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DESIGN OF ELECTROMECHANICALLY DRIVEN TRANSMISSION LIGHT VALVE ARRAYS

JIANG L.[1*], VANGARI M.[1], FELDMAN M.[2]
[1]Department of Electrical Engineering, Tuskegee University, Tuskegee, USA
[2]Department of Electrical & Computer Engineering, Louisiana State University, Baton Rouge, USA
*Corresponding Author: ljiang@mytu.tuskegee.edu

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Abstract- A non-volatile mechanical memory is described as a memory which is written electro-statically and read optically. Information is stored by compressed beams, driven by MEMS technology into one of two stable states. Each bit corresponds to a single pixel in an optical image that can be manipulated in real time on a pixel by pixel basis. The optics at each pixel leave space for controls and connecting wires, almost with no space lost between pixels. The resulting high transmission and low power consumption of the electrostatic drive are critical in some applications, such as the near infrared spectrometer to be carried on the James Webb Space Telescope.

Key words – light valve arrays, microshutter, bi-stable beams, mechanical memory, and comb drive

Introduction

Under sufficient axial compression a long, thin, and wide beam snaps to either one side or the other. This forms the basis of a mechanical non-volatile memory, since the beam will stay in that state until a sufficient force is applied to snap it to the other side. Data can be written into an array of such beams, using word and bit lines corresponding to those in a conventional memory. The center of each beam can act as an optical shutter, blocking or transmitting light depending on its state. With suitable optics, small motions of the beams in an array can control the pixels in an extended image. This may offer particular advantages to the Near Infrared Spectrometer under development by NASA for the James Webb Space Telescope.

Principles of Operation-Mechanical

The use of micro-electromechanical systems (MEMS) technology to deflect a cantilever beam is very well known. Typically a voltage is applied to an inter-digitated capacitor or “comb drive” to generate a force that pushes on the beam (Fig. **1(a)**), producing a proportional deflection. The force, F, and displacement, D are given by

$$F = \frac{CV^2}{2d} \qquad (1)$$

$$D = \frac{4F}{Ew}\left(\frac{L}{t}\right)^3 \qquad 2)$$

where V is the voltage, C is the capacitance when the plates overlap a distance d, D is the displacement, E is Young’s Modulus, and L , w and t are the length, width and thickness of the beam.

Alternatively, a transverse force may be applied to the center of a beam that is fixed at both ends and compressed (Fig. **1(b)**) [1, 2]. There is a critical value of the compression, called the Euler limit, at which the transverse force needed to deflect the beam approaches zero. The compressive force at the Euler limit, F_{LE}, is given by

$$F_{LE} = \frac{4\pi^2 Ewt^3}{12L^2} \qquad (3)$$

The corresponding change in length at the Euler limit, δ_{LE}, is given by

$$\delta_{LE} = \frac{4L\pi^2 t^2}{12L^2} \qquad (4)$$

Under compressive loading exceeding the Euler limit, a beam fixed at both ends becomes unstable, and snaps to one side or the other. A force applied transversely to the beam can snap the beam between the states, and a second force can snap it back. A beam in this condition is a nonlinear mechanical system, and a full analysis is beyond the scope of this article. However an approximation valid for small displacements is presented.

Beyond the Euler limit the total length of the beam along its curved path is substantially unchanged even as the ends of the beam are brought closer together. The difference between the total path length and the separation between the ends may be approximated by treating the curved portions of the path as segments of circles [3]. The additional change in length past the Euler limit corresponds to a displacement, h, given approximately by

$$\frac{\delta L}{L} = \frac{8h^2}{3L^2} = \frac{\delta F_L}{Ewt} \qquad (5)$$

The force, δF_L in equation (5) is the additional longitudinal force that would be required to compress the beam by δL if it were constrained to its medial position. The transverse force, F_T, required to do this may be conservatively estimated by equating moments about the center of the beam. Dividing the beam into two sections of length L/2, and substituting for δF_L from equation (5),

$$\begin{aligned} F_T &= \frac{4\delta F_L h}{L} \\ &= \frac{32Ewth^3}{3L^3} \end{aligned} \qquad (6)$$

Note that the snap-through distance is 2h.

The response of a bi-stable beam is very different from that of a cantilever beam (Fig. **2**). The displacement of a cantilever beam is proportional to the applied force, while the snap-through distance of a bi-stable beam is proportional to the cube root of the applied force. In addition the displacement of a cantilever beam has a much stronger dependence upon its thickness. The beam can be fabricated by plating nickel in a LIGA like structure [4, 5]. The slight compression needed can be obtained by varying the deposition rate to control the stress.

An array of compressed beams may be used as a nonvolatile memory, since no voltage is required to maintain the beams once they have been set in their states. To set bits to "1" the voltage V is applied to the set electrodes and 0 voltage is applied to the reset electrodes (Fig. 3). Similarly, bits are set to "0" by applying the voltage V to the reset electrodes and 0 voltages to the set electrodes. The word line selects the bits to be set. For unselected bits the word line is at V/2, and equal forces of $CV^2/8d$ are applied to the beams in opposite directions. For selected bits the word line is at 0, and set or reset forces of $CV^2/2d$ are applied in the set or reset directions, respectively, while no forces are applied in the opposite direction. Alternatively, an even greater margin in selecting bits may be obtained with the word line at –V/2. In this case a force of $9CV^2/8d$ is opposed by a force of $CV^2/8d$, resulting in twice the net selecting force. The drive voltages are expected to be in the range of 50-100 volt [6]. The response time of switching is on the scale of a millisecond.

Principles of Operation-Optical

There are two classes of applications in which the mechanical array may interact with an optical system. In the first class, each cell in the mechanical array corresponds to a single pixel of an optical image (Fig. **4**). The light enters the cell through a primary lens, is brought to a focus, and then exits through a confocal secondary lens. The mechanical beam drives a shutter which only needs to move a distance equal to the diameter of the waist to block the beam. Although the output beam is inverted, this is irrelevant for a single pixel. Both lenses have the same numerical aperture; however the secondary lens may have a slightly shorter focal length to minimize crosstalk between pixels. The microlens arrays may be fabricated by resist melting method [7], microfluidic method [8, 9] or gray scale lithography [10] using PVA, PMMA or other photoresists.

An array of pixels (Fig. **5**) may use a field lens to ensure that the chief rays in each cell are parallel to the optic axis. The incident light will then be focused at the center of each cell. If the light has a width w (which is different from the mechanical beam width), in this case equal to the width of the cell, the width w' of the focused spot is approximately given by

$$ww' = \lambda f \qquad (7)$$

Where λ is the wavelength of the light and f is the focal length of the primary lens. Since the light is focused to a small fraction of the pixel area, the remaining area is available for the mechanical drive, the electronics, and the wiring associated with the pixel. Consequently this array may be used in transmission, with little blocking of the light. This is an important advantage compared to conventional optical arrays which must be used in reflection, with their controls placed behind the optics.

This class of application may be used to read the state of the mechanical memory, or it may be used to create an image, or to selectively block parts of an image. In the other class of applications multiple pixels are controlled by a single cell (Fig. **6**). The imaging lens brings each pixel to a waist at the cell's primary lens. The width of the pixels is determined by the Numerical Aperture (NA) of the imaging lens,

$$w = \lambda/2NA \qquad (8)$$

A field lens is again used to make the chief rays in each pixel parallel to the optic axis, and bring the chief rays of all the pixels to the center of the cell. Equations (7) and (8) may be combined to find the width of the light focused by the primary lens,

$$w' = 2NAf \qquad (9)$$

However, equation (8) only holds if the depth of focus, DOF of the primary lens is small compared to its focal length, f, so that

$$8NA^2 f << \lambda \qquad (10)$$

If equation (10) is not satisfied then the focus formed by the cell's primary lens is only slightly smaller than the focus formed by the imaging lens. An important application of this class of application is the James Webb Space Telescope, which is described in the next section.

James Webb Space Telescope

The James Webb Space Telescope (JWST) [11, 12] was designed by the US NASA Goddard Space Flight Center [13-15] to simultaneously capture the spectrographs of many hundreds of stars and galaxies within its field of view using a Near-Infrared Spectrometer. It is necessary to block the images of the brighter stars and galaxies, so as not to compromise the spectra of the dimmer ones. This is accomplished with a microshutter array that transmits light from selected objects in space but blocks light from other objects, increasing the instrument efficiency by a factor of more than 100. The microshutter array described here is significantly different from the array designed for the JWST:

1) It is totally electrostatic. The Goddard design uses both electrostatic and magnetic effects.
2) It has no large mechanical motions. The Goddard design must traverse a magnet over the entire width of the array.
3) It utilizes robust metallic leaf springs which are deflected through small angles. The Goddard design deflects silicon nitride shutters that are held by a single narrow 0.5 micron thick hinge that is bent by more than 90 degrees.
4) It places control wiring in unused space adjacent to the focal spots. The Goddard design places this wiring between pixels, reducing the open area and necessitating the use of shields to block scattered light.
5) It has virtually zero power consumption, with voltages (but near zero current) required only when changing the state of the array. The Goddard design must maintain voltages during operation, and must consume power to translate the magnet used to change the state of the array.
6) It is mechanically very rugged. The Goddard design uses very thin components, and must translate a permanent magnet over a distance of many mm.
7) It uses tried and true components. Electrostatically driven springs date from the beginnings of MEMS technology, and fly's eye lens arrays arranged as telescopes are also very well known. The Goddard design, while novel and ingenious lacks a long history of proven reliability.
8) It uses refractive optics. Consequently exotic materials such as CdTe (Irtran 6) or diamond will be needed to transmit the entire 0.6 μm to 28 μm wavelength range of the JWST.
9) The JWST cell size is 100 x 200 μm. To ensure blocking bright images, especially at the longer wavelengths, several pixels will need to be closed. The shutter travel in this design will also need to be increased.

Conclusions

A non-volatile mechanical memory is described which is written electro-statically and read optically. Each bit in the memory can control one or more pixels in an optical image. The near zero power consumption and the near zero light loss in transmission are unique properties, which may offer particular advantages to the Near Infrared Spectrometer under development by NASA for the James Webb Space Telescope.

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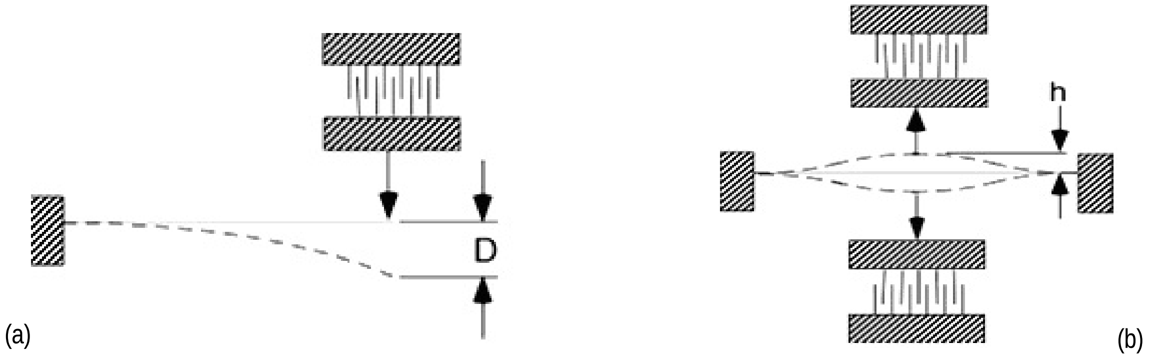

Fig. 1- (a) Deflection by a MEMS comb of a cantilever beam; (b) Deflection by MEMS combs of a beam compressed so that it has two stable states. The top comb pushes the beam into the down state, and the bottom comb pushes it into the up state.

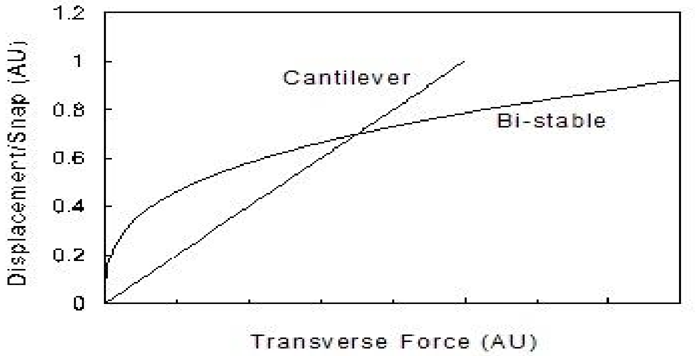

Fig. 2- Deflection curves, for a cantilever beam and a bi-stable beam. For small displacements or snap through distances the bi-stable beam requires less force, while for large displacements the cantilever beam requires less force.

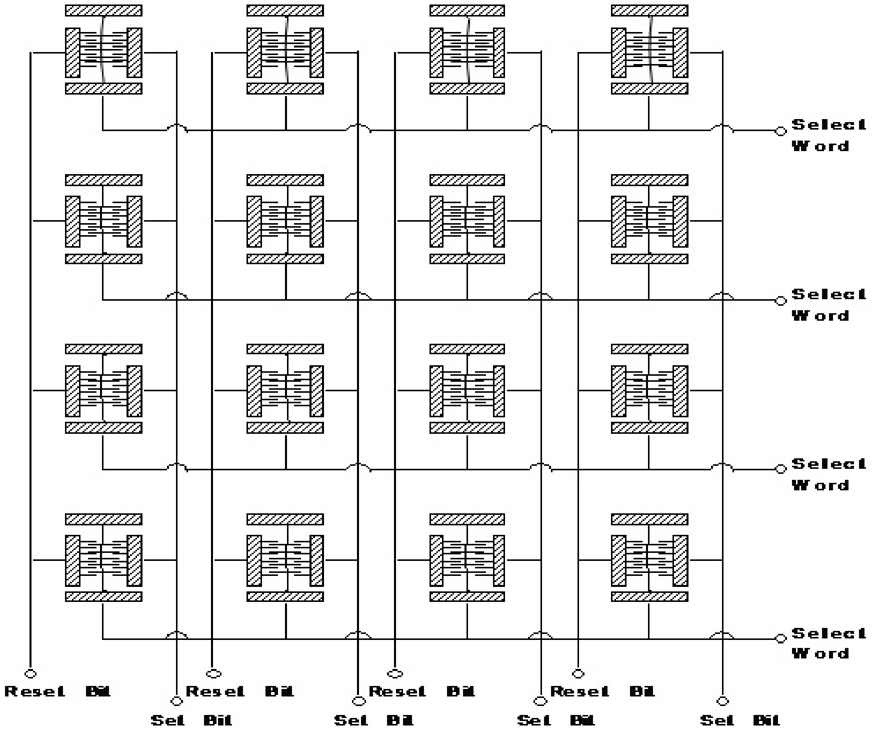

Fig. 3- Word lines and bit lines for a two dimensional array of cells of bi-stable beams capable of driving optical shutters. A more compact arrangement has been substituted for the two combs in Fig. 1(b).

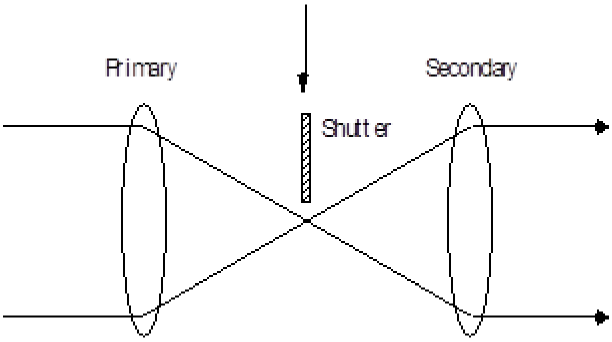

Fig. 4- A one to one telescope in a single cell. The output contains all the light in the original beam, but it is gated by a small motion of the shutter.

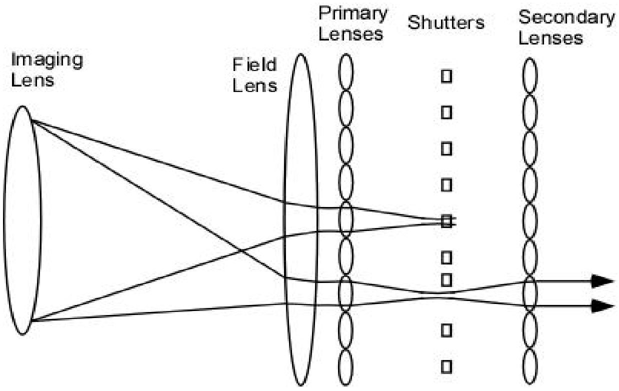

Fig. 5- An array of cells. The field lens centers the light in each cell. Each cell in the array has its own moveable shutter which gates the light passing through that cell. For clarity, only one cell is shown open and one cell is shown closed. If all the cells are open, all of the input light is transmitted.

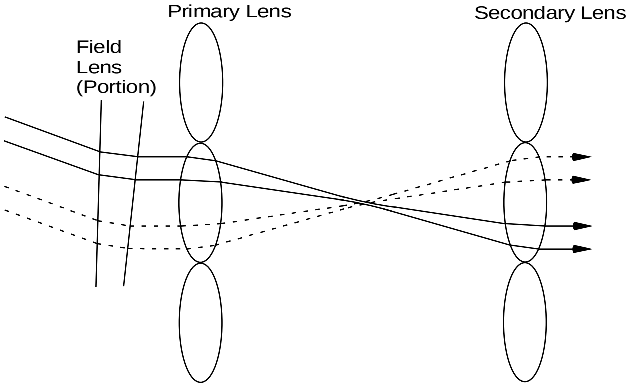

Fig. 6- Multiple pixels going through the same cell. For clarity the imaging lens is not shown. The field lens centers all the light in the cell, but the waists of the individual pixels are larger than those of a single pixel filling the cell.