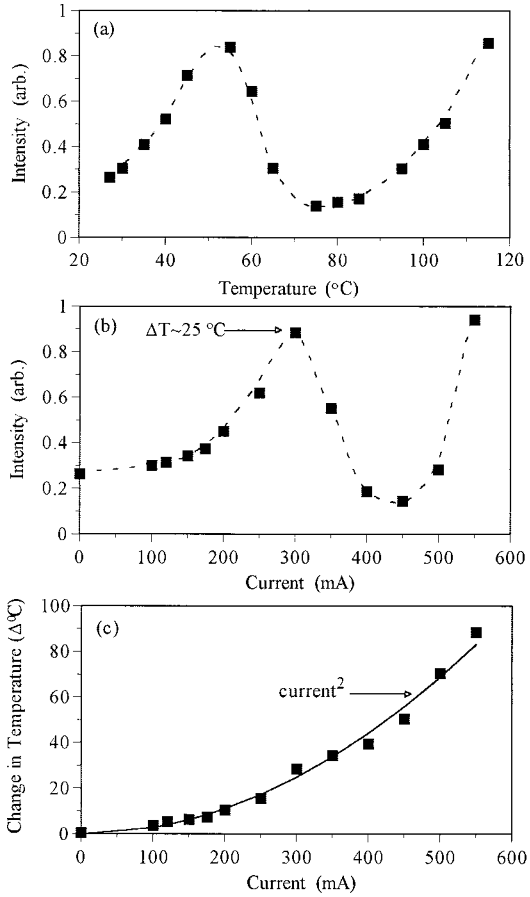

FIG. 4. (a) Intensity of 633 nm light from a HeNe laser reflected from a thermally-actuated reflection mode asymmetric Fabry–Perot optical modulator as a function of temperature of the device, and (b) as a function of current passing through the resistive heater/high reflector. (The dashed lines are guides for the eye.) (c) Change in temperature as a function of current passing through the heater; these data were derived from (a) and (b). The solid line in (c) shows that the increase in temperature is proportional to the square of the current. (The device used to collect the data shown here was not optimized to achieve large modulation depths.)

masking techniques define the high reflector/heating element (~1000 Å, Ag) and the wires (~1 μm, Ag) that connect to it. Wires with relatively large cross sections ensure that resistive heating is only significant at the position of the high reflector (i.e., the active area of the device). A film of silver evaporated on a thin film of transparent polydimethylsiloxane (PDMS) elastomer that is spin cast and cured on the high reflector completes the optical cavity; electrical connection to the wires completes the modulator.

Measurements indicate that devices fabricated in this manner can modulate the intensity of monochromatic light from a laser or from a light bulb. For 633 nm laser light, contrast ratios >15 dB and insertion losses <0.3 dB are possible with $\sim 20\ \mathrm{mW/mm^2}$ of heating intensity (Fig. 3). Changes in temperature caused by resistive heating that were determined by measuring the reflectivity as a function of temperature and current are shown in Fig. 4. These data show that (i) the change in temperature is proportional to the square of the current and (ii) a modulator with ~5.5 μm of PDMS requires a change in temperature of ~30 °C to switch. The first result is consistent with flow of heat out of the device at a rate linearly proportional to the change in temperature, and flow of heat into the device at a rate proportional to the resistive heating. The second result, with Eq. (3), implies that the thickness of the elastomeric film increases by ~150 nm[11] when the device is switched. This value is reasonably close to ~110 nm,[11] the change in thickness expected based on Eq. (2). The agreement of these two displacements indicates that the phase is modulated primarily by changes in thickness; the ~25% discrepancy is possibly due to differences in the bulk and thin film properties of PDMS or to the dependence of the index of refraction on the temperature and density of the PDMS.[12]

The optical modulators described in this letter perform well and are easy to build; their operation can be accounted for with a simple model. These devices represent examples of microelectromechanical systems (MEMS) in which thermal actuation[13,14] and elastomeric materials both play critical roles. Thermal expansion provides a convenient means to achieve the forces that are required to change the thickness of the elastomer. The enhancement of the out-of-plane CTE for thin elastomeric films tightly bound to rigid substrates and their generally large bulk linear CTEs enable optically significant out-of-plane displacements for small changes in temperature. Although the good performance and simplicity of these modulators are attractive, disadvantages of elastomers and thermal actuation include (i) sensitivity to fluctuations in temperature, (ii) potentially high consumption of power, and (iii) switching times limited by the rate of thermal diffusion and the efficiency of a sink to remove heat (e.g., unoptimized devices, with active areas of $\sim 1\ \mathrm{mm}^2$, have switching times ~1 s). In spite of these drawbacks, we believe that for many applications, elastomers and thermal expansion will provide attractive alternatives to materials and actuators conventionally used in MEMS.

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[11] Bulk polydimethylsiloxane (PDMS) has $\alpha_L = 3\times10^{-4}$ μm/μm/°C, $\nu \sim 0.5$, and $n = 1.43$. Dow Corning Technical Data Sheet.

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