Deformable mirror device uses in frequency excision and optical switching

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A spatial light modulator is described which consists of a row of 1200 electrostatically deflectable mirror elements. This deformable mirror device is included in an acoustooptic spectrum analyzer and, as such, allows the removal of interfering signals from 333 frequency bands. Radiometric scans demonstrate the contrast and resolution possible with the device. Based on these results, the suitability of the device to frequency excisors and optical switches is considered.

I. Introduction

Broadband microwave receivers used for surveillance and signal interpretation often process signals with a dynamic range exceeding that of the receiver. If large interfering signals can be filtered out, the full dynamic range of the signals will be available for analysis. The deformable mirror device (DMD), a spatial light modulator (SLM), can be included in an acoustooptic spectrum analyzer to remove undesired spectral components as these arise. This correspondence first describes structure and operation of a 1200 modulating element/row DMD. Then a Bragg cell channelizer is demonstrated which uses the DMD to notch out selected frequencies. In light of its ability to attenuate numerous parallel optical channels, some observations on the suitability of the DMD to frequency excisors, optical interconnection networks, and optical computing are given.

The deformable mirror device is a spatial light modulator that uses an array of movable microscopic mirrors to phase retard or redirect incident light. Individual mirror deflections may be induced either electrically[1] or optically.[2] Because the DMD fabrication process[3] is consistent with standard semiconductor processing techniques, the DMD can be integrated with on-chip addressing circuitry.[4] The employment of deformable mirror (although not necessarily DMD) phase modulating characteristics has been proposed for matched filter correlators[5] and adaptive phase correcting telescopes,[6] while employment of amplitude modulation, due to beam redirection, has been proposed for xerographic printers,[7] reconfigurable optical interconnection networks,[8,9] and projection displays.[10] Frequency channelizers and excisors would use the latter property to remove unwanted spectral components.

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II. Device Description

The DMD discussed here is a 1200-element SLM.[7] Shown in Fig. 1 is the structure of two adjacent mirror elements. Figure 1(a) shows that the electrically grounded mirror elements are separated from the polysilicon drive electrodes by an air gap. The electrostatic attraction between the electrode and cantilever beam deflects the beam from its rest position. With constant voltage applied to the electrode the beam deflects to a level where the electrostatic force of attraction on the beam balances with the restoring force of the beam hinge. An overly large voltage will, however, cause a dynamic instability which overcomes the restoring spring force and leads to spontaneous collapse of the beam into the well.[11]

The device in its current configuration includes an oxide barrier over the electrodes which protects the polysilicon from the plasma reaction process that forms the air gap. At present, due to material incompatibilities, we are unable to remove the oxide underneath the beam. This leads to an interesting situation. We have observed that the deflection of a beam driven at a constant voltage diminishes to nearly level after a few seconds. The field strengths in the gap approach 10^5 V/cm. At these levels air ionizes, and we believe that the ions collect on the electrodes, thus screening the field. We found that if the mirror elements are driven by a square wave with a frequency of 0.1–10 kHz, the beams do not relax. At the same time the

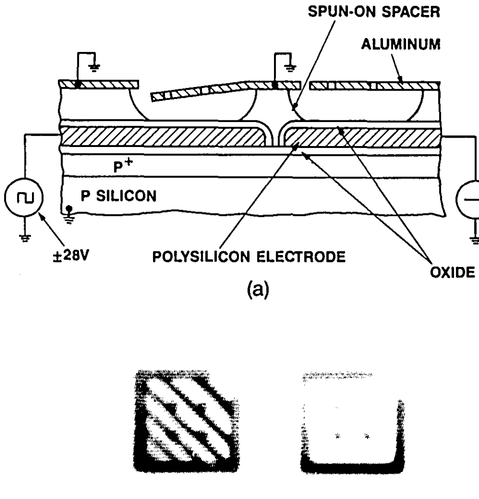


Fig. 1. (a) Side and (b) top view of DMD across two mirror elements. The top view is shown in an interferometer with a ±28-V square wave applied to the element on the left.

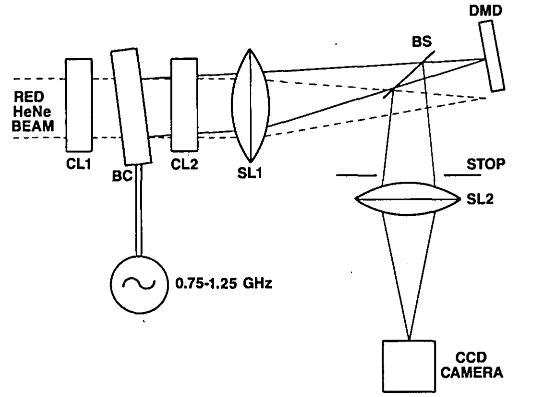


Fig. 2. Channelizer breadboard (top view). The diffracted light (solid ray trace) is focused on the DMD and reimaged on the CCD camera. The undiffracted light (dashed line ray trace) is removed from the optical train after passing through the Bragg cell.

polarity reversal and charge equilibration in the electrode are so fast that the beams essentially maintain a fixed deflection.

Figure 1(b) shows two adjacent beams on the top surface of the DMD under an interferometric microscope. Note the four holes in each beam. The holes are required in the device to avoid complete removal of the supporting spacer material during a plasma processing step. Future devices[3,4] which incorporate etch stops will not require these holes. Furthermore, the mirror elements can then be packed closer together if desired.

The mirror elements shown in Fig. 1(b) are ~13 μM × 13 μM. The device has in all 1200 of these mirror elements in a row spaced on 25.4-μm (1-mil) centers. The pixel on the left is driven with a ±28-V 1-kHz square wave, and the pixel on the right has no voltage applied. The left pixel is deflected 5.5 fringes (under a 0.53-μm green light source) which translates to an angular deflection of 4.5°. The adjacent flap is flat and coplanar with the supporting undeflectable surface.

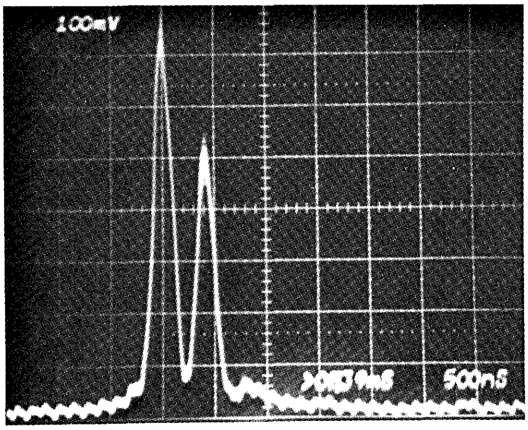
III. Antijamming Channelizer Demonstration

The device, as described, was included in the power spectrum analyzer shown in Fig. 2. A circular collimated beam (from a 6328-Å He–Ne laser) is brought into the cylindrical lens *CL*1, focused to a horizontal line in the center of the Bragg cell, and reshaped into a collimated circular spot by *CL*2. The resulting beam is actually clipped by a small amount at the edges in an effort to use the entire Bragg cell interaction length. The diffracted beam is then brought to a sharp focus on the DMD surface by spherical lens *SL*1. The on-axis beam is baffled at the DMD plane. The diffracted light is brought to a focus on a DMD mirror element corresponding to the drive frequency of the Bragg cell. The DMD and the optics train following the DMD are positioned to intercept light reflected from deflected elements and block light reflected from undeflected elements and the support surface. The light intercepted by *SL*2 is imaged on a 764 × 244 imager of a CCD camera.

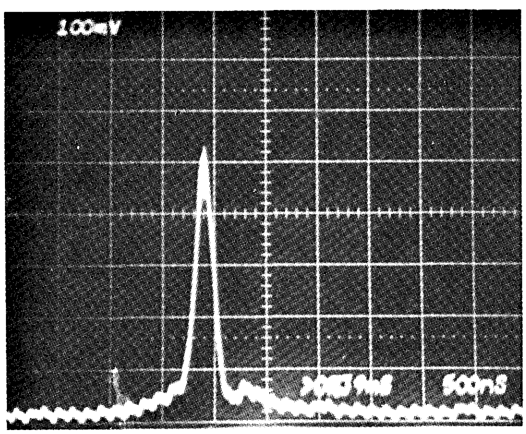
The Bragg cell used is a Crystal Technology model 41000. This lithium niobate modulator has a center of frequency of 1 GHz, a 500-MHz bandwidth, and a time bandwidth of 1000. The acoustic velocity is 6570 M/s, and the Bragg angle is 5.5°/GHz. The focal length of lens *SL*1 has been chosen as 175 mm so that the frequency sweep spans 333 mirror elements.

A 764-pixel row of the CCD consisting of 11-μM detectors intercepts the frequency sweep. The camera pixels are 27 μM in the direction transverse to the sweep. Lens *SL*2 is positioned for a 2.6× magnification of the DMD object plane. In this configuration, around 125 mirror elements can be displayed on a TV monitor at a time. The spectrum analyzer signals can be examined in closer detail on an oscilloscope.

Figure 3 gives representative scans proportional to the signal power spectrum with two adjacent mirror elements deflected [Fig. 3(a)] and only the rightmost of the two beams deflected [Fig. 3(b)] by the ±2ι ·V signal. In both cases two discrete frequencies are applied to the Bragg cell corresponding to the positions of the two mirror elements. With the voltage removed from the left element, the left signal is reduced to less than the level of the broad pedestal of the right signal and the camera clock-related noise. The ratio of peak level to the level of clock-noise indicates a 20:1 contrast ratio. The pedestal is somewhat higher than this and appears to be due to diffraction from the deflected mirror element or the optics train following the DMD. However, lens stop diffraction was set with an adjustable stop to be insignificant with respect to the existing spread. The trailing sidelobe is due to ringing of the camera circuit. The contrast ratio was found to be higher than any of these levels, as found by increasing the Bragg cell signal power at the attenuated frequency a small amount and observing no change in the pedestal. However, increasing the power at this fre-



(a)



(b)

Fig. 3. CCD camera output (a) with two adjacent mirror elements driven ±28 V and (b) with only right element deflected. The two signals are intentionally adjusted to different amplitudes.

quency until the detector output reached the unattenuated level allowed clear measurement of the contrast ratio. A contrast ratio of between 20:1 and 125:1 with average contrast of 40:1 was observed depending on the mirror element illuminated and its degree of deflection.

The two channels [Fig. 3(a)] are well resolved but not to the degree that is possible at the DMD plane. A Gaussian beam with its 99% energy encirclement diameter the same as the Bragg cell aperture (13.1 μM) would be transformed by a 175-μM lens to a spot of diameter at half intensity of 9.5 μM. An input beam only slightly larger than the Bragg cell was actually used. According to Fig. 3(a), using 2.6× magnification from DMD to camera and 11-μM pixels clocked out at a 70-ns rate, the halfwidth at the DMD would be 12.7 μM. We expect that deconvolution of the camera impulse response will reduce the discrepancy. In spite of reduced resolution, it is seen that the system easily supports 333 or more well-defined channels. In fact closer mirror spacing or defocus could be used to enhance the probability of intercept for frequencies positioned between the active mirrors.

IV. Potential DMD Applications

The channelizer breadboard is of practical usefulness with CCD line imagers. Here, without localized attenuators, when the charge carrying capacity for a single pixel is exceeded, excess charge will drift into adjacent wells, frequently saturating large extents of the scan. An additional possibility is that the excisor could be configured to reject autonomously high-level signals. Since the DMD process[3] includes CCD elements (as analog shift registers), a CCD, used as a detector, could be placed in close proximity to the mirror element. If the detector senses a level above threshold, the corresponding mirror element would be triggered to change deflection state. The electronic state of the threshold device would also be available to indicate the presence of a jammer to the operator.

The results above also suggest the potential for DMDs in frequency excisors, although lower rejection is anticipated for the same channelizer rejection.[12] While the rejection levels do not currently approach that of conventional lumped element and surface acoustic wave filter banks,[13] the variation in passband shaping is virtually unlimited. In addition to all combinations of binary deflection of the mirror elements, it is also possible to continuously adjust the degree of deflection and thus cause variable amplitude weighting.

With the currently available contrast ratio, individual DMD elements can be switched between one or more distinguishable levels. For this reason the DMD can have many applications to optical computing. With several elements imaged onto a single detector, combinatorial logic operations can be envisioned. Also the DMD can be used as a crossbar switch for parallel electronic processing computers to interconnect several optical input channels to several detectors. Requirements necessary to apply the DMD to large reconfigurable interconnection networks are considered in some detail in Ref. 8.

V. Conclusions

While the DMD controls parallel optical channels with significant contrast and resolution for digital applications, improved performance is desirable for spectrum analyzers. The average contrast of 40:1 was observed in the frequency channelizer only when the signal was coincident with a mirror element. Due to inactive areas between mirror elements, much lower contrast will occur for frequencies centered there. To improve DMD suitability for high contrast, resolution, and probability of intercept excisors, the newer material processing techniques will be used to allow closer packing of mirror elements, eliminate processing holes, and also allow dc addressing. Also, in future versions of the DMD, mirror elements will be hinged at the top side rather than at the corner of the well. In this way, greater separation is expected between the undeflected and deflected images of the row for the same angular deflection of the mirror elements.

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Meetings *continued from page 931*

1988
August

29–1 Sept. 1st Eur. Conf. on Applications of Polar Dielectrics, Zurich *H. Arends, Lab. Solid State Phys., Swiss Federal Inst. Tech., CH-8093 Zurich, Switzerland*

29–1 Sept. 11th IEEE Int. Semiconductor Laser Conf., Boston *LEOS/IEEE, 345 E. 47th St., New York, NY 10017*

29–3 Sept. Trends in Quantum Electronics Mtg., Bucharest *TQE'88, Central Inst. Physics, P.O. Box MG-6, Bucharest, Romania*

30–2 Sept. ICO Int. Top. Mtg. on Optical Computing, Toulon *ICO Int. Top. Mtg., c/o S.F.O., Institut d'Optique, B.P. 43, 91406 Orsay CEDEX, France*

September

6–9 Fiber Optics, Optoelectronics, & Laser Applications Int. Symp. & Exhibit, Boston *SPIE, P.O. Box 10, Bellington, WA 98227*

6–10 Lasers, Fiber Optics, & Integrated Optical Circuits in Science & Network Communications Mtg., Boston *SPIE, P.O. Box 10, Bellington, WA 98227*

6–10 Int. Neural Network Soc. Ann. Mtg., Boston *INNS Abstracts 1988, 10615G Tierrasanta Blvd., Ste. 346, San Diego, CA 92124*

6–10 O-E/LASE East, Boston *SPIE, P.O. Box 10, Bellingham, WA 98827*

7–9 Optical Information Systems Conf. & Exhibit, Wash., D.C. *M. Reed, Meckler Corp., 11 Ferry La. West, Westport, Ct 06880*

7–15 14th European Conf. on Optical Communication, Brighton *ECOC '88 Secretariat, Conf. Services, IEE, Savoy Place, London WC2R OBL, England*

11–23 Fiber Optics, Optoelectronics, & Laser Applications in Sci. & Eng., Cambridge, MA *SPIE, P.O. Box 10, Bellingham, WA 98227*

16–19 Physical Interpretations of Relativity Theory Conf., London *M. Duffy, Mech. Eng. Dept., Sunderland Polytechnic, Chester Rd., Sunderland SR1 3SD, U.K.*

18–24 Lasers, Fiber Optics, & Integrated Optical Circuits in Science & Network Communications Mtg., Arlington *SPIE, P.O. Box 10, Bellingham, WA 98227*

19–23 Int. Cong. on Optical Sci. & Eng., Hamburg *SPIE, P.O. Box 10, Bellingham, WA 98227*

25–30 Int. Symp. on Polymers in Information Storage Tech., Los Angeles *A. Lewis, The Kendall Co., Res. Dept., Walpole, MA 02081*

26–29 **OSA Short Wavelength Coherent Radiation Top. Mtg., Cape Cod** *OSA Mtgs. Dept., 1816 Jefferson Pl., NW, Wash., DC 20036*

26–30 Welding & Melting by Electron & Laser Beams Symp., Cannes *Tech. Sec., CEA-DTECH-STA, 91191 Gif-sur-Yvette CEDEX, France*

27–29 **OSA Optics for Astrophysics & Earth & Planetary Remote Sensing Mtg.,** Cape Cod *OSA Mtgs. Dept., 1816 Jefferson Pl., NW, Wash., DC 20036*

October

2–6 Int. Laser Science Conf., Atlanta *L. Borders, Iowa Laser Facility, U. of IA, IA City, IA 52242*

2–7 35th AVS Natl. Vacuum Symp., Atlanta *AVS, 335 E. 45th St., New York, NY 10017*

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