Microoptical Phased Arrays for Spatial and Spectral Switching

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ABSTRACT

This article describes two optical devices based on linear arrays of micromirrors. The first is a phased array of micromirrors that can be rotated as well as translated vertically to maintain coherence across the array. We demonstrate experimentally that such micromirrors are capable of high-diffraction-efficiency phased-array scanning of laser beams. The second device is a Gires-Tournois interferometer with a micromirror array that provides tunable phase modulation for the multitude of partially reflected beams within the interferometer. We demonstrate experimentally that the MEMS-GT interferometer can operate as a tunable deinterleaver for dense wavelength-division multiplexed fiber optic communication.

INTRODUCTION

Diffractive optical micro-electromechanical systems (MEMS) is a powerful technology that utilizes the capability of micromirror arrays to provide coherent phase modulation over large apertures. Two-dimensional arrays offer the ultimate functionality, combining the performance of diffractive optics with the flexibility and adaptability of MEMS, but these types of devices also present very challenging design, fabrication, and control problems. One-dimensional arrays do not require integrated electronics for addressing and multiplexing, and can be fabricated relatively easily with high fill factors, high diffraction efficiencies, and high yield.

The grating light modulator (GLM) [1] is among the simplest diffractive optical MEMS devices and therefore one of the first to be commercialized. The commercial applications of this technology include projection displays [2] and variable optical attenuators for fiber optic communication [3]. The interferometric nature of the GLM gives it an inherent high sensitivity to displacement. This property was first utilized in displacement sensors for atomic force microscopes [4], and later in a variety of other microsensors, including infrared detectors [5], pressure sensors [6], and accelerometers [7].

The simplicity of the GLM makes it attractive, but many applications require more complex diffractive elements. One such application is synthesis of complex spectra from broadband light sources for use in correlation spectroscopy. One-dimensional arrays with more than 1000 piston-motion micromirrors have been demonstrated for this purpose [8]. Adaptive optics (AO) mirrors for phase corrections in astronomical observations, retinal imaging, and optical communication through the atmosphere are examples of other types of optical elements that are well suited for MEMS implementation [9]. Most AO applications, however, require large two-dimensional arrays, which can only be realized with integrated electronics for addressing and signal multiplexing. As a consequence, MEMS AO tend to be expensive to develop and fabricate, and therefore commercially feasible only for large-volume applications.

In this article we describe linear diffractive optical MEMS arrays for spatial and spectral optical switching. These devices are more complex to design and control than the GLM, but they are based on linear arrays of relatively few micromirrors, which removes the need for integrated electronics on the MEMS chip.

MEMS PHASED ARRAYS

Scanning and steering of laser beams using monolithic micromirrors have been demonstrated in a variety of systems including scanning displays [10], fiber switches [11], confocal microscopes [12], bar-code readers [13], and femto-second laser pulse shapers [14]. Most of these beam steering applications require relatively large micromirrors, typically measuring several hundreds of microns on a side, combined with large angular deflection to achieve the required optical resolution. As a consequence, the response time of these mirrors is substantially longer (tens to hundreds of microseconds) than can be achieved with smaller MEMS structures.

To overcome the speed limitations of high-resolution optical MEMS, we create phased arrays of micromirrors as shown in Fig. 1. Each of the mirrors of the array is relatively small, measuring a few tens of microns in our implementations, which means that they can be actuated through large angles with short response times. The individual mirrors must have two degrees of freedom of motion; they must be able to tilt to deflect the beam in the correct direction, and they must be able to move up and down in piston-style fashion to keep the reflections in phase (modulo 2π radians) as shown in Fig. 1.

To understand the speed advantage of phased arrays over monolithic mirrors we consider their resonance frequency. If we model the mirror as a plate of uniform thickness that is rotating around an axis parallel to the plane of the plate through its center, the resonance frequency can be expressed as

$$\omega = \sqrt{\frac{k_t}{\rho \cdot t \cdot I}} = \sqrt{\frac{12 k_t}{\rho \cdot t \cdot b \cdot L^3}}, \qquad (1)$$

where ρ is the density, t is the thickness, L is the length (perpendicular to the axis of rotation), b is the width, and k_t is the torsional spring constant of the plate. The torsional spring constant relates the rotational angle, θ, to the torque, T, on the plate,

$$T = k_t \cdot \theta. \qquad (2)$$

The electrostatic torque on the mirror is proportional to the square of the mirror length, and inversely proportional to the square of the gap between the mirror and the underlying electrode. If we take the angle, θ, that is proportional to d/L, to be an application-dependent input parameter, it follows that the maximum allowable torsional spring constant is independent of the mirror length, L. Combined with Eq. 1, this leads to the conclusion that the resonance frequency is proportional to $L^{-3/2}$. This means that arrays with even relatively small numbers of mirrors have a significant speed advantage over monolithic micromirrors with the same total aperture.

It should be emphasized that the practical value of the speed advantage of phased arrays depends on the application. In random access systems, the individual micromirrors are simultaneously actuated so as to reach their final position in the minimum amount of time. Under these conditions the speed advantage of the phased arrays is optimally utilized. In continuously scanning systems, on the other hand, the individual micromirrors of the array have to undergo a large number of rapid vertical transitions, corresponding to a 2π phase shift, during each cycle of the scan. The magnitude of the speed advantage will then depend on the piston-motion speed of the mirrors, and on the required quality of the scan (i.e., what fraction of the mirrors are allowed to be in "transition" at any given time).

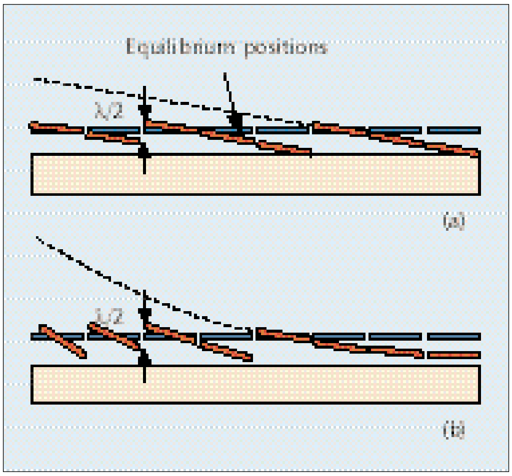


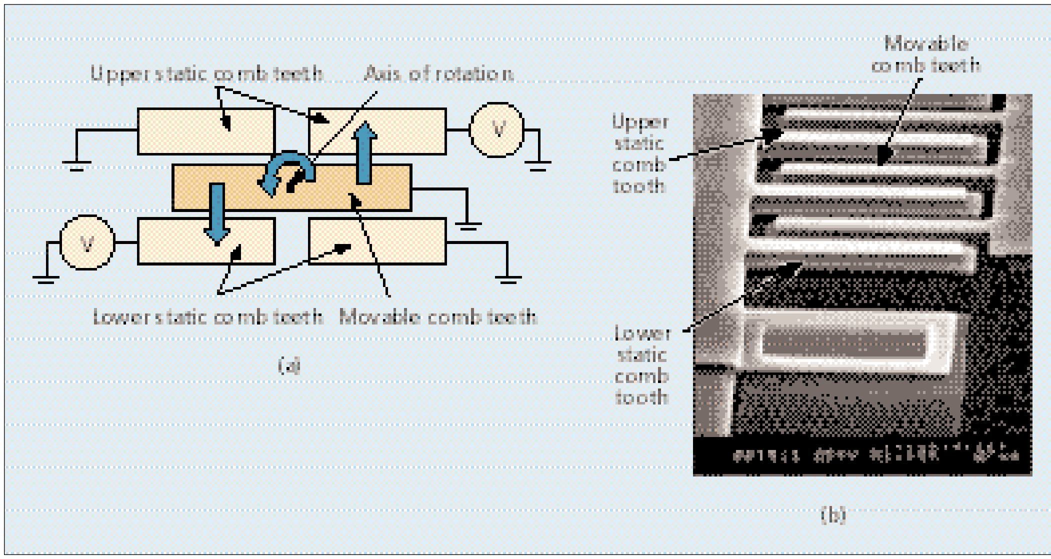
Figure 1. *Schematic representation of the operation of a scanning phased array. A linear scan is shown in (a), while (b) shows a scan combined with an anamorphic lens function. The individual mirrors tilt to the right angle and move up and down to maintain the phase, modulo 2π, of the partial reflections across the array. The small size of the mirrors allows higher speed and larger angle, and make the mirror less sensitive to curvature.*

By actuating the mirrors with pure torque, we can achieve much larger angular motion than is possible with actuators that applies a fixed ratio of torque and translational force.

The phase corrections required for high diffraction efficiency from phased arrays require that each micromirror have two degrees of freedom of motion. Figure 2 shows how electrostatic actuators with such dual-mode capabilities can be implemented in surface micromachining. The actuators consist of two sets of stationary combteeth, one set to pull the movable comb down and one set to pull it up. By arranging two such actuators symmetrically around the axis of rotation of the phased-array micromirrors as shown, we can generate pure torque, pure translational force, or a combination of the two [15].

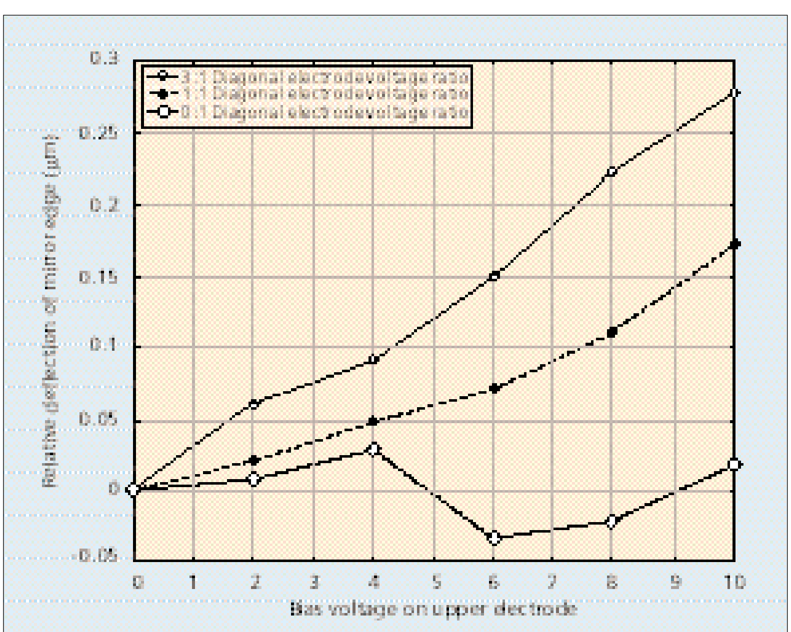
A fortuitous consequence of the dual-mode design is that it avoids the problem of unwanted translation that causes problems in many torsional mirror designs. By actuating the mirrors with pure torque, we can achieve much larger angular motion than is possible with actuators that apply a fixed ratio of torque and translational force. This is illustrated in Fig. 3, which shows the angular motion of a dual-mode mirror as a function of applied voltage. The unbalanced (torque and translational force) actuation conditions create very little angular motion, because the mirror is pulled straight up without much rotation. In fact, as the combteeth becomes engaged, a counter torque is generated, lowering the rotation angle. Balanced (pure torque) actuation, on the other hand, allows the mirror to rotate without the accompanying translation that limits the angular motion. The result is a much improved range of rotation as shown in upper curve in Fig. 3. For this actuator, balancing the forces requires a larger voltage on the lower electrode, because the gap between the lower electrodes and the movable comb is larger than the gap between the upper electrodes and the movable comb.

We have used dual-mode micromirrors of a design similar to the one shown in Fig. 2



■ **Figure 2.** *a) Schematic illustration of the dual-mode actuator. With voltage applied to diagonally opposing fixed comb teeth as shown, the movable electrode experiences a pure torque, while voltages applied to comb teeth at the same level create a translation force; b) scanning electron micrograph of a surface micromachined dual-mode actuator.*

(except that the bottom electrode is continuous) to demonstrate phased array scanning of laser beams [16]. The results are shown in Fig. 4. The frame on the left shows the far-field distribution of a helium-neon laser beam at 633 nm wavelength after it has been reflected from an array of four dual-mode micromirrors. The mirrors are then tilted through an angle of 0.4°, resulting in a far-field distribution with several strong side lobes in good agreement with the theoretical prediction shown in the center frame. The vertical position of the mirrors are then adjusted until the reflections from each of the four micromirrors are in phase, resulting in the far-field pattern shown in the frame on the right. With the mirrors brought into phase, the far-field distribution is very nearly a spatially shifted version of the original pattern, with just a minor broadening and peak intensity reduction.



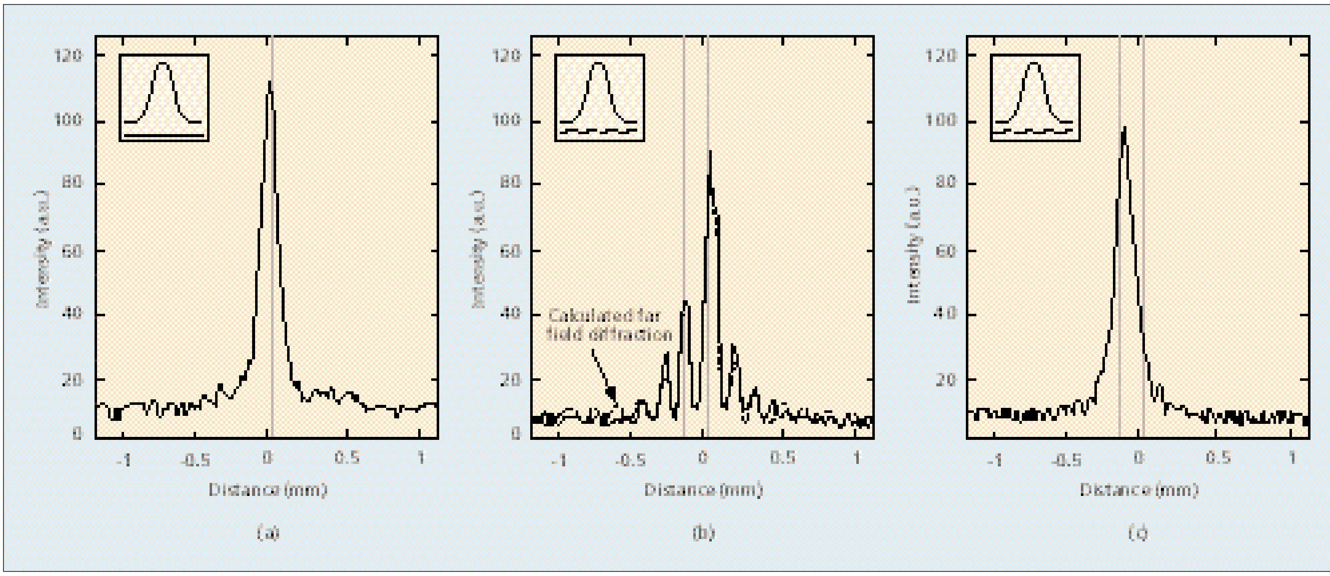
■ **Figure 3.** *Angular motion as a function of voltage for dual-mode micromirrors under different operating conditions. The lower curve shows the rotation with voltage applied to only one of the upper electrodes. As the voltage on the diagonally opposite electrode is increased, the actuator generates more torque and more rotation.*

The experimental results of Fig. 4 demonstrate that micro-optical phased arrays based on optical MEMS technology can achieve high diffraction efficiency in spatial scanning applications. The high diffraction efficiency is a consequence of the piecewise linear phase modulation made possible by the dual-mode actuators. Phased arrays with simple piston motion of the micromirrors do not have sufficient diffraction efficiency for many applications.

The strengths of the dual-mode phased array technology are high diffraction efficiency, even with relatively few elements, and high speed in random access applications. As with most MEMS devices, these phased arrays also have low optical loss. These advantages will in many applications more than make up for the increased complexity and cost of controlling an array of micromirrors with two degrees of freedom of motion. We expect that this type of MEMS phased array will find applications in free-space optical communication between moving platforms, fiber switches, printing, laser vector scanning, and other systems that rely on random access optical beam positioning, and they might also be useful for a number of continuous scan applications.

MEMS Gires-Tournois Interferometers

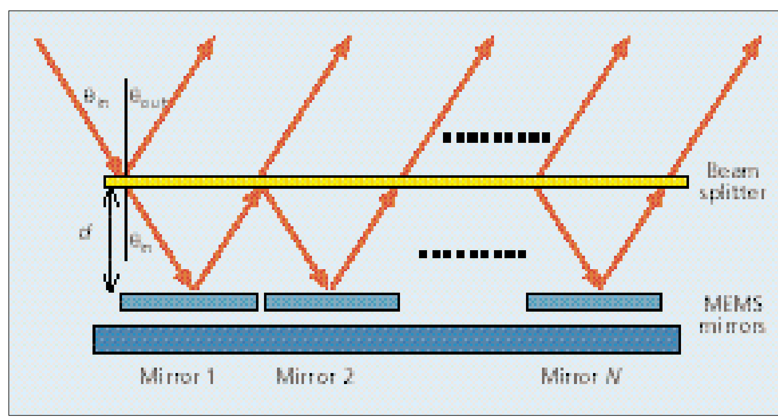
Figure 5 shows another optical device structure based on a phased array of micromirrors. The device is based on a traditional Gires-Tournois



■ **Figure 4.** *Intensity profiles showing the far-field diffraction pattern of HeNe laser beam reflected off a four-mirror, optical MEMS phased array. The drawings in the upper left corner indicate the mirror positions. In a) the micromirrors are all in their unactuated position; in b) they are all tilted the same amount, but there is no phase adjustment (no piston motion); in c) the vertical position of the individual mirrors are adjusted so that reflections from all the individual micromirrors are in phase.*

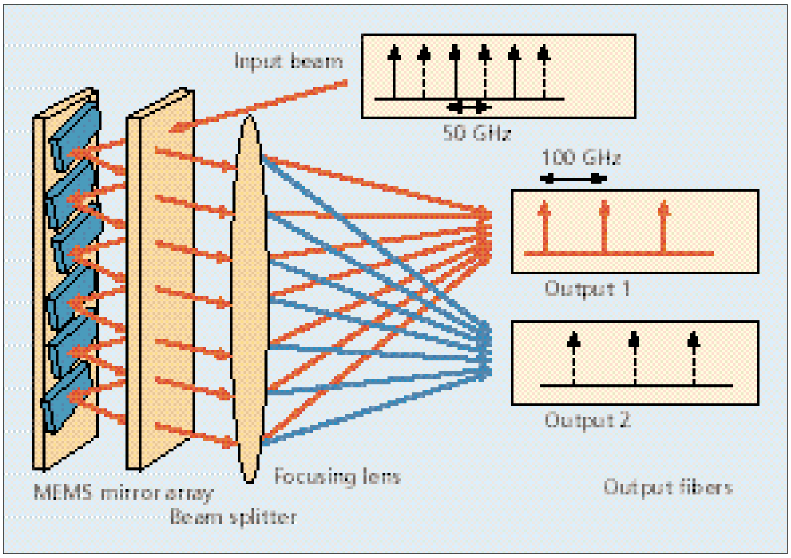
(G-T) interferometer [17] in which the back mirror is replaced by a micromirror array. The incoming optical beam is partially reflected and partially transmitted by the beam splitter as shown. The transmitted beam is reflected off the first micromirror, and again partially reflected and transmitted through the beam splitter. Unlike earlier reported G-T interferometers based on MEMS technology [18], the beams reflected from the back plane in this structure are spatially separated, allowing individual phase control of each beam. The partially transmitted reflections from all the micromirrors (as well as the initial partial reflection from the beam splitter if present) interfere in the far field to create the interferometer output. The directions of the spectral components of the output (i.e., the direction in which each wavelength constructively interferes) are controlled by the phase delay imposed on the partially transmitted beams by the micromirrors. The operation of this type of MEMS G-T interferometer is mathematically analogous to that of finite impulse response (FIR) transversal digital filters.

The micromirrors in the MEMS G-T interferometer need only a simple up-and-down piston motion to provide the required phase shift. This simplifies the design, fabrication, and operation of the microoptical phased array and makes the implementation of the complete structure simple and inexpensive. The spectral responses that can be generated by the MEMS G-T interferometer depend strongly on the number of mirrors in the micromirror array and the spatial distribution of the splitting ratio of the beam splitter. With a large number of micromirrors and a suitably tailored beam splitter, the MEMS G-T interferometer can act as a tunable filter with programmable passband profiles, synthesize a variety of complex spectra from broadband sources, and provide wavelength-to-space switching functions.



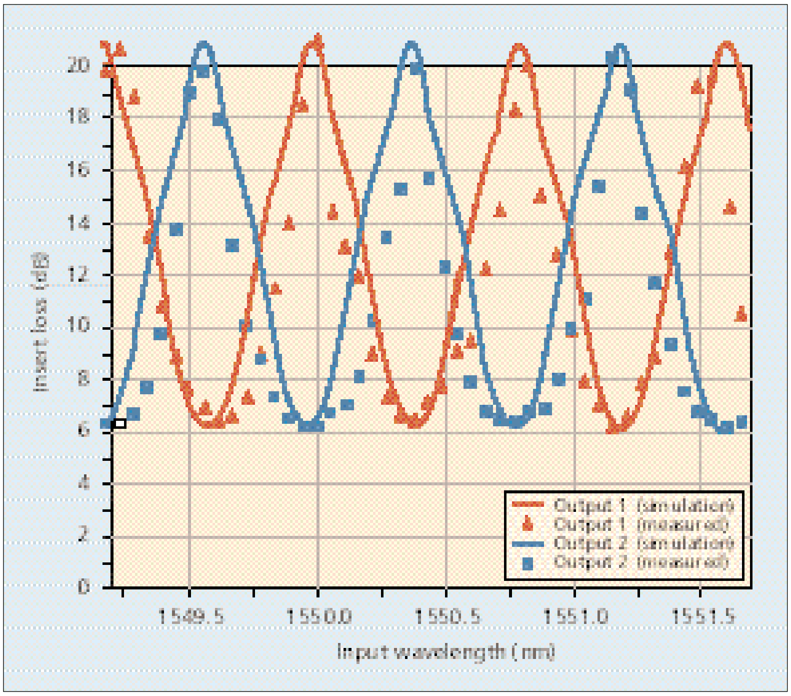
■ **Figure 5.** *A schematic diagram showing the operational principle of the MEMS GT interferometer. The micromirrors control the phase shift experienced by the spatially separated beams reaching the backplane. These phase shifts determine the interference of the transmitted beams, and therefore the spatial and spectral distribution of the far field.*

We have experimentally demonstrated switchable (de)interleavers [19] and tunable dispersion compensators [20] for wavelength-division-multiplexed (WDM) fiber optic communication based on the MEMS G-T interferometer. The switchable (de)interleaver, shown in Fig. 6, can be implemented with a small number of mirrors and a beam splitter with a fixed splitting ratio. The input optical beam to the (de)interleaver consists of evenly spaced wavelength channels. The deinterleaver separates the channels such that odd channels go to one of the output fibers and even channels to the other. The micromirrors determine the phase of the wavelengths and therefore their spatial distribution. The free spectral range (FSR) of the interferometer is adjusted to diffract every other wavelength channel (*wavelength set 1*) in the same direction, that is, onto



■ **Figure 6.** *An optical (de)interleaver based on the MEMS GT interferometer. The evenly spaced input wavelength channels are separated on two output fibers. The phase shifts controlled by the micromirrors determine which set of wavelength channels goes to each fiber.*

the same fiber (*fiber 1*). The wavelengths in between (*wavelength set 2*) are then diffracted into the other output fiber (*fiber 2*). Moving the micromirrors so that each partial reflection gets an additional $\lambda/2$ phase shift has the effect of spatially reordering these two sets of wavelength channels (i.e., *wavelength set 1* now goes to *fiber 2*, and *wavelength set 2* goes to *fiber 1*). In this configuration, the MEMS G-T interferometer acts as a switchable deinterleaver. The same structure can also act as an interleaver by simply



■ **Figure 7.** *Measurement and simulation of insertion loss into the two output fibers (output 1 and output 2) of a MEMS G-T interleaver with 50 GHz input channel spacing. The experimental data show 100 GHz output channel spacing on each of the outputs, as expected.*

interchanging the input and output ports. The switching of the two output channels only requires a common deflection on each of the micromirrors of half a wavelength (π phase shift), so the required vertical motion is less than 1 μm at 1.55 μm wavelength. This range of motion is very small compared to the distance between the micromirrors array and the beam splitter, so the effect on the FSR is negligible.

To demonstrate the MEMS G-T interferometer, we implemented the deinterleaver of Fig. 6 using micromirror arrays fabricated in a commercial MEMS foundry. The micromirrors were actuated by dual-mode vertical-combdrive electrostatic actuators to get sufficient range of motion. The G-T interferometer was set up with a mirror-to-beam-splitter distance of about 1 mm, and was adjusted to give an FSR of 100 GHz (or 0.8 nm), appropriate for an input channel spacing of 50 GHz. Arrays of only three micromirrors were used to obtain the results described in Figs. 7 and 8.

Figure 7 shows the insertion loss on output 1 and output 2 as a function of the input wavelength without micromirror actuation. The minimum insertion loss in the passband is about 6 dB, and the measured cross talk to adjacent channels is –14 dB. A substantial part of the insertion loss is caused by the uncoated polysilicon micromirrors, which have reflectivity of less than 0.4 at 1.55 μm wavelength, so we expect much better insertion loss with higher reflectivity micromirrors.

Figure 8 shows a comparison of the insertion loss on the output for two different states of the micromirrors. For clarity only one output channel and one spectral period is shown. The measurements prove that by adjusting the position of the micromirrors to give a π phase shift on all the beams reflected from the micromirror array, the wavelength response is shifted by one half of the FSR of the deinterleaver. The result of this shift is that the two output ports are interchanged. We see that the passband insertion loss and crosstalk between adjacent channels remain essentially unchanged during the channel switching operation.

The results in Figs. 7 and 8 show that useful functions can be realized in MEMS G-T interferometers with as few as three micromirrors. The switchable (de)interleaver described here will potentially play an important role in future dense WDM optical fiber networks systems, which are evolving from low bit rates with 200 GHz channel spacing to high bit rates and narrower channel spacing. In practice, narrow channel spacing is often achieved though the use of optical wavelength interleavers/deinterleavers in combination with other multiplexers/demultiplexers, and the wavelength agility demonstrated by the MEMS G-T (de)interleaver simplifies system integration and enhances network flexibility. With larger numbers of high-reflectivity micromirrors, the insertion loss, crosstalk, and passband characteristics of the MEMS G-T interferometer can be substantially improved, and the concept can be extended to more complex filtering functions with a variety of applications in optical communication and sensing.

CONCLUSIONS

In this article we have reported on two optical devices that are both based on linear arrays of micromirrors. The phased arrays for spatial scanning and positioning of laser beams utilize the fact that smaller micromirrors have a significant speed advantage in random access applications. The response time for rotation through a given angle is inversely proportional to the length of the mirror (perpendicular to the rotation axis) to the second power, so partitioning a monolithic mirror into several smaller one leads to a much improved response time and/or the ability to operate at lower driving voltages. These advantages come at the cost of increased complexity of MEMS design and control, but for many applications this is a favorable trade-off.

The second device, the MEMS Gires-Tournois interferometer, also presents trade-offs between simplicity and functionality. The experimental results presented in this article show that tunable (de)interleavers can be implemented with as few as three micromirrors. Arrays with larger numbers of micromirrors, although more complex to control, offer lower crosstalk, superior passband characteristics, and improved functionality. As in the case of the spatially scanning phased array, the MEMS G-T interferometer utilizes the large number of degrees of freedom in micromirror arrays to create optical devices with flexible and unique characteristics. We expect to see devices based on this principle in a variety of future optical communication and sensing systems.

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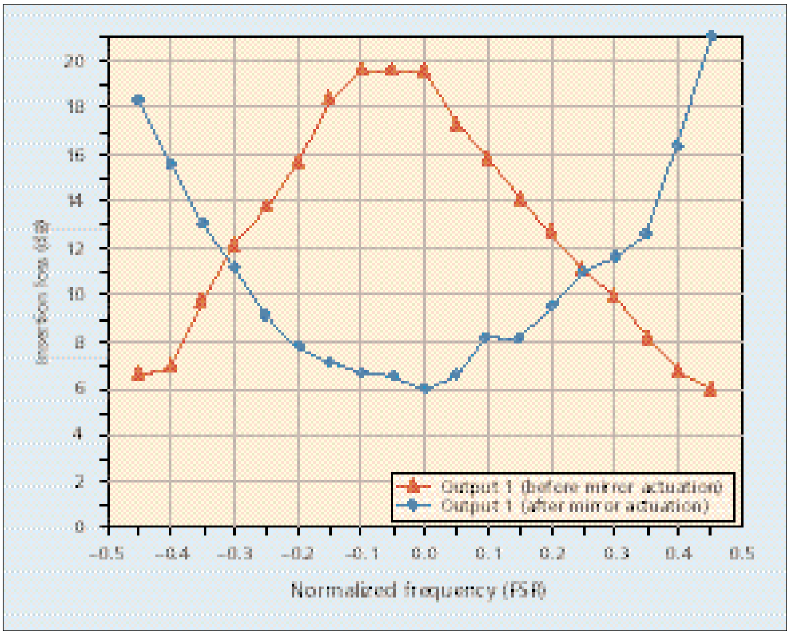

Figure 8. *Insertion loss on the output of the deinterleaver for two different states of the micromirrors. For clarity only one output and one spectral period are shown. The switching of output 2 has a similar, but opposite, characteristic.*

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The experimental results presented in this article show that tunable (de)interleavers can be implemented with as few as three micromirrors. Arrays with larger numbers of micromirrors, although more complex to control, offer lower cross talk, superior pass band characteristics, and improved functionality.

BIOGRAPHIES

UMA KRISHNAMOORTHY [StM] received a B.S. degree in electrical engineering from Drexel University, Philadelphia, Pennsylvania, in June 1991 and an M.S. degree in electrical engineering from the University of California, Davis, in 1999. She is currently pursuing a Ph.D. degree at the University of California, Davis, and is conducting her research at E. L. Ginzton Laboratory, Stanford, California. Between 1991 and 1996 she worked as a control systems engineer with Bechtel Inc., Gaithersburg, Maryland, and San Francisco, California. Her current research work focuses on optical microelectromechanical device design, fabrication and characterization for several applications including free-space all-optical switching for telecommunications, optical scanning, and spectroscopy. She is a student member of OSA.

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