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Optics & MEMS

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13. ABSTRACT (*Maximum 200 words*)

MEMS (MicroElectroMechanical Systems) are a new frontier in miniaturization. Optics and MEMS have a natural synergism. On the one hand, optical techniques are basic to the manufacturing of MEMS. On the other hand, a wide variety of MEMS have already been demonstrated to produce, manipulate or detect optical radiation. The "optical" range of wavelengths is from 0.2 micrometers in the ultraviolet to 12 micrometers in the far infrared region. Entire optical systems with volumes on the order of 1 cm^3 have been demonstrated.

This review of optics and MEMS begins with the use of optical techniques to make MEMS. Then several techniques to measure the small motion of dynamic MEMS surfaces are described. Optical MEMS sources, optics are detectors are reviewed in turn. Then, a survey of salient optical MEMS applications follows. It is likely that MEMS will be very important commercially in the display and optical fiber communications sectors, among others. Design challenges, and the status of commercially-available software germane to the design of optical MEMS, and a short study of MEMS patents are given in two appendices. It is concluded that there are great opportunities for both new technology and new applications in this arena.

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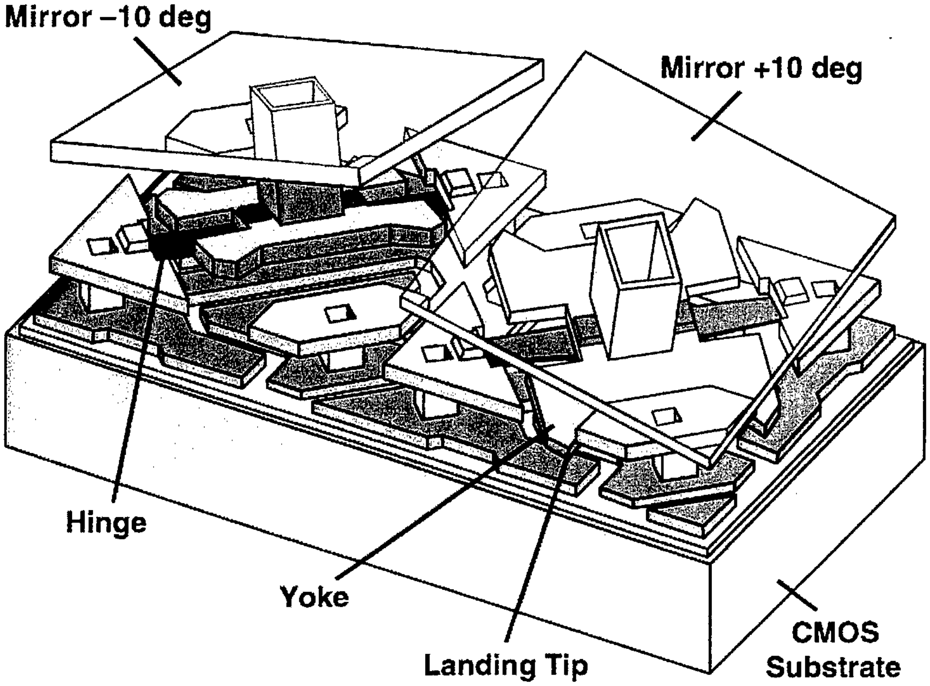

Schematic of two picture elements of the Digital Mirror Device™ manufactured by Texas Instruments, Inc. for use in image projectors at home, in offices and in theaters.

The device consists of three levels. The lower CMOS electronics level produces the electrostatic fields, which act on the middle mechanical level. Two torsional hinges, each of which is 5 by 1 micrometer in area and 60 nanometers thick, support the yoke. The hinges must last for over 10 billion flexures during the device lifetime. The top optical level consists of 16 micrometer square aluminum mirrors. Tilted one way, they reflect light through a lens system onto a screen. With the mirror tilted the other way, the light goes into a beam dump. Use of a color wheel between a white light source and the device, and time division multiplexing for each pixel, permit digital creation and projection of color images. Texas Instruments refers to the process as Digital Light Processing™.

The Digital Mirror Device™ contains over one-half million mirrors. It may be the mechanical device with the most moving parts of anything ever made.

This schematic figure has become an icon, not only for optical MEMS, but for MEMS in general, because of the large number of mechanical components.

Larry Hornbeck, who invented the Digital Mirror Device™ in 1987, provided the figure. He and Texas Instruments both received Emmy Awards from the Academy of Television Arts and Sciences on 24 June 1998 for Outstanding Achievement in Engineering Development.

OPTICS & MEMS

1. Introduction

MEMS (MicroElectroMechanical Systems) are a new frontier in miniaturization. MEMS researchers have taken technology traditionally restricted to the manufacture of electronic integrated circuits and developed methods to make machines on a chip. Not only is MEMS technology able to produce devices that operate on the scale of 100-micron diameter gears and micron-thick hinges, but the machines can be interfaced with electronic drives, control mechanisms, and other MEMS on the same chip. This implementation gives a new meaning to the phrase "integrated circuit."

The electronic and mechanical aspects of MEMS are well known, being part of the acronym. However, MEMS can also include magnetic, thermal, fluidic and electromagnetic (optical and microwave) mechanisms. The general term *microsystems* can be used, but we will continue to employ MEMS for its brevity and because of its widespread acceptance. In keeping with common useage, we take the term MEMS to include micromachined structures, even if they do not have moving parts. The term "MOEMS", for MicroOptoElectroMechanical Systems, has recently been replaced with "Optical MEMS" or "Opto-MEMS." The term "Microphotonics" has also been employed.

Optical MEMS can be loosely defined as any MEMS device that utilizes optical subsystems. The "optical" range of wavelengths is taken in its broad sense, from 0.2 micrometers in the ultraviolet to 12 micrometers in the far infrared regions, with air absorption defining this region. There is no such thing as completely optical MEMS since the second "M" represents "mechanical." Thus, we are defining optical MEMS as devices that couple photons with electronics and micromachined structures or mechanical motion in some way on the micron scale, as indicated schematically in Figure 1. Some devices, such as the monolithically integrated optical displacement measurement microsystem [Zappe and Hofstetter 1996], will test the limits of the definition. Later, these systems will probably include some form of active lens or mirror, and will ultimately meet the criteria of true optical MEMS. Several reviews of optical MEMS have already appeared [Fujita 1996, Jacobs-Cook 1996, Motamedi 1994, Motamedi et al. 1997]. Further, there is significant discussion of optical MEMS in general textbooks on MEMS [Kovacs 1998, Madou 1997].

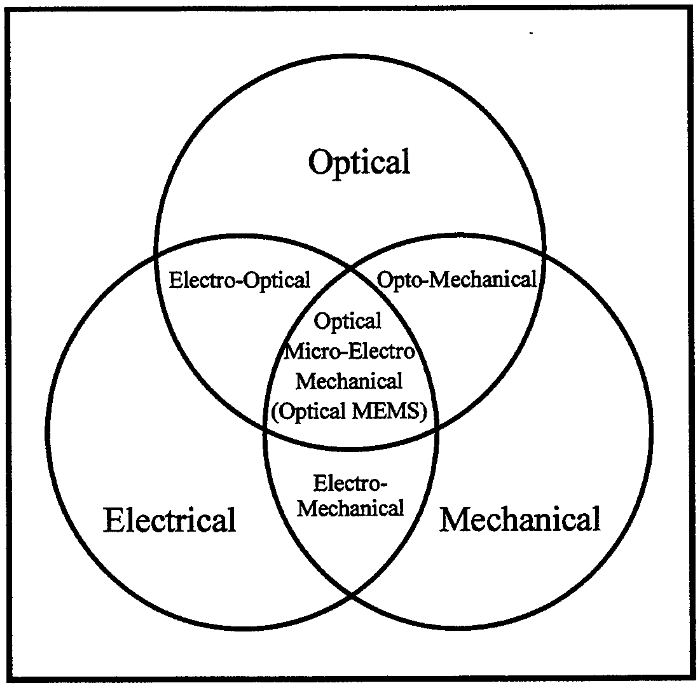

Figure 1. The synergy of Optics and MEMS.

Optics and MEMS have a natural synergism. On the one hand, optical techniques are basic to the manufacturing of MEMS. This is most true for photolithographic patterning methods. However, it increasingly applies to laser direct-write methods of etching or depositing materials during production of MEMS, and to the metrology of MEMS during and after manufacturing. On the other hand, a wide variety of MEMS have already been demonstrated to produce, manipulate or detect optical radiation. Entire optical systems with volumes on the order of 1 cm^3 have been demonstrated. Both the small ratio of optical wavelength to the lateral dimension of MEMS, and the low energy needed in MEMS to

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reflect or diffract light, contribute to the increasing interest and capabilities. The rapid motions of micro-mirrors and other optical elements, which are possible with the lightweight component parts of MEMS, are also a major beneficial factor. So also are the similar geometrical scales of integrated circuits, fiber-optic diameters and MEMS.

This review of optics and MEMS begins with the use of optical techniques to make MEMS. Diverse laser-based techniques have already proven their worth in manufacturing of MEMS devices. Following that, Section 3 describes several new and interesting techniques to measure the small motions of dynamic optical MEMS surfaces. The next section reviews the use of lasers to manipulate small mechanical components.

Virtually all uses of electromagnetic radiation have three components: sources, optics and detectors. Without a *source*, there is no radiation. Some kind of *optics* usually enters the situation, ranging from unavoidable and transparent media, such as an air path, to sophisticated components that perform complex manipulations on a beam. Finally, a *detector* is necessary to turn the radiation into electrical signals, which can be processed into information. This framework is a convenient way to organize the following material on optical MEMS. While there has been relatively little work on optical sources and detectors that are specific to MEMS, these areas show significant promise. Sources are reviewed in Section 5. The bulk of the survey of optical MEMS components treats devices that influence beams moving in waveguides (Section 6), or in free space (Section 7), including transmission (Section 8), reflection (Section 9), diffractive (Section 10) and interferometric (Section 11) devices. MEMS optical detectors are reviewed in Section 12.

A survey of salient optical MEMS applications follows in Sections 13 through 16. It is possible that MEMS will be very important commercially in the display and optical fiber communications sectors, among others. New materials and processes for optical MEMS are noted in Section 17. They can be expected to improve existing and enable new optical MEMS, with numerous and unforeseen impacts on applications. It is concluded in Section 18 that, despite great recent progress on the development and use of optical MEMS, there are great opportunities for both new technology and new applications in this arena.

There are several key functions that are common to the development and use of all MEMS, optical and otherwise. Prime among these is computer-aided design. For MEMS, detailed design requires consideration of electrical, mechanical, thermal and other factors. Design challenges, and the status of commercially-available software germane to the design of optical MEMS, are discussed in Appendix A. A short study of MEMS patents is presented in Appendix B. Both the ordinary and patent literatures document the high level of interest in optical MEMS and the current rapid growth in activities involving such devices.

2. Optical Microfabrication

One of the most valuable advantages of MEMS devices is the ability to manufacture them in large quantities and at a low cost. The cost per device, prior to packaging, can be comparable to the cost of silicon integrated circuits. There are several techniques used to produce MEMS devices. Micromachining, both bulk and surface, and LIGA (a German acronym for lithography, galvo- or electro-forming, and molding or abformung) are the main production methods. These procedures involve layered deposition of thin and thick films, and selective etching to release, or produce in the bulk, diverse three-dimensional shapes. Other techniques used to produce, configure and rework MEMS devices involve the use of lasers as machine tools and as local deposition tools.

Lasers are employed in pattern generation and replication, for removing and depositing materials in patterns and for metrology of MEMS. Hence, we begin this section with a brief review of some salient characteristics of the laser beams germane to MEMS. Then the uses of lasers for production and measuring of microstructures and MEMS are reviewed. Optical actuation of microstructures, methods for micro-component manipulation, and techniques for assembly of MEMS of many kinds are considered in Section 4.

The lasers employed to produce MEMS devices are both pulsed and continuous wave (CW) and cover a broad (0.25μm - 10.6μm) spectral bandwidth. Temporal characteristics of these lasers range from femtosecond pulse widths to continuous wave operation. Pulsed lasers that have repetition rates from one Hz to several megahertz are used. An evaluation of lasers and optical systems for MEMS production ultimately depends on three main characteristics of a MEMS design, which are: (1) optical properties of the material, (2) thermal properties of the material, and (3) geometric form of the part. The evaluation of these factors dictates the required characteristics of the laser.

The focal properties of lasers are especially germane to the production and metrology of MEMS. For example, the depth/diameter ratio of a hole drilled with a gaussian beam is controlled by the size of the laser beam at the focal spot and the "depth of focus." Figure 2 shows a schematic representation of a laser beam at its focal region. The minimum radius of the beam at the focal spot is defined as ω_o. The value of ω_o can be calculated using the laser wavelength (λ) and f-number (f), which is the ratio of the focal length to the diameter of the focusing lens.

$$\omega_o = \frac{2\pi f}{\lambda}$$

A parameter known as the "Rayleigh range" is defined as the length along the beam path where the radius increases by a factor of $\sqrt{2}$. The depth of focus (δ) is then defined as twice the Rayleigh range.

$$\delta = \frac{2\pi \omega_o^2}{\lambda}$$

The value of δ can also be calculated using f-number of a lens:

$$\delta = \frac{8\lambda f^2}{\pi}$$

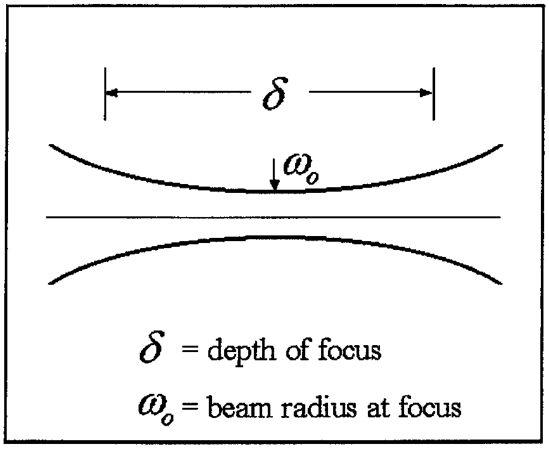

Figure 2. Axial cross-section of a focussed laser beam showing the two key parameters.

A 250 nm wavelength used with an f/4 optical system will have a depth of focus of 10.2 μm and a beam diameter at focus of 1.3 μm. A detailed treatment of gaussian optics is available [Siegman 1986].

The laser characteristic that most affects how well the laser can be focused is the spatial intensity profile within the beam. The transverse electromagnetic mode (TEM) describes the intensity distribution perpendicular to the axis of propagation [Sargent 1974, Siegman 1986]. The fundamental TEM_{00} is the lowest order mode. It consists of a radially symmetric gaussian energy distribution with a single peak in its center. Higher order modes contain multiple intensity peaks arranged in different geometries. Since no appreciable phase relationship exists between the intensity peaks of these higher order modes, the beam divergence is much greater than in the TEM_{00} mode. Focused higher order modes produce severely aberrated spots. Since the goal is very small spot sizes, the TEM_{00} mode is the most desirable for a materials-processing laser. Another advantage of using a TEM_{00} intensity distribution is the gaussian profile contains a smaller percentage of its total energy near its periphery and so the most effective part of the beam is at the center. Diffraction effects are minimized when a beam of this type is propagated through any optical imaging system.

Most lasers with nanosecond or shorter pulse durations have a gaussian temporal shape. The temporal shape of longer pulses can be tailored to many different profiles. These profiles are dependent on the quantum physics of the particular laser and how the active medium is excited or pumped. The most important implication of the temporal characteristic is that the averaged peak intensity is inversely proportional to the pulsewidth. High peak intensities cause the absorbed laser energy to be concentrated in a very thin layer near the surface of the material. The thermal diffusion depth is the distance the heat will conduct away from the interaction point in a certain length of time, such as the pulse width. Material is ablated if the thermal time constant is long in comparison to the laser pulsewidth.

The majority of laser machining is done with a single focal spot. The need to manipulate the substrate precisely can be accomplished with DC servo motors and high accuracy encoders [Christensen and Christensen 1997]. Using state-of-the-art X-Y manipulation, sub-micron position accuracy can be attained. A challenging aspect of some laser micromachining is the need to hold and feed the stock, especially for non-planar work pieces.

2.a. Pattern Generation

The interference of beams of coherent laser light produces standing electromagnetic waves, which can imprint regular patterns into the surface of photosensitive materials such as polymeric resists. Such maskless lithography is now being exploited commercially to control the optical properties of surfaces. This circular process, where optical beams modify matter to control light, has various applications in photonics, including production of linear gratings for distributed feedback lasers and wavelength division multiplexing. Two-dimensional patterns can also be produced, even on lens surfaces with modest curvature. An example produced by Holographic Lithography Systems Inc. is shown in Figure 3. This particular "motheye" surface has a 300 nm pitch for the 500 nm deep structures. Surfaces coated in this manner have low reflectance, so these structures can replace conventional multilayer anti-reflection coatings. They have wide angular and spectral acceptance. It is quite possible that such patterned surfaces will be employed within future optical MEMS in order to improve their performance.

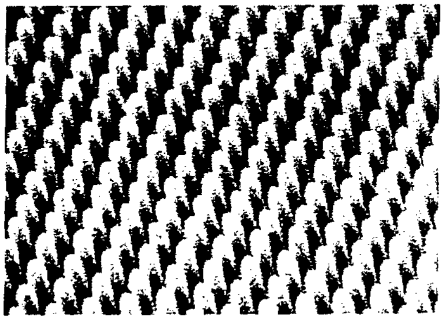

Figure 3. Motheye structure shown at about 20,000 X magnification.

2.b. Pattern Replication

The evolution of MEMS technology over the past 20 years has relied heavily on the existing photolithographic methods of semiconductor fabrication. In fact, in the early years of MEMS development, the pattering equipment was borrowed directly from the silicon semiconductor production lines. Even today, equipment for patterning MEMS is from the semiconductor industry. The difference is that shorter UV wavelengths have been used sequentially for the finest-featured ICs. Patterning equipment from earlier IC generations can be used for MEMS. For ICs, Hg G-lines at 436 nm gave way first to Hg I-lines at 365 nm and, thence, to eximer laser lines at 248 nm and 193 nm as IC critical dimensions went progressively from 1.0 μm to 0.5 μm and now to 0.25 μm and below. However, most MEMS do not require the extremely fine features of current ICs. Hence, aligners with Hg line sources will suffice for production of most MEMS.

Some shorter-wavelength optical patterning techniques are likely to be germane to future MEMS. Extreme UV lithography and X-ray lithography are under development. While these will not impact either IC or MEMS production in the near future, hard X-rays near 0.1 nm have been employed to produce microstructures and MEMS in the past few years by LIGA techniques.

LIGA is a process that uses a planar substrate, which has been coated with an X-ray sensitive photoresist. The resist is then patterned during exposure and etched to produce a three-dimensional structure. The etching may either be positive or negative depending on the photoresist and its development. Metal is then electroplated into the molds and the resist is etched away. The metal structure can serve either as the product, as in Figure 4, or as a mold for making plastic parts. This process can produce three-dimensional structures on the micron scale. It can also be modified in a variety of ways and combined with other MEMS production tools to make hybrid devices. The ability to make high aspect ratio structures is the unique characteristic of using X-rays to expose a photoresist, since the shorter wavelength X-rays cast sharp shadows with almost negligible diffractive blurring.

An interesting modification of the LIGA process is the "X-ray lathe" that can be used to produce cylindrically-symmetric parts as well as non-symmetric parts [Feinerman et al. 1996]. The key difference with this variation is the substrate is not planar. A PMMA coated wire is rotated axially in a glass-blower's lathe at approximately 1 rpm. The X-ray beam is directed through a planar mask suspended above the rotating substrate. Mask patterns can be designed to make either binary steps or reducing radius structures. Mask translation in the axial direction can produce helical structures and translation in the perpendicular direction can produce lobed structures. These structures can be electroplated and used in various applications such as waveguides, bearings, and gears.

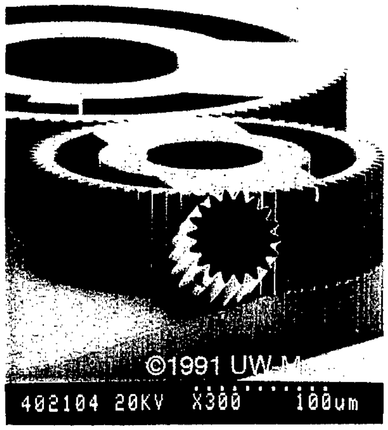

Figure 4. Nickel gears manufactured using the LIGA process.

2.c. Material Removal

Other factors cause the diameter of a laser-drilled hole to remain around the size of its waist for depths many times the diameter of the beam. Some of these factors include plasma containment within the hole as the depth increases, optical coupling into the plasma itself, thermo-physical properties of the material, and rate of laser energy deposition. In practice, producing a hole with a depth several times its diameter is complicated and requires that particular attention be given to the specific requirements of each individual operation.

As already noted, drilling a small hole, 5-10 microns in diameter, with a laser is primarily dependent on the depth/diameter ratio of the hole and the properties of the substrate material. Other parameters such as the f-number of the focusing lens, mode structure, and wavelength also influence the shape of the hole. Longer-wavelength devices, such as CO_2, remove material by heating, and tend to cause thermal damage to the surrounding area. Ablation is the best material removal process. It breaks the bonds between atoms and molecules in a material. This process produces very clean edges and will work in a variety of MEMS materials. Excimer lasers, with wavelengths near 250 nm, are used predominantly for this kind of machining. Typical pulse parameters for commercial excimer lasers are on the order of 500 mJ per pulse, repetition rates of 500 Hz, and pulse widths of 10 - 40 ns [Lizotte et al. 1996]. Another beneficial characteristic of laser ablation is the energy at which different materials ablate varies widely. This characteristic is used when stripping the insulation from small wires, and could be exploited in the MEMS arena by selectively removing polyimide from Au coatings, for example. Figure 5 illustrates the fine and detailed structures, which can be produced by laser ablation using short wavelengths.

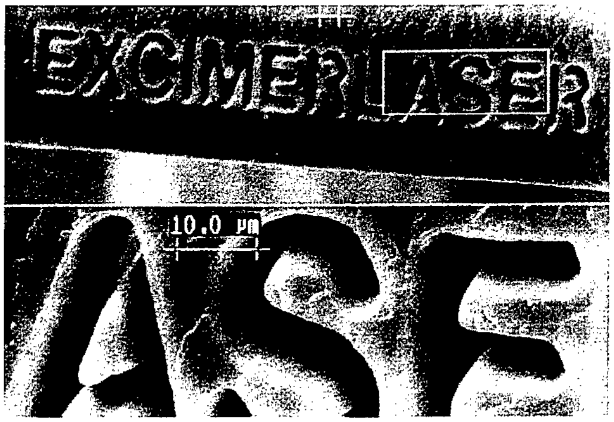

Figure 5. The words "EXCIMER LASER" ablated into a human hair.

An interesting method being developed at Technical University of Denmark [Mullenborn et al. 1996] uses an argon laser to melt silicon in a chlorine atmosphere. The sample is exposed to 400 mbar chlorine atmosphere, and then translated under a tightly focused argon laser. The molecular chlorine etches the molten silicon orders of magnitude faster than the solid silicon. This differential rate produces sharply defined edges. A 600 mW argon laser beam with a focus diameter of 800 nm can etch a 1 μm wide trench. Trench widths of less than 100 nm have been make by decreasing the laser power [Mullenborn et al. 1995]. Trench depth is a function of chlorine pressure and scan speed. This method of laser-assisted etching does not depend on doping concentration or crystal orientation and is quite versatile. The technique has been applied directly to optical devices by cutting aspheric microlens arrays, facets, mirrors, and waveguides [Bloomstein and Ehrlich 1994].

2.d. Material Deposition

Laser-assisted Chemical Vapor Deposition (LCVD) is a method to shape an object by adding material, instead of removing material by melting or ablation. It is the process of locally depositing material onto a surface from a vapor by using the focused laser beam as a heat source to induce chemical reactions near the surface. LCVD allows very small diameter (<10 μm) filaments to be formed, as well as larger-scale interconnects. The process draws on a well-established base of traditional CVD. A wide variety of precursor materials with high vapor pressures are readily available. Using a laser that produces a very stable beam is extremely important for LCVD processing.

The most common way to employ LCVD is to translate the substrate under the focus of a single laser beam and deposit the material directly on the substrate. This configuration has been used for reworking thin film wire paths on Multichip Module (MCM) integrated circuits [Wassick 1995]. This is the simplest method of implementing the technology, since it employs only two dimensions. A more versatile application of LCVD is to focus the laser on the surface of the substrate and then translate the substrate away from the focal volume. The material at the far side of the focal volume acts like a deposition substrate, and additional material condenses on it as it is being pulled away. This process leaves a thin filament, which is approximately the same diameter as the focal spot, connected to the substrate. If the substrate is pulled away along one axis, the fiber will grow in a straight line. If, however, two coincident beams are used and the substrate is manipulated in a complex fashion, a three-dimensional structure can be grown [Lehmann and Stuke 1994], as shown in Figure 6. The diameter of the rods that form the structure is approximately 20 μm and the diameter of the structure itself is about 1.2 mm. The diameter can be reduced to around 5-10 μm by lowering the laser power.

Figure 6. A 3-dimensional structure of alumina grown with the LCVD process.

Filaments grown by LCVD exhibit extremely uniform cross sections. They can be produced with widely-varying lengths [Wallenberger 1995]. The tensile and shear strength of the filaments is directly related to their chemical and physical uniformity. The growth environment can be tailored in a variety of ways, each affecting the physical properties of the fibers. As an example, carbon fibers have been grown by LCVD as elastic, brittle, and strong elements [Wallenberger 1994]. Many different kinds of vapor precursor materials may be used to produce different kinds of filaments [Bauerle 1987].

LCVD filaments can be produced in diverse shapes. A helix of tungsten was deposited on a rotating, cylindrical silicon substrate in a goniometer, as the laser focus moved along the rotation axis to produce a microsolenoid [Boman et al. 1992]. In another experiment, the same group made an open coil of tungsten by X-Y translation and withdrawl of a substrate during the deposition. The resultant structure is shown in Figure 7. Such small coils could be used as mechanical springs, or as electrical circuit elements. The process of sequential, direct-write deposition of complex structures is relatively slow, compared to the parallel manufacture of many identical devices simultaneously. However, it seems feasible to employ multiple laser beams brought to nearby foci for parallel manufacture of LCVD structures.

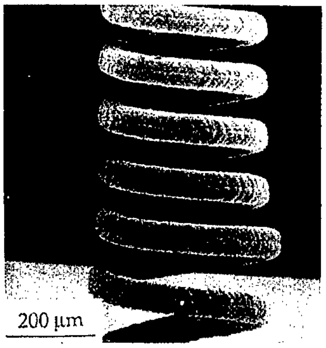

Figure 7. Tungsten coil made by LCVD.

2.e. Rapid Prototyping

The field of rapid prototyping has grown rapidly, in both research and commercial utilization, during the past ten years. It generally involves some means to quickly produce solid plastic objects, with size, shape and surface finish very close to the metal or other material product to be fabricated later by more costly means. The most common methodology is to focus a laser beam onto the surface of a liquid polymer in a container positioned on an X-Y stage, which can be precisely and quickly positioned under computer control. Absorption of the laser energy cross-links the liquid to make a solid plastic. X-Y motion of the stage (or scanning of the beam) produces one layer, or cross section, of the object. Repeatedly withdrawing the developing solid piece about one focal length into the liquid polymer and producing another two-dimensional layer builds up the entire three-dimensional object. This method of rapid prototyping is usually employed to produce pieces with maximum dimensions on the order of a decimeter and feature precision below 100 micrometers. However, it can be employed on finer scales to make micro-scale structures.

A group in Switzerland has demonstrated microstereolithography with volume resolution of 5 micrometers cubed [Bertsch et al. 1998]. The artifacts they produce can be stand-alone products, or can be built atop structures previously produced by other methods, such as LIGA. An example, shown in Figure 8, is a rescaled version of a large turbine blade structure. It was made of 110 layers, each 4.5 micrometers thick, and has a diameter of 1.3 millimeters. The axial hole is about 50% larger than the diameter of a human hair. The inset in Figure 8 shows a computer image based on the file used to create the plastic object. Another object made by the same type of process is exhibited in Figure 9. In this case also, the finest feature sizes are about 50 µm.

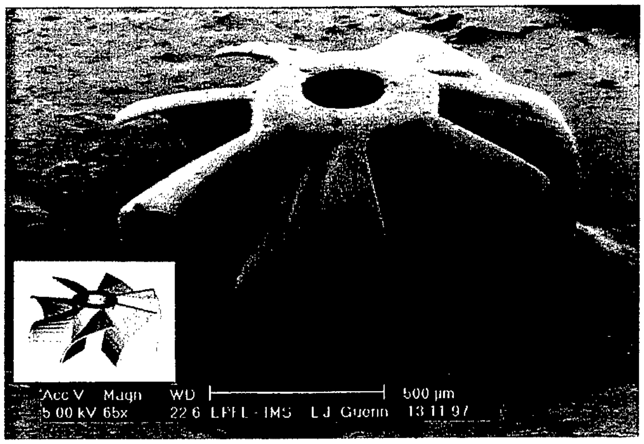

Figure 8. Plastic turbine blade produced by laser microstereo-lithography. The reference bar is 500 µm long.

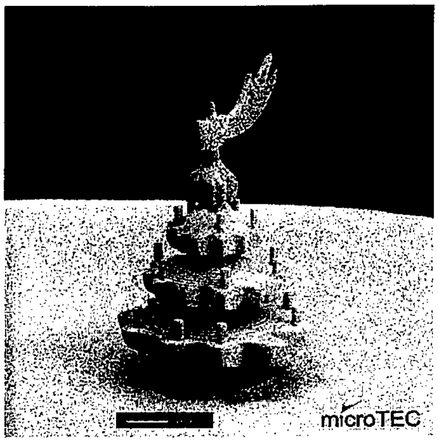

Figure 9. Christmas tree made by laser rapid prototyping. The reference bar is 300 µm long.

3. Optical Metrology

The employment of lasers to monitor the mechanical performance of MEMS structures is an excellent example of using optical characterization methods. MEMS devices are so small that micro-optical methods have been modified or developed to inspect and test them. Non-contact means of metrology are almost mandatory due to the relatively small masses and delicacy of MEMS components. Although models exist to predict the motions of MEMS structures, they cannot always do so accurately. Non-linear forces associated with electrostatic actuation, squeezed film damping, and mode coupling challenge the modeling process. Furthermore, models need to be verified with a high degree of precision. Optical methods of measuring displacements include imaging and scanning interferometry, scanning spectroscopy and stroboscopic imaging.

Interferometric methods have been used to measure displacements of cantilever beams [Burdess et al. 1997], bridges, suspended membranes [Scott et al. 1992, Scott et al. 1993], and parallel plate electrostatic actuators [Nelson et al. 1995]. Interferometric methods provide the best resolution for displacement measurements. This method has been used in both static and dynamic tests to measure the thickness [Lange and Higelin 1994] and resonant motion [Nelson et al. 1995] of Si membranes.

A technique utilizing a phase-shifting and imaging interferometer with a piezoelectrically-actuated reference mirror has been developed [Hart et al. 1999]. This method exploits a pulsed beam from a 658 nm laser diode to illuminate the resonant device under test. The stroboscopic illumination captures a time slice of the resonant motion and moving the reference mirror determines which part of the motion is captured. Figure 10 shows three aspects of this technique. The schematic of the experimental setup illustrates the simplicity of the experimental design. A two-dimensional interferogram of the scanning micromirror being tested is the data from which a three-dimensional surface height map of the mirror and its support structure results. Interferometric information gathered at closely spaced intervals throughout one resonant period can be sequenced to represent a complete picture of the structural behavior during one period. The sequence of three-dimensional graphs in Figure 11 shows the mirror shape and orientation at four separate times during one half period of motion. The picture below each graph represents the calculated far-field beam position and intensity distribution from that deformed mirror geometry. This powerful method of dynamic analysis will be of significant value to optical MEMS designers.

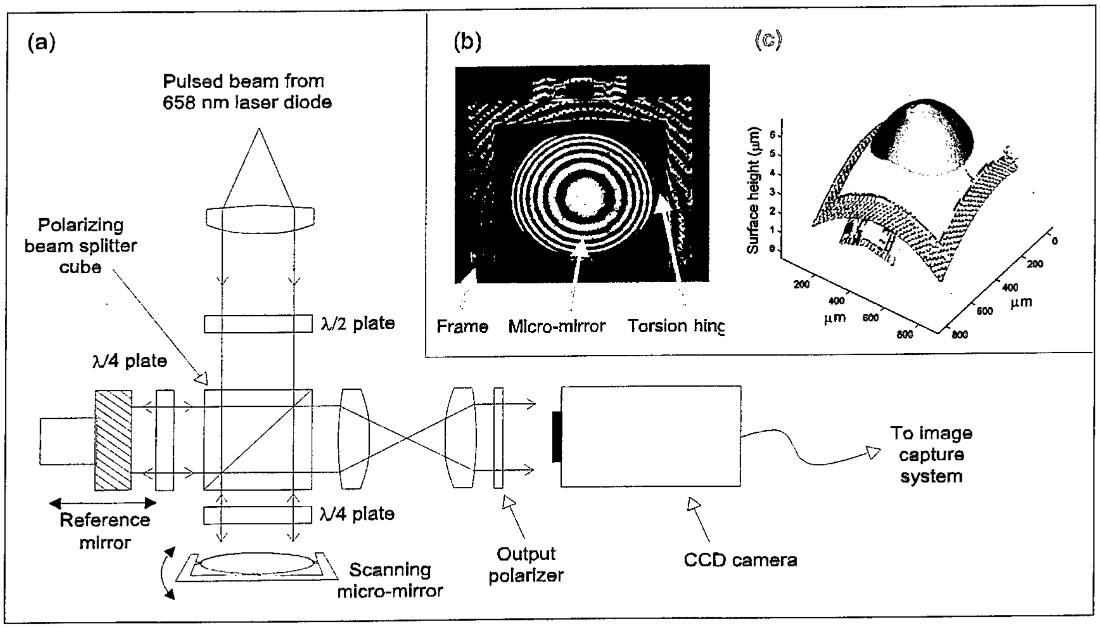

Figure 10. (a) Layout of the stroboscopic interferometer, (b) interferogram captured from a scanning micro-mirror and (c) surface height map retrieved from a phase-shifted interferogram.

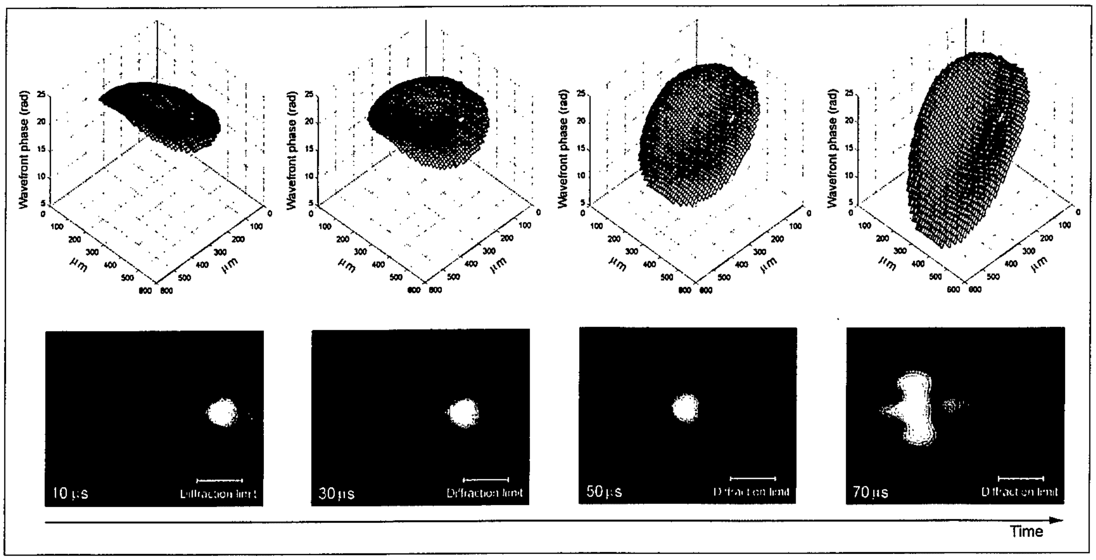

Figure 11. Series of time-resolved measurements showing changes in micro-mirror shape and orientation during one half of the scan period (top), and inferred far-field output beam position and intensity distribution (bottom).

A scanning hetrodyne laser interferometer was developed to measure displacements of the proof mass of an accelerometer, developed at the Jet Propulsion Laboratory, which employed electron tunneling as a sensor [Gabrielson 1994].Techniques used for these measurements were based on work done by a group at Navmar Applied Science [Scott et al. 1992, Scott et al. 1993]. A piezoelectric driver was fixed to the frame of the 1 cm square proof mass. Both were translated under the focal spot of the laser interferometer. The resolution in the plane of the test unit was about 10 μm, and deflections of less than 0.1 nm could be detected perpendicular to the surface. A 10-minute raster scan of the driven device yielded a three-dimensional time history of the mechanical response of the proof mass, from which animations were made. Figure 12 shows frames acquired at two drive frequencies, which exhibit very different behaviors.

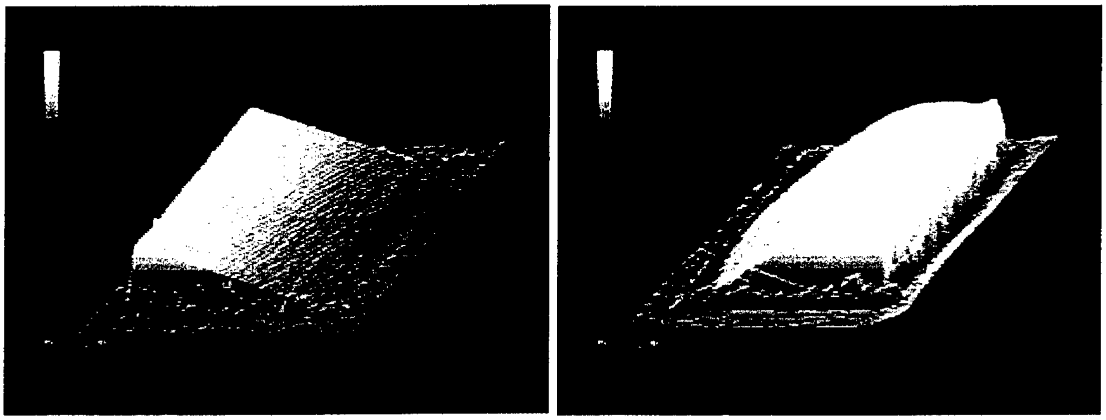

Figure 12. Measured displacement of the proof mass of a micromachined accelerometer driven at 1 kHz (left) and 4 kHz (right). A simple bending mode of the structure from the attachment hinge on its right side occurs at the lower frequency. A second bending mode propogates across the structure at the higher frequency, inducing large deflections and stresses near the hinge. The frame also deforms at the higher frequency.

The measurement of scattered optical radiation, called laser Raman spectroscopy, can be used to monitor stress in MEMS devices. Raman spectra arise from the inelastic Stokes scattering of a laser pulse from the lattice of atoms or molecules in a solid. Mechanical changes, such as stress and defects in the lattice, result in phonon frequency shifts. These changes in phonon characteristics are mirrored in the spectra of the scattered radiation. Changes in these Raman spectra can be used to investigate the physical characteristics of a MEMS device. Recent work by Gardiner has demonstrated that this method of imaging the stress in silicon can provide a very clear picture of stresses due to mechanical strain, physical defects, and also doping concentration [Gardiner and Bowden 1996]. Results of this work indicate that in silicon, boron doping profiles can be measured with sub-micron accuracy. Using a unique device (Microline Focus Spectrometer) developed at the University of Northumbria [Bowden et al. 1992], dopant concentration, stress, and crystal lattice characteristics have been measured.

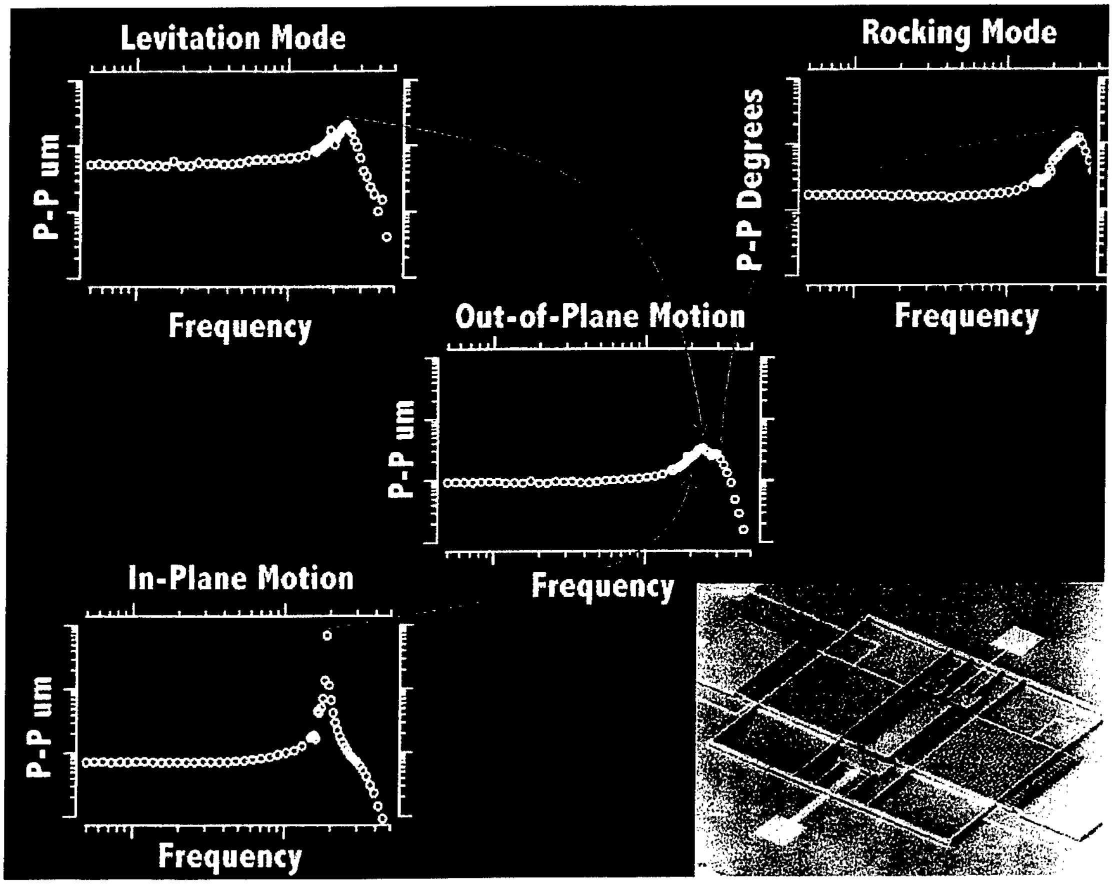

Figure 13. Three-dimensional, frequency-dependent response as determined with stroboscopic video microscopy, followed by computer analysis, for various modes of motion of a micromachined gyroscope shown in the inset. The minimum peak-to-peak displacement is 1 nm, with the maximum displacements approaching 1 μm for the two left and central graphs. The peak-to-peak angular motion shown in the right graph ranges from 1 mdeg to 1 deg. The frequency range is .5 to 50 kHz.

Recent work in video microscopy has pushed the limits of optical characterization technology. Freeman et al. have developed an optical microscopy system that uses stroboscopic illumination to measure motion with nanometer resolution [Freeman et al. 1998, Freeman and Davis 1998]. This method exploits digitized images, the known CCD pixel size and machine vision algorithms to give in-plane measurements with 4 nm resolution. Vertical translation and the depth of focus are used, again with curve fitting and peak extraction algorithms, to obtain almost as good a resolution in the third dimension. Figure 13 gives sample results from the use of this technique with a planar, comb-driven MEMS gyroscope from Draper Laboratory.

4. Moving Matter with Lasers

MEMS technology has brought machines down to a scale where photons can have a significant effects on them. Intense beams exert forces on micro-structures and -particles. Optically-induced thermal excitation of MEMS components can be used as a mechanical driver, much as resistive heating is used to drive bi-morph actuators. Laser light can be used to trap small particles, and to either translate or rotate them. Laser tweezers and other micro-photonic applications of laser light are beginning to appear in the realm of MEMS. Optical manipulation might play a role in micro assembly and related tasks.

4.a. Optical Actuation

Laser power can be used as a driving force in many interesting applica-tions. The optically actuated device shown in Figure 14 is an excellent example [Ukita et al. 1993]. The microbeam is photothermally actuated by a laser diode (LD2) that is integrated directly into the GaAs substrate. The microbeam vibrates at the pulse repetition rate of the laser. The motion is sensed by a photodiode that is optically coupled to the backside of the other laser diode (LD1). LD1 emits a continuous laser signal onto the microbeam, and as the beam vibrates the optical cavity formed between the beam and LD1 is modulated. The signal incident on the photodetector is modulated as a result. The device can be used as a sensor by placing it in a system where the resonant frequency of the beam is changed by some environmental variable, such as an adsorbed chemical analyte or external acceleration.

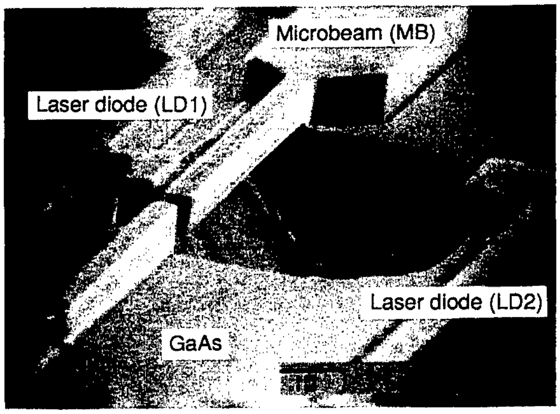

Figure 14. Optically actuated and sensed microbeam. LD2 produces the pulses that excite the microbeam. Its oscillation modulates the laserbeam produced by LD1, which is then detected by the photodiode to the left (not visible in figure).

A laser-driven microgripper has been reported [Nogimori et al. 1997]. It uses the energy from a solid state laser to actuate the tangs of a gripper mechanism. The laser heats a liquid that has a low boiling point, which expands and drives a piston to actuate the gripper. The thermal process is inherently slow, but the size scale is small and the heat dissipates quickly enough to use the device at a 1 Hz repetition rate. The gripper is able to generate a force of 0.04 mN from 80 mW of laser power. The low efficiency is due to the design of the gripper. Mechanical redesign should increase the available gripping force. Other uses for thermal actuation driven by lasers have been explored [Kawano et al. 1997].

4.b. Optical Manipulation

One of the most challenging problems with some MEMS is the need to manipulate and assemble the components. Great effort has been directed at self-assembled systems, and at systems with actuators for on-chip assembly. Some applications may require fine control of discrete optical components, such as laser modules, LED chips, or prisms. The assembly task for some MEMS may be addressed with laser trapping and optical manipulation. The mass of individual components is small and many optical devices have reflection or transmission windows at some laser wavelength. These two characteristics are key parameters needed to use laser trapping. The process of optical trapping relies on the momentum transfer between photons provided by the laser and the trapped particle [Ashkin 1970]. Optical trapping can occur in both reflective and refractive modes, provided the lasers are directed to the appropriate location on the microparticle. Counter-propagating, dual-beam systems have been used on reflective spheres to effectively cancel each other and trap the particle. Figure 15 shows two microparticles trapped by a laser.

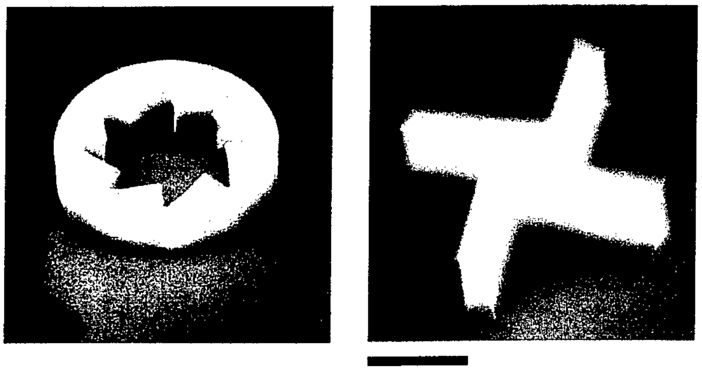

Figure 15. Structured micro-particles photographed while trapped by focused laser beam. The bar is 5 μm and applies to both figures.

A buffering fluid is used to provide a buoyant force to help balance gravity and reduce frictional forces that inhibit motion. These buffering fluids, such as water and alcohol, also provide a known change in the optical index of refraction. The differential optical index is the most important factor in imparting a force to refractive particles. The forces, which are balanced in the trapping process, are optical, gravitational, buoyant, and thermally-induced turbulence. The absorption of laser energy by the particle can produce thermal turbulence in the buffering fluid and produce instability in the trap. Selecting a laser wavelength with reduced absorption by the microparticle can minimize this detrimental effect, called photophoresis. Two beam systems have been used to assemble groups of particles and to transfer a trapped particle from one beam to another [Ashkin and Dziedzic 1980]. Symmetries, or more specifically, anti-symmetries, can be exploited to impart torques on microparticles. This effect has been successfully used to exhibit rotational control of anisotropic microparticles [Higurashi et al. 1994, Nagatomi and Ukita 1997]. Anti-symmetries in optical characteristics, such as birefringence, have also been exploited [Higurashi et al. 1997]. In fact, nickel-iron permalloy micro-gears have already been manipulated with lasers, although the thermally-dominated turbulence produced a very unstable trap [Rambin and Warrington 1994].

4.c. Optical Assembly

The ability to stimulate and control motion optically, especially for free components, leads to visions of employing lasers for assembly of MEMS and micromachines. Diverse systems already exist for moving and manipulating structures on the micrometer and even nanometer levels. Most of these have been developed and commercialized for biology research, notably studies of individual cells. However, they are labor intensive and do not appear to be good candidate technologies for the routine assembly of complex systems with parts on the micro-scale. More automated and programmable techniques seem to be needed. Laser methods might be capable of the complex and high-resolution manipulations of three-dimensional objects in free space, which will be required. It seems that performing assembly processes in liquids might be worth investigating, in order to exploit buoyancy. Further, the use of ionic solutions might permit electrical forces to be used, possibly controlled by incident laser light. The development of facile and flexible techniques for micro-assembly, including the use of optical tools, is a fertile area for more research.

5. Optical MEMS: Sources

MEMS optical sources, both ordinary emitters and lasers, fall into two broad categories. The first includes monolithic sources, which are not themselves MEMS, but can be incorporated into MEMS optical systems. The second category includes sources in which the emitter is truly integrated with one or more moving components. Both of these will be covered in the following sections.

5.a. Thermal Emitters

Thermal energy can be generated by electrically heating a filament of material. This technique has been used in making a non-dispersive infrared gas analyzing system [Bauer et al. 1996]. A polysilicon filament is operated at temperatures of 1500 K at one end of a gas filled cavity. The thermal radiation is focused with a Fresnel zone plate onto a detector placed at the other end of the cavity.

The unknown gas is placed in the cavity and a transmission measurement can then be made. While this is a simple device, more complicated systems may be fabricated that include choppers, tunable filters, and additional channels for multi-gas analysis. The source was operated in both DC and AC (31 kHz) modes.

Thermal emitters at lower temperatures also produce optical radiation in the infrared region. Micromachined arrays of heater elements have been made to simulate images for testing of infrared optical systems. The low thermal inertia associated with suspended, thin-film heaters enables frame rates exceeding 30 Hz for infrared scene generation. With the normal operating temperature near 600 °C, the device has a time constant near 1 msec. The polysilicon heater elements on each pixel have a temperature coefficient of 37.5 °C/mW, and a dynamic range from ambient to over 1000 °C. Figure 16 shows some of the pixels from a 32 by 32 array of thermal pixels. Arrays as large as 1024 by 1024 elements are projected [Johnson et al. 1994, Parameswaran et al. 1991].

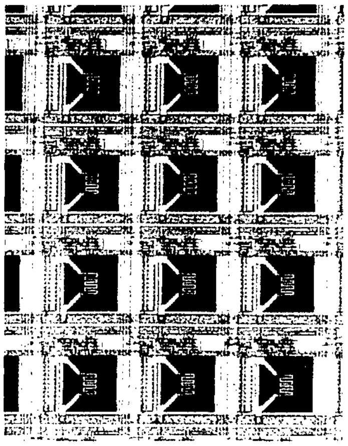

Figure 16. Micrograph of pixels in the NIST thermal scene generator.

5.b. Semiconductor Light Emitting and Laser Diodes

The monolithic, planar nature of MEMS is a natural environment for implementing semiconductor light emitting diodes (LEDs) and laser diode devices. Materials such as Si, GaAs, InP and other semiconductors have all been used to make LED's and lasers. The development of edge emitting lasers for fiber communications has fueled the rapidly growing field of opto-electronics. Recently, vertical cavity surface emitting lasers (VCSELs) have improved the spatial characteristics of the laser beam and reduced the complexity of packaging for laser diodes. Research in the area of massive LED arrays for display applications is continuing and is closer than ever to realizing a truly flat screen video display. All of this research and development is applicable to integrating lasers and LED's into MEMS. In fact, mechanical action at the chip level has enhanced the performance of some of these devices. The ability to tune the operating wavelength of a laser diode by mechanically modifying the optical cavity is a basic realization of optical MEMS. Wavelength-tunable laser diodes have applications ranging from wavelength division multiplexing (WDM) and other optical communications processes to environmental remote sensing.

5.b.i. Light Emitting Diodes

Tunable resonant-cavity light emitting diodes have been developed [Larson and Harris 1995]. These devices are the precursors to the tunable vertical cavity surface emitting lasers discussed in the following section. The 40 nm tuning range is broader than the tunable VCSEL, and there is no linewidth narrowing, as in a laser. The minimum spectral linewidth is around 1.9 nm at emission wavelengths of 957 nm. LED's made from InP and operating between 1.4-1.5 μm have also been fabricated [Christenson et al. 1997].

5.b.ii. Edge Emitting Lasers

Semiconductor lasers can be fabricated from either Si or GaAs. Early efforts to make integrated laser sources were confined to edge-emitting designs. Such lasers have several key attributes. They are easily fabricated via planar technology and require no release layers. They can use vertically-etched faces, which do not require additional processing, or cleaved edges as air-interface mirrors. They can either be mounted on edge for vertical emission [Wu et al. 1995] or on XYZ translation stages that can provide control of all axes of the laser beam [Fan and Wu 1997, Lin et al. 1996].

Edge emitting lasers are tuned by varying the temperature, carrier injection, stress or by translating an end mirror. Moving mirrors provide the greatest tunability. Various mechanisms for both static and resonant motion have been demonstrated for end mirror translation [Uenishi 1996]. A challenging aspect of the use of end mirror translation methods is fabricating high aspect-ratio-mirrors. One way of implementing high-aspect-ratio end mirrors is to use microhinge technology [Lin et al. 1994]. Both 500 μm x 500 μm mirrors and 1000 μm x 500 μm mirrors have been demonstrated in an external cavity semiconductor laser [Kiang et al. 1996]. The mirrors were aligned with two degrees of freedom using integral comb drives for translation. This system provides excellent accuracy and high-speed tunability. While simple and effective, edge emitting lasers lack the improved spatial characteristics of the newer VCSEL designs.

5.b.iii. Vertical Cavity Surface Emitting Lasers

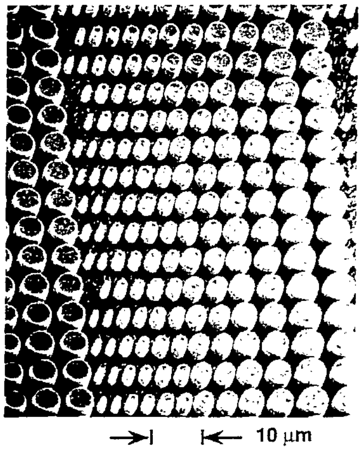

Figure 17. Micrograph of dense array of VCSELs of different diameters.

VCSELs have several inherent advantages. They generate a radially symmetric output beam due to their radially symmetric construction. Photolithography techniques used for MEMS production are easily adapted to produce VCSELs. They can be made in a variety of diameters, and densely integrated with each other, as illustrated in Figure 17. Also, they can be integrated with on-chip electronics for feedback and control. VCSELs employ a distributed Bragg reflector (DBR) as the mirrors. These DBRs are constructed by alternating layers of index-mismatched materials such as GaAs/AlAs. This set of layers operates as a multilayer dielectric mirror. Fixed-wavelength VCSELs can be fabricated so that the cavity is in bulk, transparent material. These devices do not benefit from the great index mismatch that occurs at an air interface. Air gap devices have two inherent advantages. The reflection from the end mirrors is enhanced due to the high index mismatch at the air interface, and the release layer construction allows for a moving mirror design for tunability and modulation of the output wavelength.

VCSELs with movable mirrors are a primary example of a true MEMS source. Moving-mirror devices require release layer construction. Due to the short cavity length of the VCSEL, they have widely spaced cavity modes. This means that their output is very sensitive to changes in cavity length. Hence, these devices can be tuned over a broad spectral range of ~19 nm. Several methods of obtaining this motion are being investigated, and are discussed below.

The cantilever arm tuning method developed at Stanford [Chang-Hasnain et al. 1996] uses a bias voltage to electrostatically adjust the cavity length. Voltage is applied between the cantilever arm and the substrate. The cantilever holds the end mirror of the laser. The end mirror and cantilever arm can be seen in Figure 18. Typical tuning voltage and current parameters for a 19.1 nm tuning range are 0-14V at 460 μA [Vail et al. 1996]. A peak optical power of 0.9 mW has been observed at 955 nm.

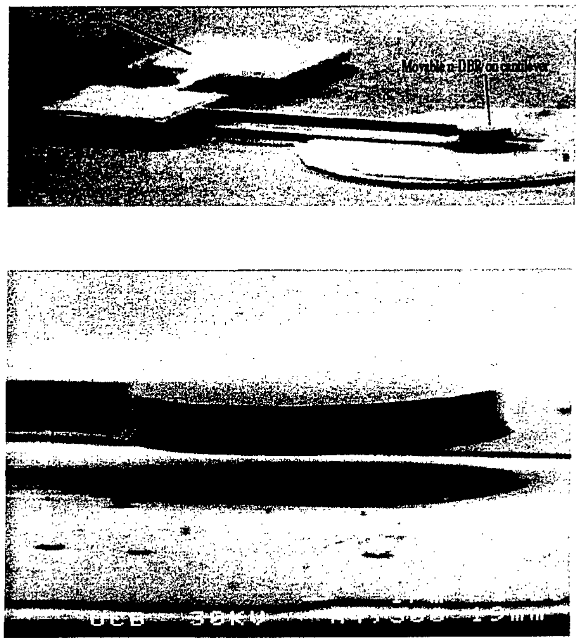

Figure 18. Cantilever arm and mirror from tunable VCSEL.

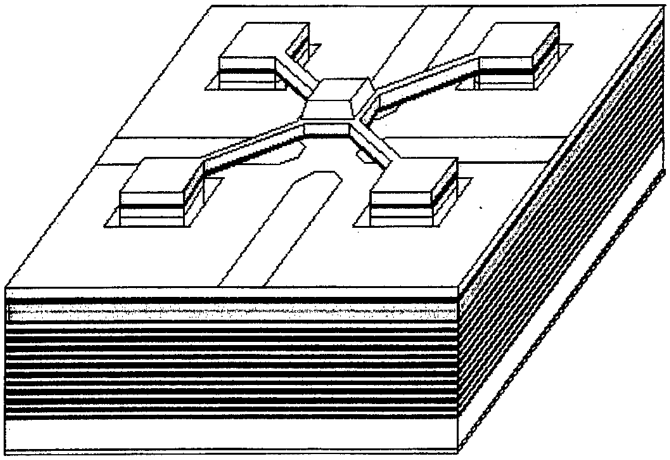

Figure 19. **Schematic of a tunable VCSEL with end mirror suspended on four deformable arms.**

A flexible-structure with multiple support arms for cavity tuning was also developed at Stanford [Harris et al. 1996]. It uses a bias voltage to electrostatically adjust the cavity length. The voltage is applied between the suspended structure and the substrate, which are indicated in Figure 19. The deflection of the structure allows a continuous tuning range of ~19 nm. The active region of these devices generally consists of a GaAs cavity with an oxidized AlAs current aperture and two or three $In_xGa_{1-x}As$ / GaAs quantum wells placed in the intrinsic region of the *p-i-n* laser diode. The membrane is composed of a gold reflector/electrode on top of a $SiO_x/SiN_xH_y/SiO_x$ phase-matching layer and GaAs quarter wave layer. The metal reflector can be replaced with a dielectric mirror for better reflectance, but the reduction in conductivity adversely affects the tuning voltage [Harris and Sugihwo 1996]. The bottom mirror is a DBR centered near 970 nm. The top mirror is a distributed structure which is composed of the membrane, air gap, and semiconductor air interface. These VCSELs have been operated with a 0.34 mA threshold current at 6.5% quantum efficiency [Sugihwo et al. 1997].

5.c. Polymer LED's and Lasers

Recent advances in thin film polymer optoelectronics have demonstrated that an efficient and versatile emitter material is available for photoluminescence applications. This class of polymers is represented by a π-conjugated polymer known as poly(p-phenylene vinylene), or PPV, and its derivatives [Diaz-Garcia et al. 1997, Wei et al. 1997]. PPV polymers are reported [McGehee et al. 1997] to be compatible with silicon substrates. Some polymers, such as DOO-PPV, have even shown superradiance [Frolov et al. 1997]. The group of polymer materials exhibits many of the properties needed in a good lasing medium, including low excited-state absorption in the photoemission spectral region, high quantum efficiencies for stimulated emission and high photo luminescence quantum efficiency. These materials might provide the active material for both LED's and lasers in diverse geometries.

Integrating polymer materials onto silicon substrates is the crucial process that will determine how well these polymers perform in MEMS applications. LED's are typically configured as a sandwich where the active region is between the electrodes. This structure requires that the LED emit its light either perpendicularly through one of its electrodes or transversely from between its electrodes. A thin transparent conducting layer of indium tin oxide is commonly used as one electrode. A significant problem in LED production is the need to lay down the active material before the last processing step. This exposes the active material to the potentially harmful materials and environments of subsequent processes. With the planar configuration, the electrodes are patterned on the substrate and then the active material is laid down. Using this process, planar polymer micro-LED's have been reported [McGehee et al. 1997]. The electrodes for these devices were fabricated using photolithography. The polymer was then applied using a spin casting technique. The electrodes were aluminum and gold, and the device showed reasonable I-V characteristics. The electrode spacing was fixed at 0.41 μm, resulting in a 35 V threshold for turn-on at room temperature.

Polymer lasers require some sort of optical cavity to provide the feedback necessary for lasing. Recent research has investigated two general configurations [Diaz-Garcia et al. 1997, Diaz-Garcia et al. 1997]. Microcavity lasers were constructed with a DBR mirror, polymer layer and silver top mirror. This arrangement was optically pumped and exhibited gain narrowing above the lasing threshold. Waveguide lasers were made with a variety of polymers in various active/cladding layer combinations. These structures also exhibited gain narrowing with a well-defined threshold.

A barrier to the use of polymer lasers with MEMS is the application of the polymer. Most of the literature reporting electroluminescence in thin film PPV polymers used material that was deposited via spin coating. This process will apply the polymer to the entire surface of the substrate and therefore a suitable masking and selective etching process will need to be developed.

6. Optical MEMS: Waveguide Optics

Fiber optic technology is an integral and indispensable part of integrating MEMS devices to the outside environment. Fibers are used to optically connect illumination sources to MEMS chips, as well as connecting optical signals that will be analyzed by MEMS sensors. Both single mode and multimode fibers are used for such connections. Coupling lasers and other single wavelength devices to MEMS chips is best done with single mode fibers. However, the alignment tolerance with single mode fibers can be challenging. Multimode fibers are better suited to incoherent, multi-spectral sources such as ambient light or emission spectra from some illuminated samples. Both types of fibers can be used for interconnections.

Planar waveguides have been implemented in a variety of MEMS devices [Tabib-Azar and Beheim 1997]. Straight and curved geometries, signal splitters, mixers, phase modulators, and spectral filters have all been investigated. Planar waveguide manufacturing processes, and the devices they produce, are critical to some optical MEMS, and will be a focus of this section.

Achieving and maintaining high coupling efficiency between fibers, sources and detectors is the key technical challenge. The most basic (and least efficient) method of coupling a fiber to a waveguide is to point the polished end of a waveguide at the cleaved end of an optical fiber. This implementation has inherently high Fresnel reflections at the waveguide-air interface. Optical index matching fluid can be applied at the junction to mitigate the problem, but this will not naturally match waveguide mode structures. Index matching fluid would also tend to slow mechanical fiber switching. Fiber alignemnt with micromachined structures is also reviewed in this section.

6.a. Planar Waveguides

Planar waveguide construction in MEMS can be categorized into two general types. First, the integration of $Si_3N_4/SiO_2/Si$ or doped $SiO_2/SiO_2/Si$ waveguides on silicon chips provides platforms for creating a variety of sensor and communications devices [Tabib-Azar 1995]. This strategy is very amenable to on-chip electronics integration. These structures can also provide preform masters for replicated polymeric waveguides. In the second category are waveguides that use polymeric materials. These devices may be constructed by LIGA [Bauer and Ehrfield 1997, Gerner et al. 1995], embossing [Dannberg et al. 1993], spin casting [Tomiyoshi et al. 1997], and injection molding [Baraldi et al. 1993] techniques.

Waveguides that are grown on the silicon chip can be made in a variety of ways. Flame hydrolysis deposition (FHD), chemical vapor deposition (CVD), and plasma enhanced CVD (PECVD) are all methods of growing materials on silicon. The index of refraction on these layers can be tailored by doping with various materials (i.e., germanium, phosphorus, nitrogen, arsenic, silicon, titanium, fluorine) [Vogus and Hoffmann 1996]. Adjusting the physical and optical characteristics of the layers affects their guiding properties. Silicon itself can be differentially doped and act as a waveguide. Doping usually lowers the refractive index, so the doped areas are typically the cladding of the waveguide while the undoped areas act as the core. Suitable masking will determine the geometry of the waveguide. This type of waveguide construction limits the transmission window to between 1.2 and 1.6 µm.

An interesting implementation of the waveguide idea is the Anti-Resonant Reflecting Optical Waveguide (ARROW) structure [Nathan and Benaissa 1996]. Conventional waveguides use the large index mismatch between the core and cladding materials to provide total internal reflection for the guided wave. The ARROW structure is a slab waveguide. It employs anti-resonant reflection, which allows for low index waveguide materials to be used on high index substrate materials. The technique employs materials and processing methods that are compatible with typical MEMS processing. ARROW waveguides offer a variety of advantages including low losses, simple fabrication, and efficient coupling to fibers.

Grating structures written into the fiber or waveguide can provide a means of spectral selectivity. These waveguides can be tuned with stress [Shibano et al. 1997], heat [Shibano et al. 1997], and other physical means. These tuning mechanisms can all be effected via MEMS technology.

6.b. Planar Mixers and Switches

Waveguide structures used in switching applications fall into two general categories. Waveguides can be physically translated [Ollier et al. 1996], or they can exploit physical coupling techniques to switch optical signals. Mixing optical signals can be accomplished by using close proximity and collinear waveguides, that couple signals via evanescent waves [Chollet et al. 1996], and by mode coupling [Choo et al. 1994]. Simple patterning of waveguides has been used to create signal mixers and splitters by making "Y" structures. A good example of this is the multimode waveguide structures created via LIGA processes [Bauer and Ehrfield 1997].

A mechanical method of moving fibers may be the most intuitive method of switching a signal propagating down a fiber. In a very simple system, an optical fiber switch could be the transmit-receive selector for fiber-to-home applications. Mechanical switches have been made and actuated with thermal [Field et al. 1996] and electrostatic [Ollier et al. 1996] methods. These non-resonant methods have switching times on the order of 1 ms, and thus are only suitable for configuration switching. Alignment and insertion losses continue to be the critical issues in developing these types of devices. V-grooves and spring clamps are common solutions to the alignment problem. Cutting the fiber ends at an angle will also reduce the Fresnel losses.

6.c. Input and Output Fiber Alignment

Optical fibers provide an excellent conduit for getting optical signals on and off optical processing modules. The technical challenge for optical MEMS is how to do this task cheaply, efficiently, and in batch quantities. The most significant challenge in this area is coupling the fiber to waveguides, lasers and detectors. The simplest way to accomplish this is to use passive alignment techniques. A V-groove, anisotropically etched [Strandman et al. 1995] into a silicon substrate, can provide a very simple passive alignment tool for optical fibers [Walko 1995]. Various methods for maintaining fiber position in the groove have been demonstrated [Daneman et al. 1996, Strandman and Backlund 1997, Strandman et al. 1997]. The SEM shown in Figure 20 is a silicon substrate with three etched V-grooves. Each V-groove has a different fiber clamp configuration. A fiber is shown in the right-most V-groove. A multi-fiber ferrule has been developed using LIGA techniques and V-groove alignment [Gerner et al. 1995]. The ferrule is capable of using both active and

Figure 20. Three fiber V-groove clamps with one holding an optical fiber.

passive alignment methods. This passive alignment method can be modified to an active mechanism by using electrostatic actuators to position the end of the fiber [Kikuya et al. 1993]. Another method of actively aligning a fiber in a groove is to use a movable mirror as an alignment tool [Daneman et al. 1996].

Some interesting work has been done in passive alignment using flip-chip mounting techniques [Ahfeldt 1997]. Fibers are mounted in a silicon carrier chip with V-grooves in the standard way. A laser diode array is then attached to the carrier via solder bumps. As the bumps melt and subsequently solidify, surface tension in the solder will align the array chip to the fiber carrier with repeatable accuracy of ± 2 µm. Critical alignment of the inter-element spacing is done photolithographically. The solder bumps perform the final package alignment. The silicon carrier and completed package is shown in Figure 21.

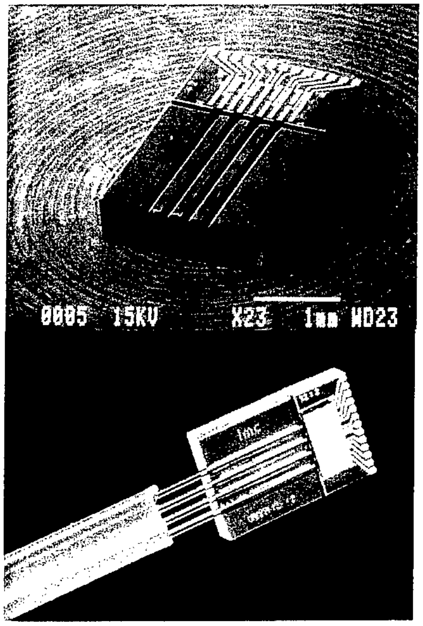

Figure 21. The silicon carrier for the laser diode array , with the fiber alignment grooves, is shown on the left and the completed assembly with the fibers and laser module is shown on the right.

7. Optical MEMS: Free Space Optics

Free space micro-optical devices can be defined as having an area on the chip where an optical signal travels in the open air or some other gaseous ambient, in which beam-atmosphere interactions are small. Free space designs have the inherent advantage of a high index mismatch between the optical material and its surrounding. This characteristic is beneficial in refractive and dispersive elements. Optical MEMS that are small (relatively speaking) will not function well refractively due to diffractive effects. Lenses need aperture sizes of at least 5-10 times the wavelength to operate as refractive elements and an order of magnitude greater in order to operate with high performance. An excellent example of how free space optics can be integrated into MEMS is the micro-translation device shown in Figure 22 [Fan and Wu 1997]. This actuator enables the precise, three-axis, positioning of optical elements. Positioning elements like this will enable both "set and forget" and feedback-controlled optics positioning.

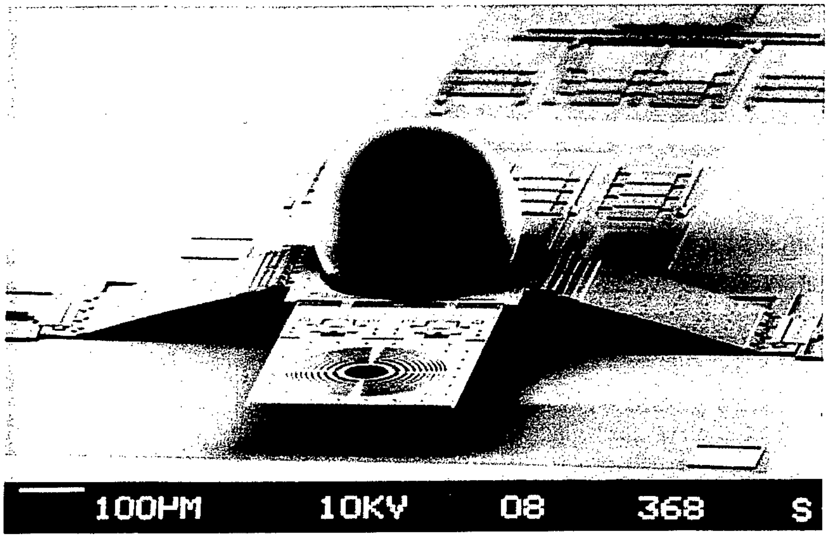

Figure 22. Micro-ball lens and Fresnel lens on a 3-axis translation platform.

Free space optical components can be loosely classified into two categories, elements that need to be elevated to operating level and those that do not. Good review articles are available on these types of devices [Motamedi 1994, Motamedi et al. 1997]. Some vertically-integrated optical elements are fabricated by surface micromachining in the horizontal plane using common lithographic techniques. After release, these elements are pushed into the vertical position via linear microvibromotors. Many methods of elevating and latching free space optics are being developed [Chu et al. 1997, Tien et al. 1996].

This discussion of free-space micro-optics could be organized in different ways. We employ the basic physical processes as the organizing principle. Transmission and reflection optical MEMS are reviewed first. Both depend on beam-surface interaction. Then devices using diffraction and interference are surveyed. Both of these methods employ phase-sensitive, free-space interactions of optical beams. A good reference book on micro-optics is available [Herzig 1997].

Surface finish is of utmost importance in MEMS optical design. Surfaces must transmit or reflect efficiently, that is, with little scattering. Chemical-mechanical polishing can be used [Yasseen et al. 1995] to obtain surfaces with RMS surface roughness values (R_a) of 17Å from a polysilicon surface with initial R_a=420Å. Some work has been done with magnetically-controlled reactive ion etching on flourinated polyimide. These surfaces can have very good optical properties after etching [Furuya et al. 1993] and are suitable for optical components. Surface production and modification in optical MEMS is a good area for development of new and versatile techniques.

8. Optical MEMS: Transmission Devices

Transmission mode optical elements are essential to micro optical systems. This set of devices is comprised of refractive lenses, optical spectral and spatial filters, beamsplitters, prisms, apertures and optical shutters. Each type of device can be made on the micro scale with essentially no degradation in utility. Some aspects of these devices, such as materials selection for spectral filters, can be challenging. The following subsections will cover the fundamental devices in each of these categories.

8.a. Refractive Microlenses

Lenses are an interesting component in the MEMS environment. Refractive lenses make up the bulk of the optical components in full-sized optical systems. They are typically cut from molded optical blanks and then polished to their final configuration. Standard MEMS manufacturing processes make this method all but impossible. Therefore MEMS production requires a new approach to manufacturing refractive lenses. Photolithographic techniques, followed by non-traditional optical processes, provide the ability to produce lenses that are extremely small.

Refractive lenses made from polysilicon work well at near-IR wavelengths. LIGA techniques provide a promising method for creating refractive MEMS lenses and have produced polymethylmethacrylate (PMMA) aspheric cylindrical lenses with near diffraction-limited beam waists [Gerner et al. 1995]. Beam waists of PMMA lenses have been experimentally determined as a function of the focal length of the lens. These aspheric cylindrical lenses have shown that they can approach the theoretical gaussian performance limit with surface roughness (R_a) of 30-40 nm [Gerner et al. 1995]. By using injection molding or embossing techniques, transparent optical materials may also be used to make optical elements [Bauer et al. 1994]. Simultaneous ion sputtering of two different targets has shown that graded index (GRIN) microlenses are possible [Sawada et al. 1994].

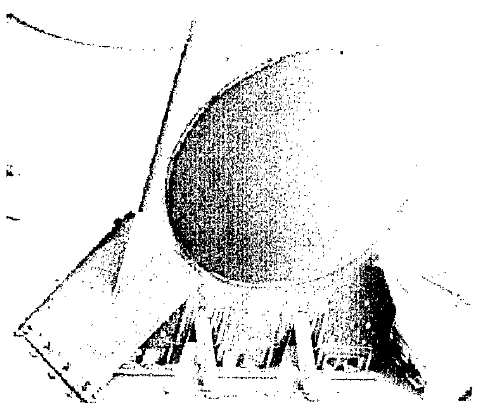

Figure 23. Refractive micro MEMS lens 300 μm in diameter. The lens is made with polymer reflow technology.

The structure in Figure 23 is a refractive lens, elevated in to the vertical plane [King et al. 1996]. It is based on Fresnel lenses that are described in section 10.2. This lens is similar in mechanical construction but has the diffraction-based Fresnel lens replaced with a photoresist material. The photoresist is spun on the substrate before the lens is elevated and latched into position. The chip is then heated to 200°F for 20 minutes to let the photoresist reflow into a spherical shape. The lens is 300 μm in diameter and has a focal length of 699 μm.

Refractive lenses have been made in the GaAs substrate of a bottom emitting VCSEL using reflow of photoresist and dry etching [Strzelecka et al. 1995]. These lenses, with radii of curvature ranging from 4 μm to 900 μm, and lens diameters of 10 μm to 200 μm, were used to collimate a 9 μm diameter beam to a divergence of 2.7° from a divergence of 12.5°.

8.b. Filters

Optical filters may have any number of characteristics ranging from varying spectral bandpass to spatial attenuation. These may be implemented in waveguides or as freestanding elements for free space propagation. Tunable filters that use physical motion as the tuning parameter are a logical choice for optical MEMS applications. A variety of methods are used to accomplish the goal. Most of them use some variation of a tunable Fabry-Perot cavity. Micromotors can be used to move the optical elements of the cavity [Lin et al. 1995]. Other schemes use electrostatic actuation [Raley et al. 1992] or external pressure [Miller et al. 1997] to deflect thin membranes. Some filters use magnetic actuation to provide the large range of motion needed in variable spacing waveguide filters [Cox et al. 1997, Cox et al. 1997, Ohnstein et al. 1995].

8.c. Beam Splitters

Beam splitters are an integral part of many optical systems. Free-space Michelson interferometers could not exist without them. The physics behind a beam splitter is rather simple. An optical beam is partially transmitted through a section of some thin material. The path of the transmitted beam is unaffected while the reflected beam is diverted by reflection at the first surface. Other types of beam splitters can be used if specific applications require them. One example of this is the half mirror in Sawada's micro-laser displacement sensor [Sawada et al. 1997]. This mirror was made using a differential index epoxy interface.

8.d. Prisms

Prisms are a very versatile optical component and will perform many tasks in optical MEMS devices. They may be used in total internal reflection mode to function as a mirror or optical coupling device. They can also be used as a dispersive element and function in a spectral dispersion function. These components may also be used to couple light into waveguides. Microprisms can be driven piezoelectrically to perform switching operations [Goring et al. 1996].

8.e. Apertures

Apertures are an essential element in many optic designs. They are easily manufactured and used in MEMS devices. Various shapes and sizes are possible. The particular challenge for MEMS designers is to make a variable diameter circular aperture. Some interesting work has been done on an automatically aligning aperture [Sasaki et al. 1997]. The aperture is integrated into the center of a quadrature of silicon photodetectors, as shown in Figure 24. The feedback from the detectors adjusts the X-Y position via shape memory alloy actuators. This type of integration is an excellent example of how optics and mechanics can work together to perform alignment.

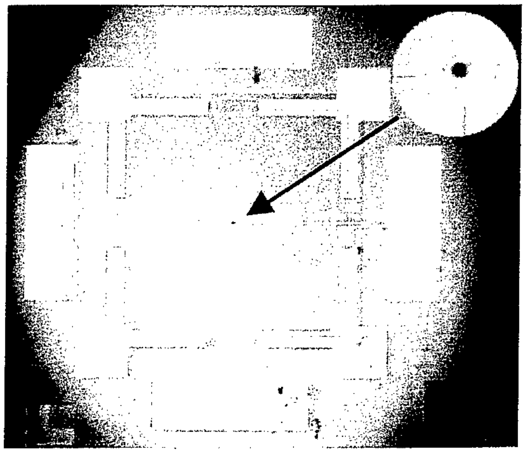

Figure 24. Four detectors are located in the four corners of the central square. The aperture of the self-aligning pinhole can be seen in the center of the quadrature and is also shown in the inset.

Spectrometers and optical isolators are two driving applications for apertures. Adjustable slits are the key to making miniature spectrometers. Spatial resolution and spectral resolution are both affected by the quality and repeatability of slit widths. Adjustable slits for spectrometer applications are reported in the literature [Kraiczek and Vuilleumier 1996, Vuilleumier and Kraiczek 1995]. Slit widths from sub micron to thousands of microns are easily attained.

Optical isolators employed in critical applications such as safe-and-arm devices for munitions require 100% certainty in their operation. Sandia National Laboratory coupled an optical isolation aperture to a mechanical lock. The mechanism requires the appropriate binary encoded electrical signal to release the aperture [Sniegowski 1997].

8.f. Shutters and Choppers

A shutter can be thought of as a one shot chopper, so these components may be considered together. Both devices provide optical control by physically blocking the optical path. A shutter is useful in shielding sensitive optical elements. A chopper can provide an AC component to a DC signal. Chopping is a key function of many optical systems. Optical micro-shutters have been reported [Jaecklin et al. 1993] with displacements on the order of 10 μm. Optical MEMS choppers operating at a frequency of 2.4 kHz have been demonstrated [Toshiyoshi et al. 1994]. These devices are capable of chopping a 50 μm diameter laser beam. Different resonant frequencies should be attainable by redesigning the suspension elements. Chopping frequencies will be limited when using resonant structures. Low frequency devices are especially challenging because of the high frequencies of small, stiff structures. A device that addresses both of these challenges is a fiber optical gate switch developed at NTT [Uenishi et al. 1997]. The switch uses a torsion bar to provide the return force for an electrostatically-actuated cantilever. Nickel micromachining was used to produce a low cost, high performance optical chopper.

9. Optical MEMS: Reflection Mode Devices

Mirrors are perhaps the most critical component for optical MEMS technology. They are used to modify the optical path on the chip, couple light in and out of optical fibers, and to redirect light in image formation devices. Without mirrors, optical devices would be largely constrained to coaxial light paths. The ability to reflect light makes a true micro-optical bench a reality. One of the challenges for MEMS designers and process engineers is to provide designs that are compatible with the standard IC process. An optical quality reflective layer was never used in the standard IC process, nor was a sacrificial etch. These processes must be integrated into the existing IC process in order to provide the most cost-effective method of production of optical MEMS.

Mirrors come in a wide variety of implementations in the MEMS environment. Some devices use the thinnest possible membrane for actively deformable mirrors [Mall et al. 1997], while others involve double coating the substrate with a metal layer for stiffness [Buhler et al. 1996]. They can be etched into the substrate, with reflection from bulk surfaces, or made as vertical freestanding structures, as described in the section on free-space optics. Etching substrates along crystalline planes with either wet or dry processes can achieve optical quality surfaces. These surfaces can be used as-is or coated with other materials to enhance their optical characteristics. Total internal reflection mirrors can be made in waveguide optics, if the light is incident at a shallow enough angle. This angle can be increased if the outside of the waveguide material is coated with a higher index material [Sawada et al. 1994].

9.a. Reflective Surfaces

The principles of optics dictate that when light is incident on an interface between two materials with different indices of refraction, some of the light is reflected. Surfaces of mirrors can be made from any materials where differential indices of refraction can be achieved. Surface quality and surface figure, in addition to the reflection coefficient, are the three most important characteristics to consider.

High quality mirrors require surfaces of optical quality. Good surface quality is quantified by the surface roughness. Root mean squared (RMS) surface roughness is measured with a variety of non-contact optical and stylus methods. Values that are at least two, and usually three orders of magnitude less than the operating wavelength, are considered acceptable. Such surface finishes must be achieved with techniques that do not require contact polishing. Surface figure defines how well the overall surface conforms to the desired form. A typical mirror in a laser laboratory has $\lambda/10$ or "tenth of a wavelength" deviation from the designed surface figure. Reflection coefficients of 99% are routinely achieved via a variety of methods on commercial macroscopic laser mirrors.

While these types of surface characteristics are routinely available in macro-optics, they can be challenging to fabricate in micro-optics. Many different processes are used for optical MEMS, and each device must be designed with the required processes in mind. There are always tradeoffs when deciding how good the optical surfaces must be and what processes can be used to fabricate the whole MEMS device. The majority of the optical surfaces used in MEMS for either external or internal reflection fall into three categories. In one, uncoated surfaces will reflect some light because of the index of refraction mismatch between it and the air that surrounds it. This type of Fresnel reflection is used extensively. Secondly, surfaces are sometimes coated with a metal to increase this type of reflection. Thirdly, it is sometimes convenient or necessary to use a multi-layer approach to enhance the reflection. This technique is used extensively for macro-optics by applying many layers of dielectric material to the surface of a mirror substrate. Growing many thin layers of different materials such as GaAs/GaAlAs in alternating layers can give the same effect. Each of these three basic approaches is discussed in the following subsections.

Bare Silicon. Silicon is the material of choice for optical MEMS mirrors as it is readily available in standard MEMS processes. The silicon surfaces can often be used "as-is" without additional treatment. The use of silicon can be a great advantage when coupling near infrared (NIR) light in and out of fibers. Its anisotropic etching characteristics can be exploited to align fibers and make mirrors.

One of the most intuitive applications for a bare silicon mirror is the bulk micromachined V-groove with a (111)-oriented end mirror [Strandman et al. 1995]. This technique uses an anisotropically etched V-groove, defined by the (111)-plane, on an off axis cut (100)-silicon substrate, to act as the optical alignment aid for an optical fiber. A fiber is placed into the groove and secured with adhesive. The end of the groove acts as a mirror and reflects the light perpendicular to the substrate where it is accessible to other optical components. Several efforts have been reported using similar techniques. The major difference between these efforts is the crystallographic orientation of the substrate. While some researchers have concentrated on using 9.7°, off-axis-cut silicon so that the mirror angle is 45°, others have used a standard wafer with (100)-orientation, which uses the natural 54.7° angle between the (111) and (100) crystallographic orientations. Work has been reported on using the (110)-orientation for a 45° mirror. These mirrors require precise alignment, yield a rougher surface than the (111)-planes, and are etch depth dependent, since the (110)-plane is not a natural etch stop like the (111)-plane. Several tradeoffs are made with the two approaches. Mirrors at 54.7° have several advantages including inexpensive materials, ease of fabrication, and inherent crystallographic symmetry. Their disadvantage is that the mirror angle is not symmetric. Mirrors at 45° have a "mirror image" of the advantage-disadvantage comparison. The 54.7° mirrors fabricated from standard (100)-wafers have a reflectivity of about 60% between 1.3μm and 1.5μm. Recent work has investigated the relationship between etch temperature, etch rate, and reflectivity [Sadler et al. 1996]. No relationship between reflectivity and etch temperature was found. As an example of how this V-groove technology can be applied to optical MEMS, a pressure sensor using the V-groove process has been reported [Chan et al. 1994].

Metallic Surfaces. Silicon can be coated with aluminum [Jaecklin et al. 1993], gold, or nickel using a wide variety of deposition techniques. Aluminum and gold are used extensively during integrated circuit production and, thus, are easily available for MEMS. They have been employed as high quality mirror surfaces for many years. The main characteristics that affect the quality of the mirror are the substrate surface roughness and the surface oxide on the metal itself. For standard mirrors, such as those found in optical laboratories, sputtering the metal onto the substrate is the last process step. For some MEMS devices, there are several processes after the sputtering is completed. These post-sputter processes typically include etching of sacrificial layers. Atomic force microscopy has been used to study the effects of post-sputter etching [Buhler et al. 1996]. These studies indicate that a wet etch in various solvents including water, acetone, and ammonium fluoride reduces the reflectivity of aluminum by less than 2% in the visible region and has no effect on reflectivity above 1 μm. The reduction in reflectance is attributed to a thicker oxide layer as determined by scanning auger spectroscopy. The aluminum layer used in the MUMPS (Multi-User MEMS Processes) has been replaced with gold, which is unaffected by the hydrofluoric acid release etching, has lower internal stresses, and makes wire bonding easier. Information on the MUMPS process can be found on the internet at "http://mems.mcnc.org/."

Device design can have some effect on whether or not a post-sputter etching process needs to be done. If the optical fill factor is high enough, the device can be etched before the sputtering process is performed and the mirrors will be untouched by etchants of any kind.

Differential-Index Multilayers. Multilayer dielectric mirrors are the standard in the optics industry for applications where wavelength specificity is a key issue. These mirrors are commonly referred to as Bragg reflectors or Bragg gratings. The thickness and index of refraction of the individual layers dictates the reflectance characteristics. It requires a few layers of material with a high index mismatch or many layers of material with a small index mismatch in order to achieve high reflectivity. For devices where conductors would adversely affect device performance, or where partially transmitting mirrors are needed, differential index multilayer dielectric mirrors are quite useful. This method of making a mirror is used extensively in the design of VCSELs.

A clever way of using a Bragg reflector with a large number of layers is to manufacture the substrate in a CVD chamber to the required specification and then build the MEMS device on top of it. This provides a simple way to incorporate a large number of layers into an optical device without complicating the mechanical release processes. The most common devices to use this technique are VCSELs. A true MEMS implementation of this design are the tunable VCSELs being designed at Berkeley [Vail et al. 1996] and Stanford [Larson and J.S. Harris 1996], as described in Section 5.2.3.

Bragg reflectors can also be patterned into the bulk material of optical waveguides in a variety of ways. Two-beam interferometry is used with UV-photosensitive materials such as germanium doped glasses [Campbell and Kashyap 1994]. This method actually changes the index of refraction within the bulk material. Surface machining can also be used to mill away trenches in the bulk material. Reactive ion etching is used in this manner to cut very precise trenches in the top surfaces of silicon waveguides. This pattern of silicon/air has a very high index mismatch so gratings with reflectivity as high as 98% have been made with as few as 12 trenches [Liu and Chou 1996].

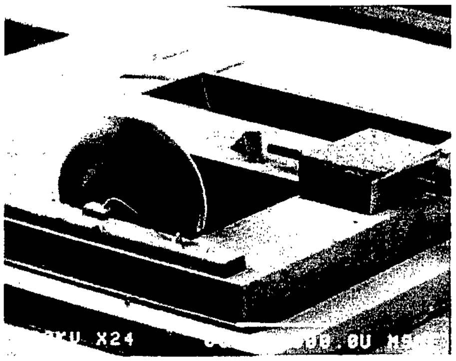

Figure 25. Single element micromirror implemented for active alignment of laserbeam to fiber.

9.b. Single Element Mirrors

Mirrors, regardless of their surface treatment, may be classified in two distinct categories, single mirrors and mirror arrays. Single element mirrors are intended to perform their function individually and in series. Typical uses for single element mirrors include redirection of light [Lin et al. 1996], laser end mirrors, Q-switches [Peter et al. 1996] and couplers for optical fibers. They are also used extensively in scanning applications.

One of the most effective uses of optical MEMS is to provide an active element to align lasers with fiber pigtails. Static methods of alignment are appropriate for some tasks, but in high-speed optical networks, coupling efficiencies of 30% or higher are required. As illustrated in Figure 25, researchers at the University of California at Berkeley have developed an active alignment micromirror that has two degrees of freedom [Daneman et al. 1996]. The laser is the small chip near the circular lens. It has a thin wire attached to the top for power. The lens focuses the laser onto the fiber that can be seen clamped into a block at the right of the figure. The micromirror is just off the end of the fiber and is the active element in the system. This micromirror is able to compensate for both vertical and horizontal misalignments. It has consistently demonstrated coupling efficiencies of 40%.

9.c. Mirror Arrays

The micromirror array has been an excellent showpiece of what is possible with MEMS. Both one-dimensional and two-dimensional arrays have been demonstrated, and are produced commercially. Arrays of micromirrors have attracted a great deal of interest because they are nicely susceptible to mass production by IC processing techniques and to integration with control electronics, which independently address each pixel.

A key feature of most micromirror arrays is the separation of the electronic, mechanical and optical structures, with electrostatic interactions between the electronic and mechanical features, and rigid mechanical coupling between the mechanical and optical structures. These characteristics are possible because of the availability of processes that involve multiple sacrificial layers and produce multiple layers of polysilicon structures. The MUMPS process, available at the Microelectronics Center of North Carolina, and the SUMMiT process, developed by the Sandia National Laboratory in Albuquerque, are primary examples.

Different functions can be performed by micromirror arrays. The simplest is steering beamlets to either continuously variable or discrete and predetermined angles in order to form images. This can be done either reflectively by tilting rotational mirrors, or diffractively by altering the phase with piston-style mirrors. The equations that govern the phase change (ϕ) and deflection angle (θ) are:

$$\phi = \frac{4\pi d}{\lambda} \qquad \Delta\phi = \frac{2\pi b}{\lambda}\sin\theta$$

The phase difference imparted by each element is determined by the distance (d) it is translated and the wavelength (λ) of normally-incident light. The angle of the diffracted light is determined by the adjacent element phase difference (Δϕ) and the pixel spacing (b), as well as the wavelength of the light. For arrays to operate with scan angles of ±30°, the translation distance must be at least 0.5 μm. Such phase manipulation can also be used to adjust the far-field pattern by correcting beam aberrations. In this case, the micromirror array serves as an adaptive optic. Employment of two mirror arrays in sequence, or one array with some other spatial light modulator, such as a liquid crystal device, permits optical correlation.

There are two ways in which the individual mirror elements in arrays are controlled. They can be thought of analog and digital in character. Mirrors in an analog array are deflected through a range of motion via a continuously-variable voltage, and can be used at any position within their range of motion. Mirrors in a binary mode arrays have an "on" state and an "off" state. The binary mirrors are typically electrostatically actuated to the on state and utilize springs or their own tension to return to the off state. Individual mirrors can be designed to behave in either continuous or discrete fashion. For some of their range, the electrostatic force can be continuously and controllably balanced against the elastic restoring force, permitting analog control. But, the electrostatic interaction is not linear, and the mirrors can reach a critical position, where they "snap through" to the substrate and are held in place by the electrostatic force. This binary behavior is reversible, but hysteretic.

The mirrors in arrays have two fundamental types of motion, tilt or translation. Arrays with tilting mirrors deflect light spatially by rotating the mirror surface relative to the plane of the array. The Texas Instruments Digital Mirror Device™ is an example of this style [Hornbeck 1997]. So is a new mirror array from Samsung Electronics Corporation, which uses a vertical spring for the restoring force [Koh et al. 1997, Lim et al. 1997]. Mirrors in a piston array move perpendicular to the plane of the array and shift the phase of the incoming light [Burns et al. 1997, Christensen et al. 1996]. Each technique has some unique device-specific characteristics. One drawback of the tilt array is that it imparts complimentary phase shifts to the light on each side of a given pixel. When the tilt array is used as a simple digital reflection device, this phase shift is not a problem. However, the phase shift can be detrimental in beam steering and adaptive-optics applications.

There are three main classes of elements in micromirror arrays, depending on the type of mirror motion and the degrees of freedom for each micromirror. In the first, the individual elements control the reflected light by rotation, that is, tilting about a single axis parallel to the plane of the array. In the second, there are two orthogonal, nearly in-plane rotation axes, which permit tilting in two directions. In the third class are mirrors that translate without tilting, in piston fashion, in a direction perpendicular to the array plane. Examples of each of these mirror types follow.

Burns et al. have designed and tested a linear array based on their variable blaze grating (VBG) design [Burns and Bright 1997]. This array, shown in Figure 26, contains 128 elements. Each element is 110 μm long and 27 μm wide, and tilts controllably about the long axis. The vertical range of each element is 2 μm. This array has the capability of being operated in either variable or binary mode. Each element can be pulled down 0.67 μm before snap through, and therefore can cover the entire visible range with a 2π phase shift. The maximum angle of deflection for this device is 1.21°. Its maximum efficiency was calculated 31.3% for an angle of 0.64°. This low efficiency is due to the relatively large width of the array elements, variations in the mirror surface topology, and the non-reflecting area between the elements. Modeling of an improved array indicates that efficiencies can be improved to 63% at 0.56°.

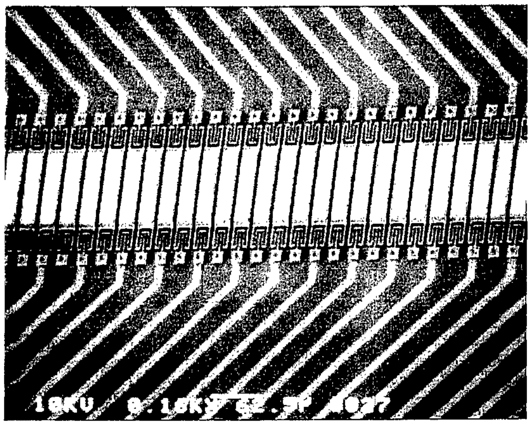

Figure 26. Linear mirror array for beam steering. Each element has independent piston motion for phase control of a beam in one angular dimension.

Piston arrays have the unique capability to maintain a flat surface while adjusting the phase relationship between different parts of the beam. Such arrays can be used as a beam steering device, or adjust the far-field mode pattern, or provide beam aberration corrections. Binary mode and variable mode piston mirror arrays are both capable of beam steering. Figure 27 is a micrograph of one type of piston array [Comtois et al. 1998].

Mirror arrays, in which the elements can rotate about either of two axes, permit control of the reflected beamlets within a solid angle. A micrograph of such a device is shown in Figure 28 [Michalicek et al. 1998]. The two diagonal axes form an "X" shape in the center of each pixel. The surrounding four electrodes can be biased independently to point each micromirror in any direction within the range of motion permitted by the structure, material properties and voltages.

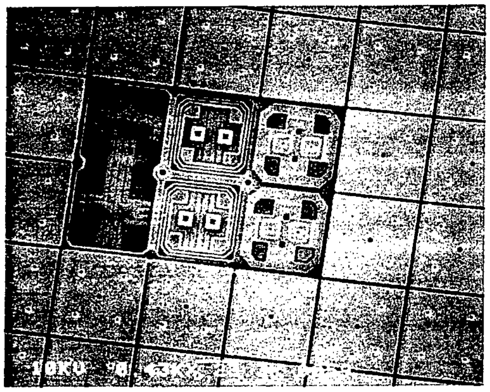

Figure 27. A piston micromirror array in which the individual mirrors translate only along a normal to their surface.

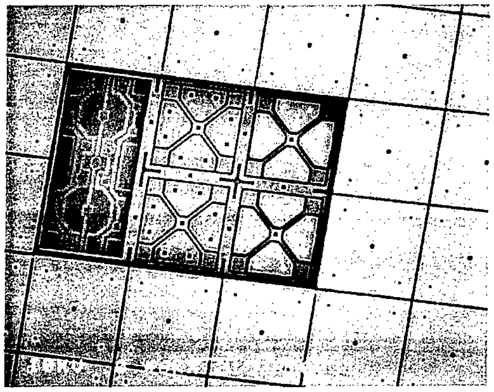

Figure 28. Pixels in a mirror array in which the individual mirrors tilt in two directions relative to their normal.

Some of the applications of mirror arrays are reviewed in Section 15. They include spectral correlation, phase correction of optical images, information display and printing.

10. Optical MEMS: Diffraction Mode Devices

Diffraction is the phase- and amplitude-sensitive interference of the components of an optical beam after they interact with a structure that modifies the beam. Diffraction effects are both a hard design limitation and a valuable asset for optical MEMS. The design limitation imposed by diffraction effects will be encountered when the dimensions of the optical elements approach the size of the incident wavelength. There are three types of optical MEMS that exploit diffraction. Microlenses, in which thickness differences produce phase differences across a beam, which affects its pattern, are the first. Fresnel zone plates, which break a beam into circular elements that interfere with each other, are the second. Gratings, the beamlets from which interfere to produce spectrally-sensitive patterns, are the final type of element. These diffractive optical MEMS are discussed in this section.

10.a. Diffractive Microlenses

Refractive lenses require a substantial curvature (thickness of material) to produce a focused beam. This can be difficult to integrate into a standard MEMS design without using polymer reflow technology. Diffractive microlenses eliminate the need for a “thick” lens, and therefore they are very useful for MEMS designed to operate as planar systems. The photolithographic patterning employed to make diffractive microlenses is also well suited to MEMS. Diffractive lenses have broad application in non-MEMS devices. The development of this technology for these applications has resulted in a large, and growing, literature.

The simplest diffractive lenses have only two levels, so they are called binary optics even though such devices are commonly made with many more levels [Swanson 1989]. The tight tolerances required to produce high quality binary optics necessitate the use of photolithographic techniques naturally suited to integration with MEMS. Binary optics can be created in two distinct ways. In the first, thin film deposition and material lift off methods are used to build up a diffractive lens. This approach has the advantage that the deposition process can very precisely control the step dimensions. The second and most common way of making a binary diffractive optic is to use multi-mask-level photoresist patterning with interleaved RIE to remove material from a bulk substrate. This method will create a multi-level pattern in the bulk material that represents a kinoform surface. A theoretical efficiency of 95% can be achieved if a three-mask process is used. Each mask will double the number of phase levels per zone, so the number of phase levels goes as 2^n, where n is the number of mask layers. Some work has been done recently on a single mask, using anisotropic etching of (100) silicon [Chung et al. 1997]. Both on-axis and off-axis diffractive lenses have been demonstrated [Du et al. 1995]. Off-axis lenses have diverted beams by as much as 20°.

Binary optic microlenses can be characterized by three parameters; wavelength (λ), f number (f), and smallest processing dimension (Δl). For an eight level binary optic microlens [Motamedi et al. 1992], the smallest processing dimension is:

$$\Delta l = \frac{\lambda f}{4}$$

Substituting a approximate value of 0.5 μm for the smallest processing dimension and assuming a wavelength of 0.85 μm, lens speeds of f = 2.4 can be attained in a typical optical MEMS application.

Various methods of trying to increase the fill factor of MEMS optical arrays have been demonstrated. The Texas Instruments DMD puts the mirrors on pedestals and all of the electronics underneath. Other mirror arrays have springs that wrap around the outside of the mirror. These are mechanical solutions to a problem that can be solved optically. Micro-concentrators can be used to increase the fill factor of an optical array [Farn 1992]. These concentrators effectively collect light from the entire image surface and focus it onto the active photo elements below. Such concentrators can be made with either refractive or diffractive microlens arrays.

10.b. Fresnel Zone Lens

Fresnel zone lenses can function as focusing, collimating, and beam steering elements. They can be implemented in a planar device by manufacturing the lens in the plane of the substrate and then elevating it into a vertical position, as illustrated Figure 29 [Lin et al. 1995]. The focal lengths of Fresnel lenses can be tested before they are raised into their vertical position by analyzing reflected light [Bright et al. 1997].

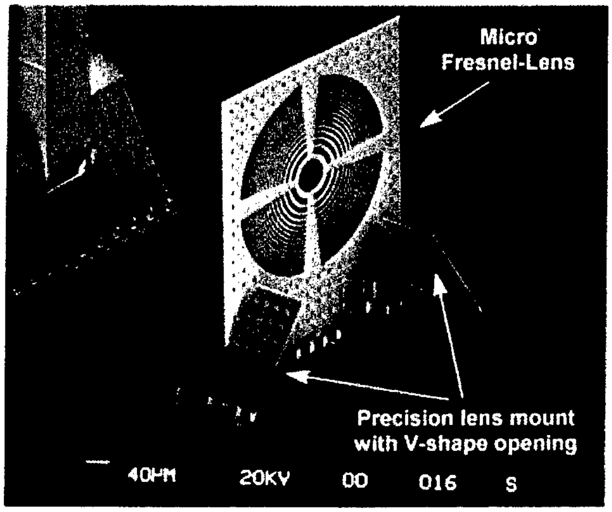

Figure 29. Erected Fresnel zone plate lenses, with an edge-emitting laser seen in the background.

Recent research has produced a switchable lens [Ferstl and Frisch 1996]. Glass plates were etched with a Fresnel pattern and then coated with a thin layer of indium tin oxide for electrical contacts. The channels were then filled with a nematic liquid crystal material. In the non-activated state, the liquid crystal material is oriented perpendicular to the incident light and the Fresnel pattern is active. To change the Fresnel pattern into its "clear" state, an AC voltage is applied so that the liquid crystals orient parallel to the incoming light, and the device appears transparent to the incoming light. This technology, while not specifically MEMS, may be adapted to function as part of an optical MEMS chip.

Lens arrays are also possible and can be used for laser diode arrays and optical interconnections. Figure 30 is an example of an array of Fresnel lenses fabricated by surface micromachining of silicon [Bright et al. 1996]. An inherent advantage of this type of array is the lens placement is very accurate due to the photolithographic patterning process. The utility of such lens arrays is just being realized, and the future applications for high-power laser diode arrays should be important. Even non-coherent IR sources have been collimated using zone plate lenses [Bauer et al. 1996].

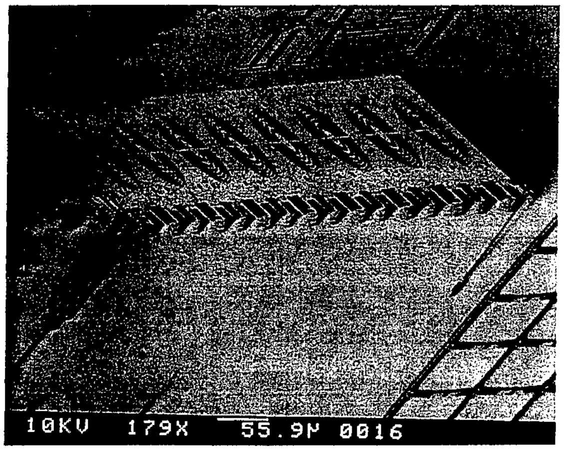

Figure 30. Fresnel zone lens array.

10.c. Gratings

Gratings are dispersive optical elements and will be a key component for many systems incorporating optical MEMS. Gratings can be used to separate incoming radiation into its components, or as a method of redirecting a single wavelength [Yasseen et al. 1995]. Precision gratings can be produced in MEMS with sub-micron accuracy. They can also be replicated with injection molding techniques. Gratings can be written into materials via standard two-beam interferometry techniques. High reflectivity gratings (80%) have been fabricated in germanium-doped glasses via two beam UV interferometry [Campbell and Kashyap 1994]. Gratings can be used in dynamic sensor devices by placing them where the period of the grating is affected by the motion of a mass or diaphragm [Storgaard-Larsen et al. 1996].

Coupling the mechanical action of MEMS and the small feature size of a visible wavelength grating has lead to the idea of a variable grating. This type of grating is an excellent candidate for modulating optical signals. Sene et al. have designed and tested actuated gratings that can direct light through the first three diffraction orders [Sene et al. 1996]. They have built two different gratings. The gratings are comprised of two etched silicon plates that have complementary comb structures. The vertically actuated grating uses electrostatic forces to pull an interdigitated comb toward the substrate. The horizontally actuated grating employs thermal actuation to translate one comb structure over another stationary comb structure. These devices were tested with a bare silicon surface, but a metal coating could be applied. The gratings acted as a single optical element, because individual areas of the grating were not independently addressed.

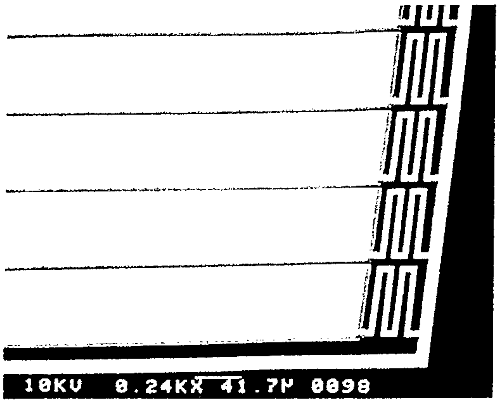

Figure 31. Variable blaze grating with torsional hinges at the end of each element.

Actuation on the scale of microns leads to the ability to control the grating surface itself. Continuous control of the grating pitch enables a variety of new, tunable devices. Burns has developed the variable blaze grating (VBG) shown in Figure 31 [Burns and Bright 1997]. Three different VBGs were produced and three different parameters were investigated. Electrostatic and thermal actuation were demonstrated. Grating elements that rotated about a central axis, as well as elements with one fixed edge, were fabricated. Typical grating slat dimensions were 58 μm x 2.3 mm with a 2 μm spacing between each element. The thermally actuated devices were used to steer a HeNe laser over four diffractive orders for a total deflection of 1.7°.

Electrostatically-actuated gratings rotated about a central axis were used to deflect a HeNe laser over six diffractive orders for a total deflection of ±2.5°.

The gratings made by Burns were fabricated using the MUMPS process [Koester et al. 1996]. The aspect ratio of the grating elements combined with the disparate physical characteristics of the polysilicon and gold resulted in buckling of the slats after the release etch. This effect can produce a concave surface with a 500 nm peak-to-valley curvature over a 100 μm slat. Various methods are being developed to address this problem [Burns and Bright 1997]. The most effective solution to date is a trapped oxide layer between two polysilicon layers. This method of balancing the mechanical stresses reduced the peak-to-valley curvature by 87% [Burns et al. 1997]. Driving the thermal actuators to their critical point can cause a shrinking in the length of the actuator. This is known as "back bending" of the thermal actuators [Comtois and Bright 1996]. The effect may impact the number of useable diffractive orders for the thermally-actuated devices. Diffraction efficiencies of over 50% have been achieved with these devices. Such gratings have a very high fill factor. For active areas of 5-7 mm^2, optical power handling has been estimated at over one watt for 632.8 nm light [Burns and Bright 1997].

11. Optical MEMS: Interference Mode Devices

Interference methods are a valuable tool in the MEMS environment. They provide a unique way of measuring spectral variations, a powerful tool for measuring small displacements and an interesting method of switching optical signals. The general method for interference techniques is to separate an optical signal into two components, influence one of the signals, and then recombine the individual components to form interference fringes [Jenkins and White 1957]. The Fabry-Perot method uses a single beam, but with multiple reflections to achieve the same result. The Mach-Zehnder and Michelson configurations split the incoming beam into the measurement beam and the reference beam, prior to beating them against each other.

11.a. Fabry-Perot

Fabry-Perot devices are natural candidates for optical MEMS due to their mechanical configuration and their need for precise optical alignment. The small longitudinal dimension of the cavity is an excellent match for the low coherence length sources, such as LED's, that can readily be integrated with MEMS. The precise spacing of the mirror surfaces is a critical factor and can be achieved via active alignment or via design considerations [Kim and Neikirk 1996]. New devices being designed at UCLA, like the one in Figure 32, show the fascinating possibilities of implementing a variable Fabry-Perot cavity. This device consists of two partially reflecting mirrors that are placed between the ends of two coaxial fibers. As the distance between the mirrors is adjusted the cavity is tuned to a particular wavelength.

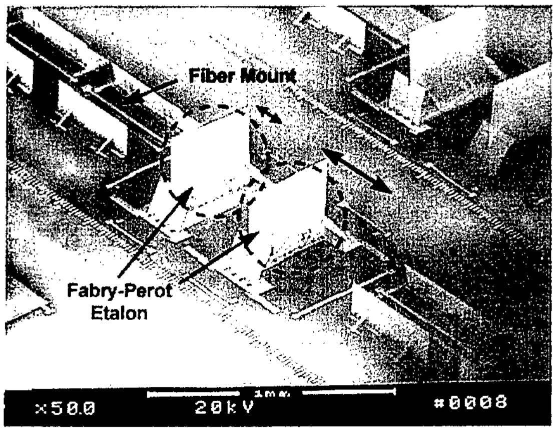

Figure 32. Variable Fabry-Perot cavity placed between two fiber alignment structures. Cavity adjustment is made via movable etalon.

Translation of the mirrors is not required to make a Fabry-Perot cavity. The rotation of a flat plate will effectively change the optical path length and tune the cavity. One implementation of this technique is illustrated in Figure 33. Lin et al. have coupled a rotation stage to an etalon to create a tunable optical element [Lin et al. 1996]. This device has a tuning range of 45 nm through an angle of 70°. They tested etalons coated with Au both with and without a high reflection dielectric coating. Cavity finesses values were 11 and 4.1, respectively. The ability to rotate optical elements with precision is extremely important to the development of optical MEMS. It will enable alignment of optical

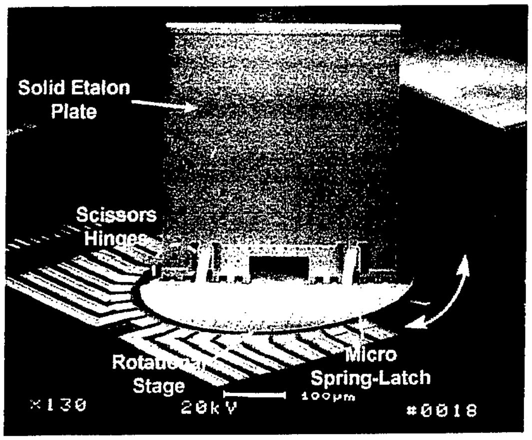

Figure 33. Etalon on a rotating platform.

elements for both rough optical alignment and for more delicate dynamic operations such as feedback control loops.

More complex designs, such as the Mechanical Anti-Reflection Switch (MARS) [Walker et al. 1996, Walker et al. 1996], will give better performance, and also permit these devices to be used as optical modulators for data communications. The MARS relies on optical interference to block the light from a fiber. It is a very simple device that consists of a silicon substrate with a suspended dielectric optical window. The light is incident on the window, as shown in Figure 34, and either passes through or is reflected. The activation method for the switch is electrostatic deflection of the window. The spacing between the window and the substrate is tailored so, in the relaxed state, the window, air-gap and substrate form an efficient reflector. In the activated state, the membrane is pulled down so the window, air-gap and substrate make a non-reflecting optical element. A change in air-gap thickness of as little as $\lambda/4$ will switch states. Because the required deflection is so small, the MARS is capable of data rates greater than 2 Mbytes/s. MARS optical modulators have significant potential for applications in consumer fiber networks, specifically fiber-to-home applications.

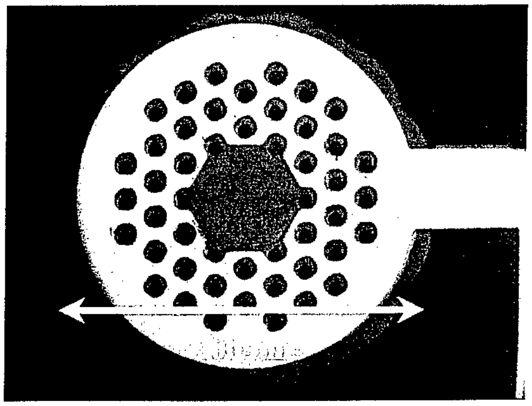

Figure 34. MARS device with the optical window in the center.

11.b. Mach-Zehnder

Mach-Zehnder interferometers may be used to switch, mix, and modulate optical signals. This type of micro-interferometer uses a dual path for the light beams, but does not use a conventional beamsplitter. Its configuration lends itself to planar waveguide implementation. Figure 35 shows a schematic diagram of a Mach-Zehnder interferometer implemented as a planar waveguide structure. This type of interferometer is an excellent match for MEMS because the insulator waveguides can be deposited on a silicon substrate. The interferometer can be used as a pressure sensor by inducing mechanical strain in the substrate below the sensor arm [Benaissa and Nathan 1996], or as a chemical sensor in which the analyte will be adsorbed onto the sensor arm and affect its refractive index [Kherrat et al. 1996]. Optical signals may modulated by perturbing the reference arm via surface acoustic waves [Bonnotte et al. 1997]. The interferometer can also be implemented completely in silicon if the appropriate wavelengths are used. In this configuration, the interferometer can be used as a sensor by injecting electrical carriers into the sensor arm [Zhao and Li 1995].

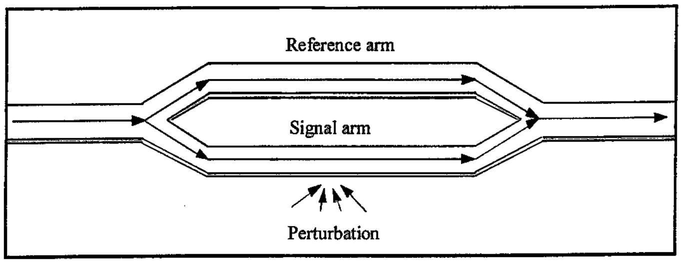

Figure 35. Schematic of a Mach-Zehnder interferometer implemented in a planar waveguide configuration.

11.c. Michelson

The Michelson interferometer is best suited for non-contact measurements of the displacements of either macroscopic or microscopic objects. The reference beam can be completely contained on the chip while the measurement arm of the interferometer goes into free space. The coherence length of the laser source limits the length of the measurement arm.

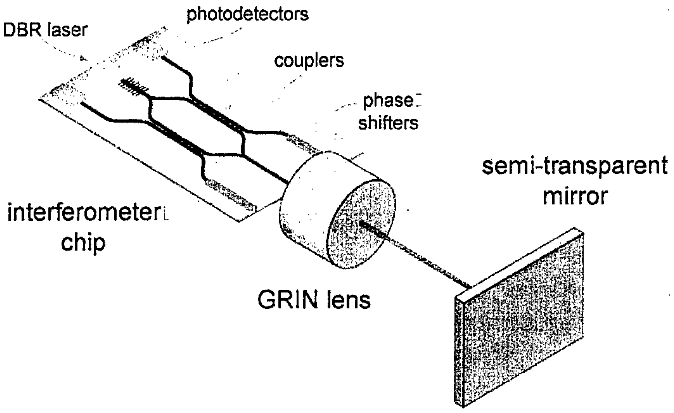

Figure 36. Schematic of Michelson Interferometer.

Hofstetter et al. has demonstrated a monolithically integrated double Michelson interferometer that can measure both displacement and direction of motion [Hofstetter et al. 1997, Hofstetter et al. 1994]. This device consists of two separate interferometers that use the same laser source. Figure 36 is a schematic representation of the device while Figure 37 shows the actual chip. The sensing beam is collimated with a GRIN lens. The device has a displacement resolution of 20 nm over measurement distances of 5 cm. Longer measurement distances yield decreased resolution. While this device was manufactured entirely out of GaAs and AlGaAs, other devices use polymeric waveguides. Sawada et al has fabricated a displacement sensor with an integrated optical microlaser on an AlGaAs substrate using fluorinated polyimide waveguides [Sawada et al. 1997]. Michelson interferometry can also be used as a non-contact method of measuring the displacement of micro-components.

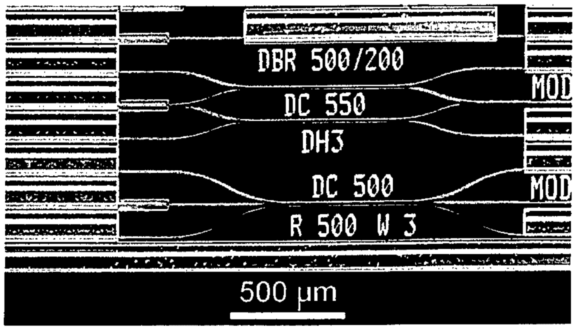

Figure 37. Micrograph of Michelson interferometer chip.

12. Optical MEMS: Detectors

MEMS detectors provide excellent performance for many types of environmental measurements. Their small size and batch fabrication makes them idea for distributed sensing applications. Silicon p-n junctions and PIN structures, which have been manufactured for many years, are highly compatible with MEMS. Such sensors have been used to detect spectral as well as temporal characteristics of incoming radiation. In conjunction with active filters, they can track and control illumination sources. Coupled with a movable diaphragm they have been shown to detect both pressure and temperature changes [Dakin et al. 1987, Halg 1992, Lee and Taylor 1991].

Many semiconductor and other materials, and diverse design technologies, have been employed for small detectors. The materials band gap primarily determines the long wavelength cutoff, while absorption commonly sets the short wavelength limit. Detector technologies fall into two broad categories. In the first, radiation absorption directly produces detectable electrons. In the second, radiation absorption produces heat, which then produces an electrical effect. Of all of these, photodiodes based on Si or GaAs, and bolometers made of Si, are the most germane to optical MEMS.

12.a. Photodiodes

Photodiodes are a natural sensor to use in MEMS devices due to the ease of integrating them into the MEMS production environment [Sawada 1995, Sawada et al. 1994]. Simple integration of both Si and AlGaAs detectors is straightforward, and will not be given much attention in this section. Semi-transparent detectors have been fabricated and characterized [Sasaki and Takebe 1997]. These detectors may have some applications in active alignment of micro-optics. Tunable detectors have been fabricated with tracking capability [Wu et al. 1996]. Such detectors are basically identical to the cantilever-beam tunable VCSEL discussed earlier, except they are operated in a resonant cavity mode. They can be employed in two different ways. By setting the cantilever to a specific position, the device can operate in a spectral tuning mode. This will enable the device to respond to a center channel wavelength with a bandwidth of 3 nm. In this approach, the extinction coefficient can be as high as 17 dB. Peak responsivity values were measured at 0.093 A/W. This mode of operation enables one device to detect a reasonably broad range of wavelengths. A 30 nm bandwidth has been demonstrated. The other operating mode is called tracking tuning. The device employs a feedback circuit to track the wavelength of a incoming signal. This device should be invaluable in communication links where wavelength drift is an unavoidable artifact of a system design. It could also be a simple and inexpensive way to measure the wavelength of emitter devices.

12.b. Microbolometers

Resistance bolometers are devices that transform photons into electrical signals via a thermal process. The absorbed photon is converted into heat that changes the resistance of the bolometer element. The resistance change is read out as a voltage. Arrays of these devices can be used to create images in the same way a CCD camera does. In the past, bolometers were operated at lowered temperatures to increase sensitivity. Micromachining technology has provided a way to thermally isolate the bolometer element from the substrate, so a micromachined bolometer may be operated at or near room temperature with adequate sensitivity.

Single element devices can be used in a variety of applications. The most attractive uses require small size, low power consumption and non-contact measurement techniques. A single element bolometer has been made [Mori et al. 1994] with a polysilicon Schottky-type thermistor, as well as a germanium thermistor. This sensor was developed for clinical use as a tympanic thermometer. The volume of the sensor chip was only 4 mm^3, so it fits the size constraints of the ear canal quite well. The bolometer element was designed as an air bridge device, and then vacuum encapsulated to reduce conductive heat transfer to the surrounding environment. Modeling was done on the mechanical suspension to optimize the air bridge thermal isolation. As is usual with the vacuum isolation process, lower pressures translate into better performance. The device was tested at a variety of pressures. It was found that 10^{-3} torr is the threshold for optimal operation. Recent work has incorporated a dual element design to compensate for the ambient thermal environment [Kudoh et al. 1996]. This device has a resolution of 0.1°C when used to detect the temperature of a tympanic membrane.

Polycrystalline silicon-germanium alloys have been used to make a single element, suspended, bolometer [Sedky et al. 1997]. Due to its lower thermal conductivity, this material has better thermal isolation of the absorbing layer than the more common polysilicon. Other materials such as $Si_{1-x}C_x$:H [Ichihara et al. 1997]and Ti [Tanaka et al. 1996] have also been explored for microbolometers.

The feasibility of bolometer arrays has been demonstrated. These arrays have been grown from amorphous silicon and germanium [Unewisse et al. 1995]. They exhibit a D* (detectivity) of 5 x 10^8 cm Hz ^{½} W^{-1}. Staring arrays need D* values near 1 x 10^9 cm Hz ^{½} W^{-1}. A significant addition to the bolometer design is the implementation of an integral optical cavity in the bolometer element [Liddiard 1993]. These three-layer designs can increase the thermal absorption of a thin film bolometer to as high as 90%. Electronic readout of individual elements can be accomplished with CMOS using DC bias and AC modulation techniques. An interesting method for converting the incident radiation to digital signals is described [Ringh et al. 1995]. In this work, a CMOS oscillator is incorporated into each pixel. The resistance change due to the incident radiation affects the frequency of the oscillator. This frequency shift is then used to compute the incident intensity.

A micromachined bolometer array with 240 X 336 pixels, each about 50 μm square, nicely illustrates the advantages of thermal decoupling from the substrate [Wood et al. 1993]. Both schematics of the design and a micrograph of several pixels are shown in Figure 38. The array has a 50% fill factor and 80 absorption efficiency in the 8 to 12 μm range. A material with a high thermal coefficient of resistance (TCR), that is, a rapid change in resistance with temperature, forms the resistor for each element. Vanadium oxide was used in the case illustrated. The disadvantage of this approach is that the best performance is available only in a small temperature range, where the TCR is highest. However, in the design range, the performance is equivalent to what could be obtained earlier only with refrigeration. A noise equivalent temperature difference of 0.04 °C was realized with f/1.0 optics and a 30 Hz frame rate.

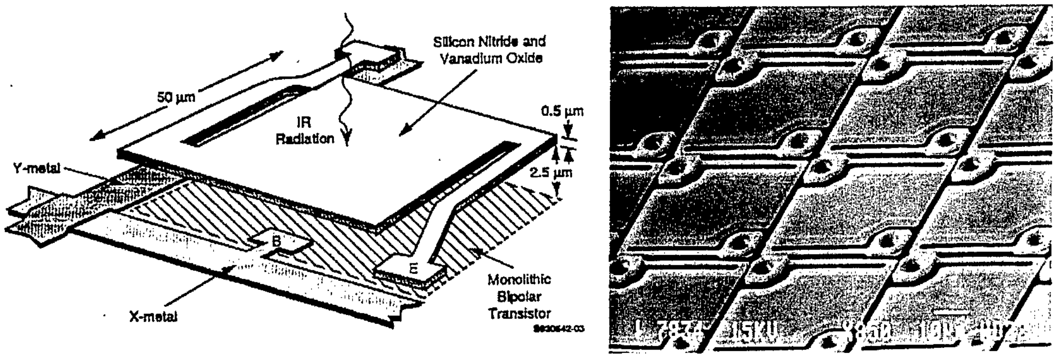

Figure 38. Schematic (left) and micrograph (right) of pixels in the uncooled thermoresistive microbolometer array developed by Honeywell.

13. Introduction to Applications

The applications of optical MEMS technology are as widely varied as the technology itself. There are applications that are, in effect, just a shrinking of the current method of performing a task to the level of an optical MEMS device. An excellent example of this idea is the compact disk optical pickup head shown in Figure 39 [Lin et al. 1996]. This device embodies the notion that optical MEMS can do the same basic tasks as macro-optics at a fraction of the cost, weight and manufacturing complexity. It also exploits the inherent advantage of a lower overall inertia. This characteristic makes the device less susceptible to some unwanted resonant vibrations. While the optical pickup head depicted here may not be optimized for production, it represents the push toward insertion of optical MEMS into common consumer electronics. It is also a nice example of the ability to concatenate the individual optical elements reviewed in the preceding sections to produce "micro-optical

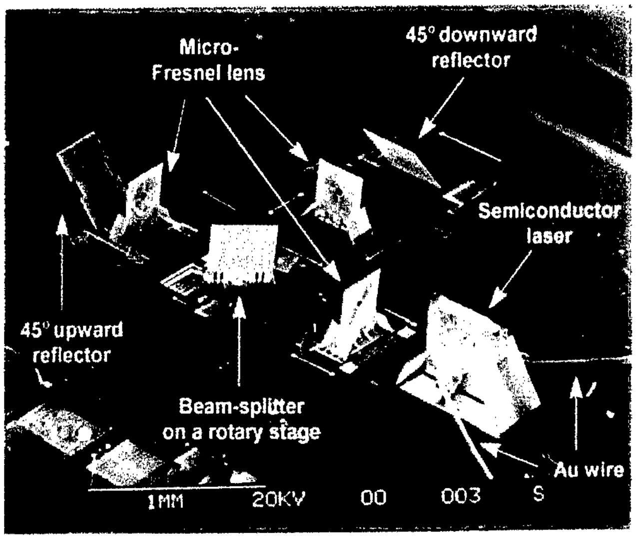

Figure 39. Compact disk optical disk pickup head, a prime example of a micro-optical bench.

benches". The precision and parallel production of the separate components, rather than the assembly of components made individually, exploits a hallmark characteristic of integrated circuit mass production.

The following three sections survey a variety of demonstrated and potential optical MEMS devices that utilize the types of components described in the preceding sections. A complete review of optical MEMS applications would be a major undertaking, even at this early stage in development and use of the technology. However, the items covered below will give a broad overview of salient opportunities.

There are many potential ways to organize this review of the uses of optical MEMS. We employ a fundamental subdivision of applications into the generation and manipulation, first, of information in general (Section 14) and, secondly, of images in particular (Section 15). Of course, images are basically information arranged in two-dimensional arrays, but their use of so distinct and pervasive as to merit separate attention. In Section 16, we include speculations on potential applications of optical MEMS.

14. Applications: Generation and Transfer of Information

Information can be generated in many ways ranging from human creativity to the employment of computers to measurements of physical and other phenomena. Of these, the acquisition of information from any system using transducers involving optical MEMS is of interest here. A few examples will be presented in this section. The processing of information can be done optically, so called optical computing. However, it does not now involve MEMS and is excluded from this review. The communication of information through fiber optics or free space does bring MEMS into play, as we have seen. Hence, switches and interconnects are also surveyed from an applications perspective.

14.a. Acquisition of Information

Transducers involving optics and micromachines are already numerous and proliferating rapidly. These are commonly used to record motions, including acceleration, velocity, and displacements, and sometimes to sense pressure, which can be made to cause a displacement. Optical spectra can now be acquired by use of micromachined systems. These applications are each surveyed.

14.a.i. Motion and Displacement Detectors

Optical methods may be used to interrogate the mechanical motion of accelerometers. Capacitive and piezoelectric coupling are common methods used to read out accelerometer data. Capacitive techniques suffer from vulnerability to electromagnetic interference, whereas piezoelectric techniques can have large sensitivity drifts and relatively small signals. Accelerometer data can also be read out as an electrical signal from a photodetector. This method has been implemented in various accelerometer designs. A suspended grating structure moving over a fixed grating can modulate a light beam incident on it [Chen et al. 1997]. The intensity of the transmitted light is related to the acceleration of the moveable grating. Fiber optics and interferometers may also be used to provide optically-coupled accelerometers. Both accelerometers and velocimeters, which involve optical readouts, have been demonstrated. A strain gauge based on the bending of an optical fiber has also been produced.

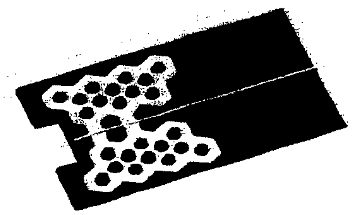

Figure 40. Optically coupled vibration sensor in which the optical waveguide is also the support for the proof mass.

Optical methods can be useful in environments that have very high ambient electro-magnetic fields and elevated temperatures. One such application is sensing vibration on generators in electrical power plants. A design based on a moving optical fiber has been implemented as a vibration sensor for electrical generators [Ollier et al. 1997]. This device uses a resonant mass that incorporates a optical waveguide, as illustrated in Figure 40, and an interferometric detector. Laser light from the tip of the resonant mass structure is incident on a sensor incorporated in the opposing wall of the device. The sensor is a multimode interference coupler that detects the relative motion of the mass. Light is coupled on and off the chip via fibers mounted in etched v-grooves. Another method of acceleration detection involves forming a Fabry-Perot cavity between the proof mass and the fiber end. This method has been used to develop a two-axis accelerometer [Schropfer et al. 1997].

Measurement of the doppler effect of a laser beam provides a powerful method for non-contact measurements of velocity. Current miniature velocimeters have remotely-mounted laser sources and detectors coupled via fiber optics. This configuration involves complexity and alignment difficulties. A monolithically integrated device has been developed that is only 0.9 x 0.8 mm square [Ito et al. 1997]. It incorporates the laser source, waveguides, lenses, and detectors into one package, which is aligned photolithographically, as shown in Figure 41. This detector has the ability to measure velocities as slow as 5 µm/s. A similar device has been made [Sawada et al. 1997] by the same group for use as a micro-focusing and tracking sensor. This sensor will maintain the selected distance from the sensor head to the moving substrate, as well as track a guide pattern etched into the substrate. Focusing and tracking errors on the order of a few tenths of a micron were demonstrated.

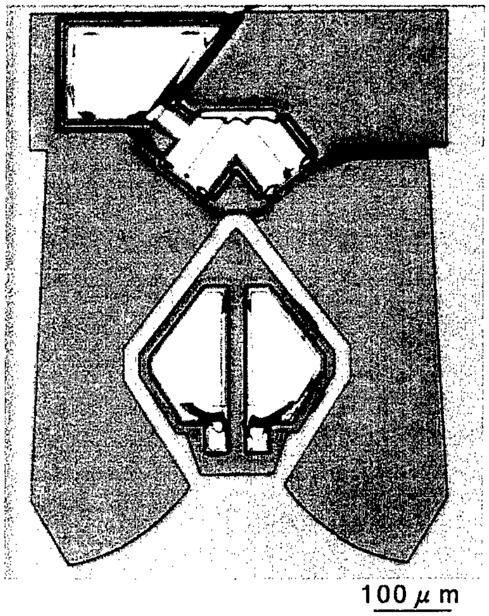

Figure 41. Optical micro-encoder showing the V-shaped laser diode in the center, near the top, and the photodiodes below. Laser light is reflected off the sides of the device and focused with the curved lenses on each side at the bottom.

The ease with which fibers can be integrated into new systems, or added to existing systems, makes them an excellent candidate for sensor applications. Optical fibers are lightweight, cheap, robust, and are available in a variety of optical configurations. Using a fiber is not, in and of itself, an optical MEMS application. When the mechanical motion of a fiber imparts some decipherable signal, then it becomes an optical MEMS sensor. A simple example of this type of sensor is the fiber-bending sensor. This sensor employs a Bragg grating written into the fiber material. Bending the fiber changes the pitch of the grating and the reflected signal may be analyzed. This technique may be applied in various ways. A distributed optical bending sensor has been reported [Tomiyoshi et al. 1997]. It can detect where on the length of the fiber the bending is occurring and the magnitude of the bend angle.

14.a.ii. Pressure Sensors

Pressure sensors are a very natural application for optical MEMS. Thin planar layers are easily fashioned into diaphragms, and silicon is sufficiently robust to handle significant deflections. As with motion detectors, there are alternative ways to monitor the deflection of a MEMS diaphragm. Capacitance measurements will allow the measurement of diaphragm deflection, and piezoresistance is also used. However, the intrinsic sensitivity of sub-wavelength resolution makes optical interrogation an attractive method for pressure transducers.

A simple method of implementing an optical MEMS pressure sensor has been developed at the University of Texas, Austin [Kim and Neikirk 1996]. This device employs the Fabry-Perot scheme shown in Figure 42 to monitor the deflection of a suspended silicon membrane. This method of optical sensing has wide application. The device can be mounted on the end of a fiber, and is an excellent candidate for distributed sensor networks. Some work on this type of pressure sensor has also been done at Tohoku University in Sendai, Japan [Katsumata et al. 1997].

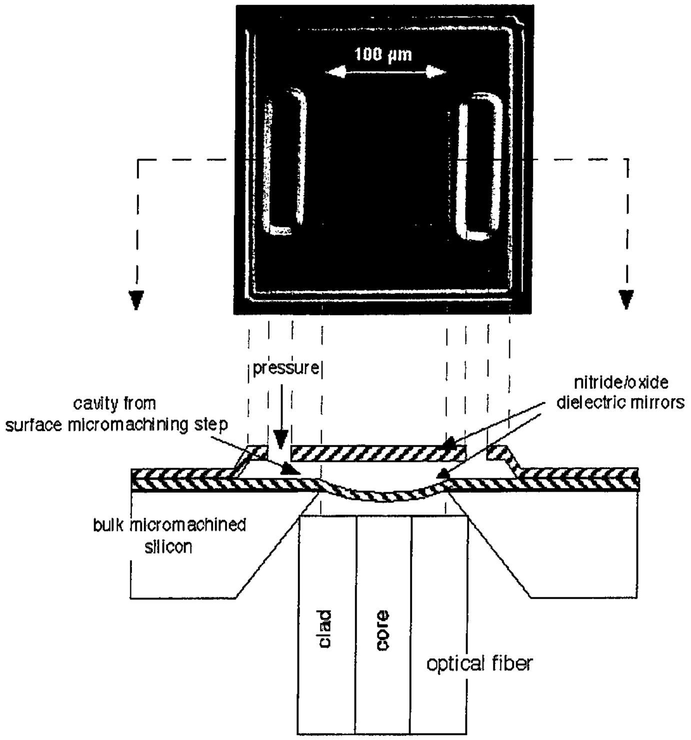

Figure 42. Photographic top view and schematic cross section of a Fabry-Perot pressure sensor.

Benaissa et al. have developed an elegant method of utilizing a Mach-Zehnder interferometer as a pressure sensor, which is indicated schematically in Figure 43 [Benaissa and Nathan 1995]. This device consists of an ARROW waveguide structure on a silicon substrate. The back side of the silicon is etched so that a thin layer of silicon forms a flexible diaphragm underneath one arm of a Mach-Zehnder interferometer. As the pressure in the cavity changes, the sensor arm of the interferometer is perturbed and an optical fringe pattern is read on the output side. This type of sensor has exhibited optical phase changes of up to 180 μrad/Pa.

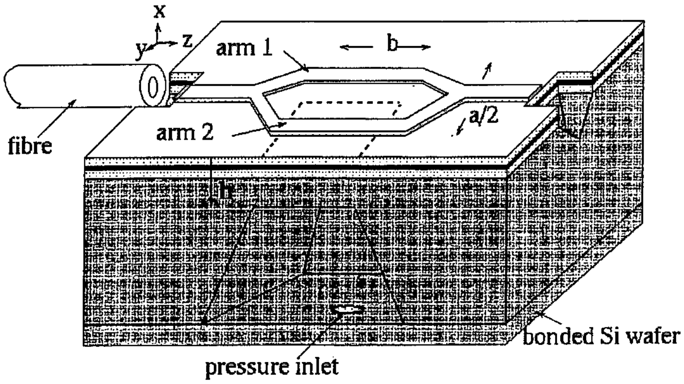

Figure 43. Schematic of a Mach Zehnder pressure sensor.

14.a.iii. Optical Spectrometers

Measurement of the spectral distribution of light in the visible, and nearby infrared and ultraviolet regions, has countless applications in science and technology. Diffraction grating and other spectrometers are used with point and array detectors in laboratory, factory and field settings. The control of manufacturing processes is a major use of optical spectrometers. An example is the determination of the end points of energetic processes used for production of semiconductor devices and chemicals.

Certain optical instruments need comparatively large path lengths to accomplish their tasks. Optical spectrometers commonly use long path lengths to separate light into its individual wavelengths because longer path lengths yield better resolution. These long path lengths are not feasible in a

MEMS device. Nevertheless, the optical components that are central to optical spectrometers have been constructed, and fully functioning spectrometers have been made using micromachining techniques. Microparts GmbH (http://www.microparts.de/ home.htm) makes, and American Laubscher Corporation sells, both IR and visible spectrometers with integral diffraction gratings, one of which is shown in Figure 44. While these instruments do not have any moving parts now, rotable gratings and moveable slits seem possible. Micromachined variable slits are being used in a full-sized spectrometer manufactured by Hewlett-Packard [Maute et al. 1997]. Tunable MEMS gratings will enable IR spectrometers [Guckel 1997]. A polychromator based on programmable diffraction gratings, for use as a dark-field optical correlation spectrometer, is under development [Sinclair et al. 1997, Sinclair et al. 1997].

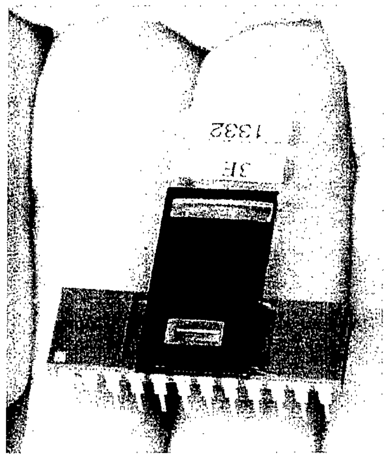

Figure 44. Micromachined optical spectrometer (black) with the integrated detector array (gray.)

14.b. Communication of Information

As with the acquisition of information, there are many ways to pass information from one place to another. Carriers in much of both the electromagnetic and acoustic spectra, suitably modulated, can be used for communications. Of all these possibilities, the employment of light, either guided in fibers or in free space, has already involved the use of optical MEMS. A brief survey of such applications follows.

14.b.i. Optical Switches

Optical MEMS will undoubtedly play a significant role in the future of the communications industry. It is quite clear that fiber optics will be a major conduit for information. The need for inexpensive, high quality, efficient fiber optic technology is not only obvious but also largely unfulfilled. While discrete switches and lasers are the workhorses for the current fiber network configurations, integrated MEMS switches and lasers for wavelength division multiplexing (WDM) will be standard in the not so distant future. Surface micromachining, bulk micromachining and LIGA [Mohr 1997] techniques will all be used to fabricate fiber optic switching components.

Fiber switches are classified in two basic categories. "On/off" switches can block the light that propagates along the fiber. They may be simple in design and manufacture. A mechanical shutter, which blocks the light transmitted through a gap between fiber ends, is a good example of a simple on/off switch. Any beam block that can be placed in the path of a fiber interface will accomplish the task. Different configurations of this basic principle have been described [Hashimoto et al. 1997, Uenishi et al. 1997]. One embodiment is shown in Figure 45 [Bishop and Giles 1998]. A vertical polysilicon surface is coated with gold to form a mirror that is inserted between two closely-spaced optical fibers. With passive assembly, the coupling loss is 16%, while active alignment reduces the loss to 10%. The

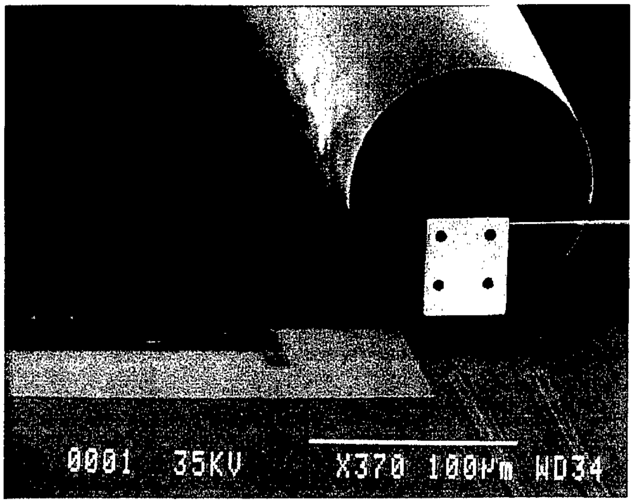

Figure 45. Colorized micrograph of a micromirror near the end of an optical fiber. The mirror is the gold structure and the core of the fiber can be seen just above it. The actuation mechanism moves the mirror vertically and is just out of the picture to the left.

mirror is on the end of hinged and erected surface, which passes over a pivot to a plate parallel to the substrate. A few volts is adequate for actuation, and only 2 μW of power is needed, even for frequent reconfiguration of optical routers containing these MEMS switches.

Devices that switch optical signals from one fiber to another are called "n x n" switches. The first "n" is the number of input fibers and the second "n" is the number of output fibers. The 1 x 2 switch is the simplest such device. A novel approach to the waveguide coupler [Boysel et al. 1993] uses a suspended metal membrane to selectively inhibit one path of the coupler and create a 1 x 2 switch. The membrane is electrostatically pulled to the substrate and it contacts one side of the coupler. This contact destroys the optical transmission of the waveguide and forces the light to the other path. The thin membrane and small deflection distance contributes to the 20 µs switching times.

Designs that perform n x n optical switching may involve redirecting the light path or translating the fiber. The most common optical switches are designed so a mirror can be actuated in and out of the light path and act as the switch. Various mirror configurations are used to accomplish this task. The cross-bar switch is illustrated in Figure 46. The terms refer to four fibers that are in a plane with a cross configuration, so that their ends face a central point. If the mirror is not present, the two fibers, which are 180° apart, will form a transmission pair in the bar state. When a mirror is placed at the central point then the two fibers, which are 90° apart, will form a transmission pair in the cross state. Translating a mirror to the cross state can be done with a linear actuator that drives the mirror into the desired position. Crossbar switches have been made using deep reactive ion etching [Marxer et al. 1997, Marxer et al. 1997] and bulk micromachining [Toshiyoshi and Fujita 1996]. They have been implemented using scratch drive actuators [Lee et al. 1997] and PZT meander actuators [Riza and Polla 1992]. Another common method of switching the mirror into the optical path is to mount one edge of the mirror on a torsion spring and electrostatically move it into place. This method has been done with both vertical [Lee and Wu 1997] and horizontal [Miyauchi et al. 1997] torsion springs, as well as cantilever leaf springs [Mita et al. 1998]. These methods provide switching times that are suitable for slow speed applications such as transmit/receive switching, but they are too slow for high-speed multiplexing applications.

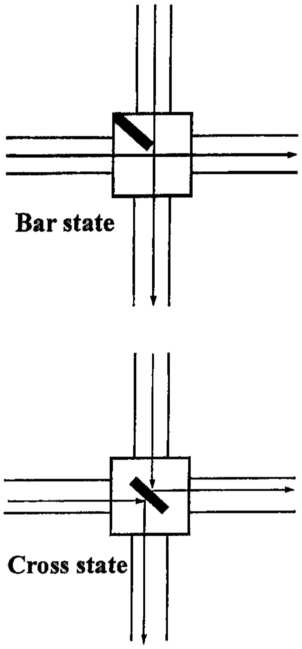

Figure 46. The two states of a cross-bar switch.

Other designs for fiber switching involve a variety of geometries and optical components. One idea employs microprism arrays [Goring et al. 1996] has been adapted for fiber switching. A piezoelectrically-driven microprism was used to redirect light from an input fiber to as many as nine output fibers for a 1 x 9 fiber switch. This device showed less than 1 dB insertion loss and greater than 50 dB isolation between output channels. Thermo-capilliary optical switches have also been used to switch optical paths in waveguide structures [Sato et al. 1997].

The fiber translation method of n x n switching can be implemented via micromachining techniques. The general design is to attach an input fiber or waveguide to a movable structure and translate it between mechanical stops. If the air gap can be kept small, coupling losses can be minimized. Index matching fluids will also decrease optical losses, but at the expense of switching speed. Various approaches have been reported [Field et al. 1996, Hoffman et al. 1998, Kobayashi et al. 1997, Nagaoka and Suzuki 1997, Nagaoka et al. 1997, Ollier et al. 1996].

14.b.ii. Optical Interconnects

Electronic circuits rely on paths for electronic signals to travel. These paths can occur in wires, metal layers on printed circuit board, and circuit paths inside integrated circuits. Multichip modules (MCMs) involve large capacity, high-speed data paths between chips. Using optical MEMS technology and current MCM components, a new optoelectronic multichip module (OE-MCM) is a logical development [Koh et al. 1998]. Optical paths can exist on many different levels. Computer to computer, board to board, chip to chip, and intra-chip communications are all fair game. Optical communications also alleviates the bottleneck of the limited number of pins on microprocessor packages. If this technology is coupled with current WDM techniques, the number of data channels will expand enormously [Kobayashi et al. 1997]. Optical logic gate designs [Murdocca et al. 1990] are elaborations of optical interconnects, which enable optical computing.

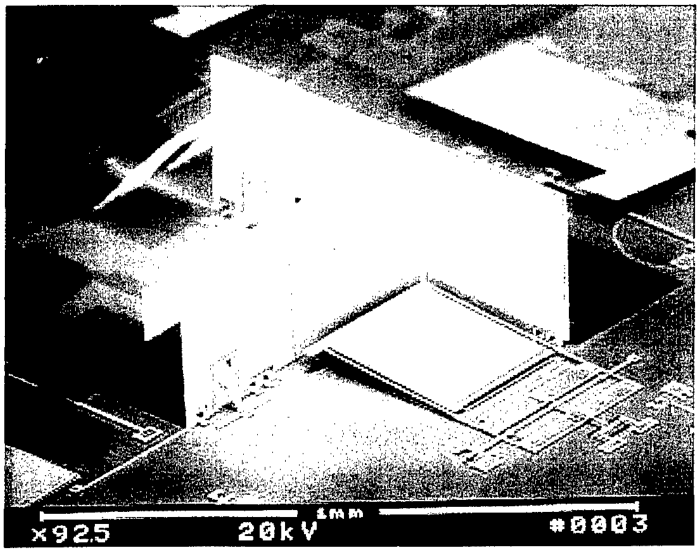

Figure 47. Corner cube reflector showing the bottom mirror out of plane.

Corner cube reflectors (CCR's) have been used for years in the macro-optics community because of their characteristic of reflecting incident light directly back to the source. This feature can be used on optical MEMS chips for on-chip optical interconnects and off-chip communications. Micro-CCR's have been fabricated and tested [Chu et al. 1997, Chu et al. 1997, Gunawan et al. 1995]. Figure 47 shows a micro-CCR with an electrostatically actuated bottom mirror. Deflecting the bottom mirror can modulate the micro-CCR. When the mirror is pulled down to the substrate, the CCR functions normally. When the mirror is released, the mutual orthogonality of the three mirrors is destroyed and the CCR will not function retroreflectively. This mechanism enables the CCR to be used in a transmitter. The low power needed to operate these devices make them attractive for solar or battery operation.

15. Applications: Generation, Manipulation and Presentation of Images

Digital cameras and frame grabbers now make the acquisition of images quite routine. Most of the systems do not involve optical MEMS, but some infrared sensor arrays employ micromachined elements. The processing of images, specifically phase correction using adaptive optics, has also involved MEMS. The display of images is one of the hallmark applications for optical MEMS. Each of these topics is reviewed in turn.

15.a. Acquisition of Infrared Images

Use of the uncooled micromachined 240 X 336 array discussed in Section 12.2 yields images at night or in daytime which depend on the temperature of the scene. Night vision has long been a major need of military units. Cooled, narrow-bandgap semiconductor detector arrays and uncooled microchannel plate electron multipliers are used extensively by the military. However, such units remain relatively expensive, so their civil use is limited to police and emergency units. However, widespread availability of thermal imagers for nighttime use would contribute to the safety and security of the general population. Hence, the good performance of uncooled detector arrays made by micromachining, and their potential for low-cost production in large numbers, are attractive.

15.b. Phase Correction of Optical Images

Some work has been done in using MEMS deformable mirrors to do aberration correction for image plane improvement. When discrete element mirror arrays are used, diffraction effects can become severe in some cases [Roggeman et al. 1997]. However, arrays of micromirrors with square and other shapes are useful for telescope adaptive optics applications [Michalicek et al. 1998]. Lenslet arrays may mitigate diffraction effects. Another approach is to have a continuous membrane as the mirror and place the actuators underneath the membrane, which is illustrated in Figure 48. [Bifano et al. 1997, Bifano et al. 1997, Vdovin and Middelhoek 1997]. This eliminates the diffraction effects but has other limitations, such as greater actuator demands, coupling of neighboring segments and higher operating voltages. Work continues on both of these deformable mirror technologies. Image phase correction should find many military and civil applications.

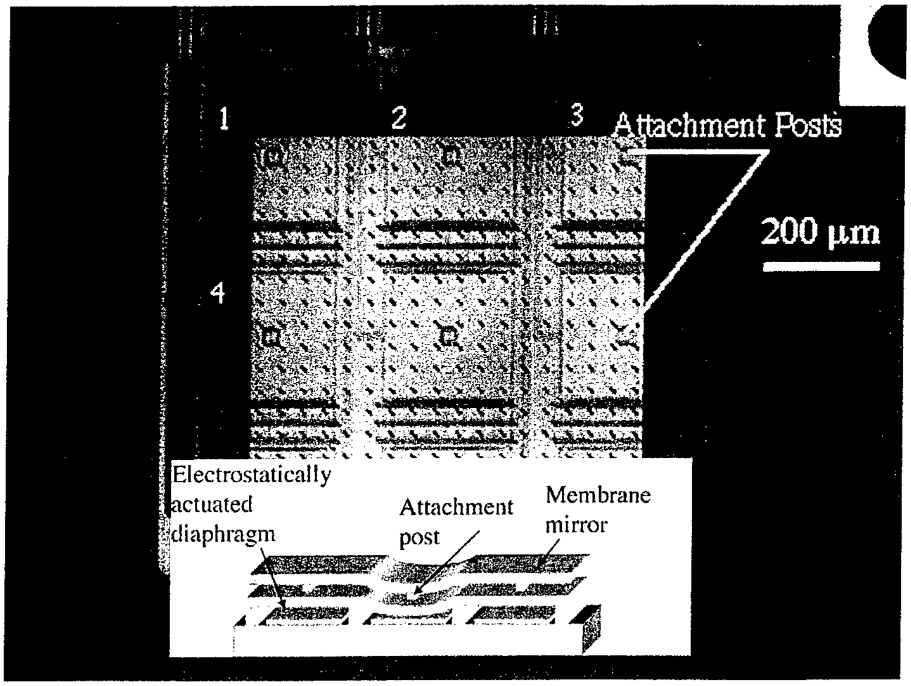

Figure 48. The continuos membrane mirror is shown as well as a schematic view of a cross section of the device.

Control of the emission profile of a phase-locked laser diode array is related to the control of image quality. It has been demonstrated using a 1x10 linear array of piston micromirrors [Christensen et al. 1996]. The piston array was able to provide far field phase correction to a linear diode array. It was also able to steer the corrected beam over 0.81°.

15.c. Image Display Devices

The presentation of images for viewing can be done serially or in parallel. Optical MEMS have been developed for both modes. Scanners, which construct images serially, are surveyed next. Then we review two types of devices, in which the monochrome images are displayed at once, or color images are projected by a mix of serial and parallel means.

It should be noted that display devices, which ordinarily put images onto a screen for real-time viewing, also can be used to present images to recording media, for example, photographic film or various kinds of paper using xerography. That is, display devices can be configured as printers.

15.c.i. Scanners

Optical scanners are effected in a variety of ways. They can be employed as bar code readers, as well as visual displays. Bar code readers record reflected signal intensity. The active element scans a laser beam over the surface to be "read" and a sensor then detects the return signal. The critical parameters for the scanners are beam quality, scan rate stability and spatial stability.

Vertically-erected optical MEMS are beginning to extend scanner performance. A surface micromachined mirror was pushed into position with a linear microvibromotor and resonantly driven with an electrostatic comb drive. These scanners have the advantage of using an in-plane actuator for driving the mirror, as shown in Figure 49 [Tien et al. 1996]. Such a system provides greater actuator travel than vertical actuators and therefore greater scan angles. Both one-dimensional and two-dimensional scanners have been fabricated with this technology.

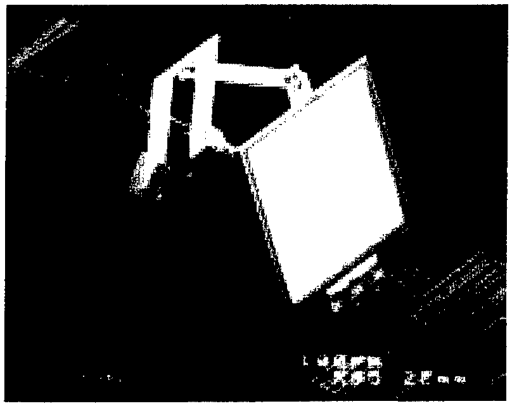

Figure 49. Actuated micromirrors capable of scanning the beam from an external semiconductor laser module.

Recent developments have shown that a scan mirror can be fabricated and used parallel to the substrate. Researchers at UCLA have developed a process called Micro-Elevator by Self-Assembly (MESA) [Fan et al. 1997]. This process is able to lift micromachined structures several hundred microns above the wafer surface. The results of this process are shown in Figure 50. Large mirrors (400 x 400 μm) produced in this manner have been driven electrostatically in two dimensions to produce scan angles greater than ±14° at frequencies of 1.5 kHz.

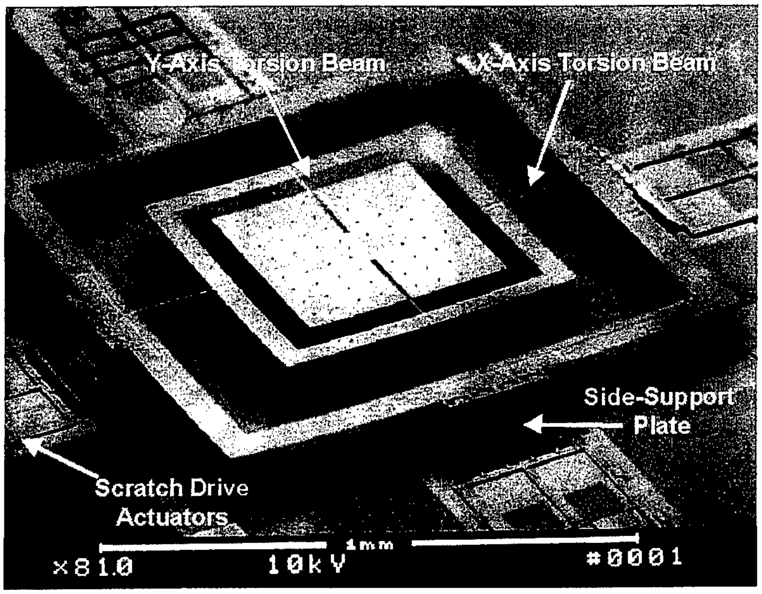

Figure 50. MESA structure showing a two-dimensional scanner.

In-plane micromotors can be used as rotating platforms for a scanning device [Yasseen et al. 1995]. Two scanning techniques are obvious. If a polygonal mirror is attached to the rotating platform, the MEMS device becomes a miniature of the scanners that are in use by the millions today. While this is an interesting solution to the miniaturization process, the inherent problems of attaching a mirror to the silicon rotor, and aligning the center of mass with the center of rotation, proves to be to difficult. The related problem of bearing design to accommodate the added mass of the mirror makes this approach untenable. A better design is to incorporate a diffraction grating on the rotor and use the rotation to scan a monochromatic source. The grating can be a simple straight pattern or a more complicated quadrant pattern. Scanners have been fabricated from both wobble motors and salient pole devices. These scanners, although conceptually simple, suffer from the same problems as all micromotors. They include stiction on release, microprobing to start the motion, high failure rates in high humidity, and rotor warpage after processing.

Bimorph actuation is an alternative to resonant comb drive structures for scanning. One method is to support the mirror on torsion hinges, and to use the bimorph element to provide the rotation. This method can be extended to a coupled system to provide a two-dimensional scanner [Ohtuka et al. 1995]. Bimorph actuation of a cantilever arm has also been used to scan an optical beam [Motamedi et al. 1997].

Another method of actuation is a piezoelectric cell. A mirror supported on a post can use piezo actuation to excite independent modes of fundamental oscillations. These modes can scan a two-dimensional pattern. This scanner mechanism has been tested as a bar code reader. It is capable of scanning a standard bar code pattern at a distance of 20-100 mm. The mechanism is also being incorporated into a robotic inspection system that will travel down a length of pipe and map the surface topography. By adding motion in the axial direction (traveling down the pipe), the robot can actually map the entire inside surface of the pipe. One suggested application of this device is the inspection of pipes in the cooling system of nuclear power plants [Goto 1996].

A scanning mechanism based on a magnetic mirror material was demonstrated [Judy and Muller 1996]. A nickel-iron plate is attached to a silicon torsion hinge and exposed to a controllably-variable magnetic field. When configured as an optical scanner, the mirror deflects a laser beam through an angle of 135°. While these devices were operated with an external field, one could imagine integrating a small solenoid near the mirror. Clearly, if an array of these devices is needed, crosstalk between individual elements may be a problem. Another magnetically-actuated mirror was developed at the California Institute of Technology using a similar technique [Miller and Tai 1997].

15.c.ii. Grating Light Valves

A display device based on research done at Stanford is being developed as an electronically-controlled light modulator [Solgaard 1997]. Silicon Light Machines of Santa Clara CA is currently producing it for applications in the display market. The grating light valve (GLV) is made of thin deformable ribbons of silicon. Each pixel is composed of two sets of ribbons. One set is fixed. The interleaved movable set is suspended over an air gap. The ribbons can be seen the lower right portion of Figure 51, and the address electrodes are in the upper left portion of the figure. Figure 52 shows the full array width. In the on state, the ribbons form a flat mirror, while in the off state the suspended ribbons are pulled down by one quarter of a wavelength, so a grating is formed. The incident light is diffracted by the grating into the plus and minus first order of the grating. There are other implementations of fixed and moveable pairs which can reverse the on and off state.

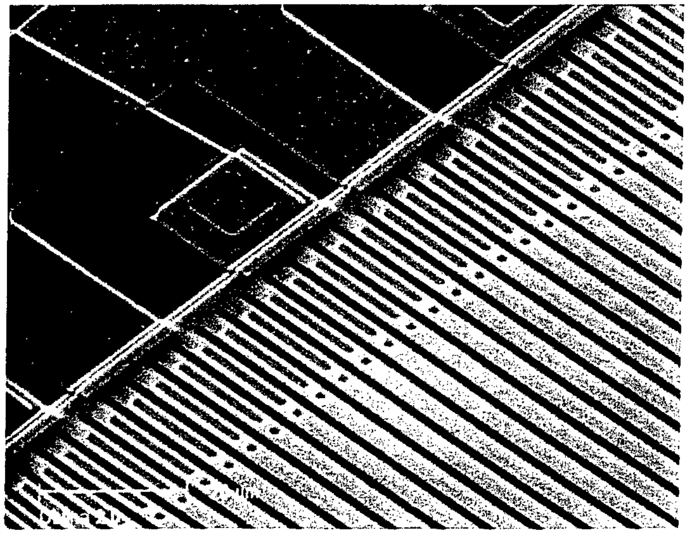

Figure 51. Close up of GLV Device showing interface between the address electrodes and the silicon ribbons.

GLV are reflection mode devices, so they have high throughput and relatively high power handling capabilities. Diffraction efficiencies greater then 80% have been reported [Bains 1997]. The tensile stress in the ribbons keeps the reflecting surface relatively flat even with very thin ribbons. The ribbons are mechanically stable in the up position. The electrostatic force that pulls the ribbons down operates against this mechanical stability. These forces are not linearly balanced at all ribbon-substrate separation distances, and a voltage/deflection hysteresis results. This electrostatic hysteresis enables these devices to utilize a high-speed switching scheme for video processing. The low inertia of the silicon ribbons contributes to 20 ns switching times. Screen refresh rates near 50 million frames per second are theoretically possible. Two-dimensional images are obtained by a combination of the GLV and a mirror that can oscillate or rotate. Close inspection of the projected image shows no delineation between video scan lines. Projectors that have been made using the GLV have excellent image quality and a rich color depth. GLV devices are used as linear scanners, also.

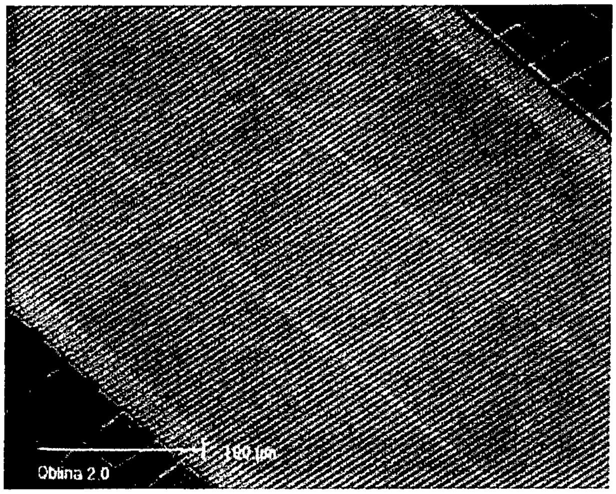

Figure 52. GLV device showing entire cross section of the linear array.

15.c.iii. Digital Micromirror Devices

The Digital Micromirror Device (DMD™) is a showpiece of what MEMS can do [Hornbeck 1995]. It is the culmination of years of development at Texas Instruments. The original design for the device was proposed in 1987. It is an array of mirrors, which are independently addressable and can deflect through a tri-stable range of motion (+10°, 0° -10°), as indicated in Figure 53. These devices can be used in a variety of optical systems. The current commercial applications are for projection devices. The DMD is used as a reflective element in the optical train of a system. A light source is directed onto the DMD while a signal is input to the device. Each individual mirror is placed in a binary mode. The mirrors that are "on" will reflect the light into the optical train and onto the projection surface. The mirrors in the "off" state will reflect the light into a baffle, and the associated pixel on the projection surface will appear dark. Using one array and a single light source, a DMD can be used as a monochrome display driver. A full color display can be implemented with a single DMD and a color wheel after a white light, or by a combination of three DMDs and associated basic color sources. DMDs can be used in linear arrays for printing applications. Arrays may have multiple columns for gray scale control.

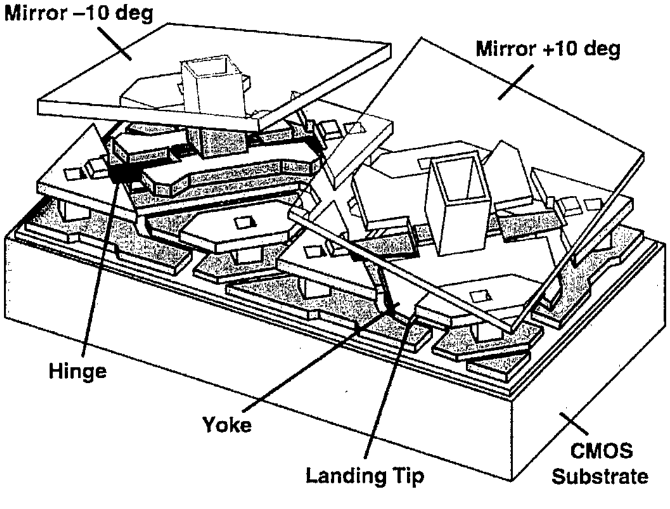

Figure 53. DMD cutaway view showing two mirrors in opposite tilted states.

The DMD is fabricated on top of a completed CMOS memory circuit. Six photomask layers build a complex, multilayer, aluminum structure. The general construction approach is to isolate the electrical, mechanical, and optical layers to effectively decouple their operation. Posts support the mirrors. The posts are connected to a yoke that is suspended by a pair of torsion springs. The electrical layer underneath the mechanical structure electrostatically deflects the yoke. Each pixel is independently addressable by digital signals, so the overall technology is termed Digital Light Processing, or DLP™.

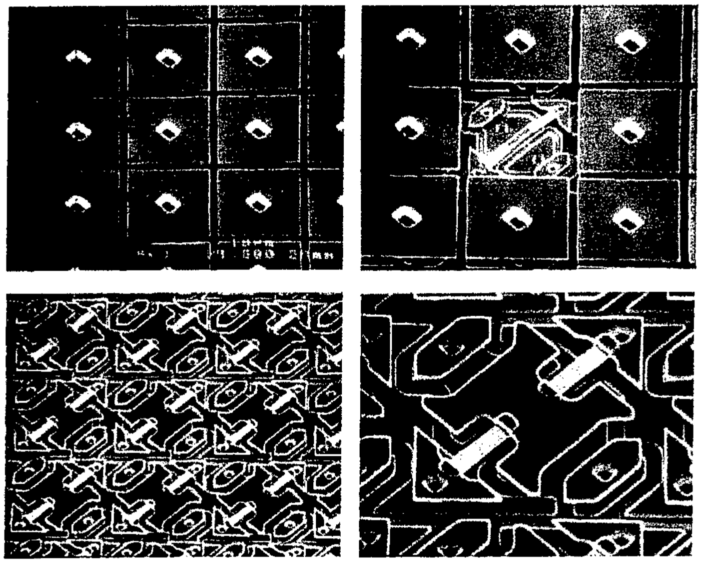

Figure 54. DMD array with various layers showing.

Figure 54 shows four SEM images of part of a DMD array. The image in the upper left is the finished array before metalization. The mirror surfaces can be seen with the underlying support post showing through at the center of each mirror. The image at the upper right is the same view with one of the mirrors removed to expose the mechanical structure underneath. The lower left image is the mechanical layer with no mirrors. A close-up of one pixel's mechanical structure is shown in the lower right image. When viewed from the "top" or mirror side, the device has a 90% optical fill factor. After other losses, such as scattering, on-time delay, and aluminum reflectivity, the total efficiency of these devices is about 62%.

The major problems with the DMD technology over the last ten years have been the issues of reliability and yield. Reliability problems were solved through design changes. Yield problems have been solved primarily through improved processing techniques. One of the most vexing problems was dead pixels. Pixels malfunction for three main reasons: stiction, hinge failure, and hinge memory. The stiction issue was addressed by incorporating a small whisker of hinge material on the landing tip of the mirror yoke. This whisker acts like a spring. When the mirror is electrostatically released from the tilted state, the spring provides the release energy to overcome the stiction force. Hinge failure is the mechanical fracture of the torsion hinge, whereas hinge memory is the failure of the hinge to reset to the 0° position. Implementing a new, more stable hinge material and a bi-polar reset circuit corrected these problems [Hornbeck 1996].

Until recently, DMDs have been sold by Texas Instruments in Display Engines for the digital display and printer markets exclusively. Now, devices are available to independent researchers in two forms [Lewotsky 1997]. The basic Digital Light Processing kit has a 640 x 480 DMD array and all the associated electronics to interface it to a PC. The Optical kit has the optical assembly needed to focus light onto the DMD array. Alternative uses for DMDs, such as autocorrelation and rapid prototyping of plastic parts, are being explored.

16. Other Applications of Optical MEMS

The applications just reviewed represent a fair but small sampling of the numerous current and potential uses of optical MEMS for the generation, manipulation and communication of information and images. Future possibilities may come from many fronts. They might involve either replacements of existing functions with optical MEMS, or the development of really new applications. We speculate on a few other new applications in the remainder of this section.

An example of a replacement is the use of micro mirror arrays in projectors. Another is the application of current, commercial micromachined optical spectrometers in areas now employing large, classical spectrometer systems. There are many examples of possible new applications. Useful optical systems could be made by concatenation of some of the components reviewed above. For example, a micromachined thermal infrared source could be combined with a grating made by LIGA or deep reactive ion etching, and read out with a MEMS microbolometer array. Such a system might be useful for infrared spectral analysis of samples in a wide range of industries, process control being one of them.

One challenging, but attractive new possibility is the melding of micro-Fabry-Perot elements with micromachined detector elements to make spectrally-sensitive and tunable arrays for recording infrared images. The individual picture elements would include either a tunable filter and detector, or a spectrometer and detector, if Fourier transformations of the data recorded while scanning the Fabry-Perot cavity were made. The latter would allow acquisition of a "data cube" of two-dimensional spatial information, plus one dimension of spectral data. Current research and development on such "hyper-spectral" imaging is demonstrating numerous applications, ranging from microscopic biomedical research to satellite remote sensing of agriculture.

Applications of optical MEMS in biology and medicine seem especially attractive, both because of numerous opportunities and the importance of these fields. There is an explosion of work on array-format, chip-level systems for manipulating and sensing DNA, and on "lab-on-a-chip" systems for microanalysis of materials in biology and medicine. Many of these techniques involve optical readouts of fluorescent stains, but optical MEMS have not yet been employed in the schemes. It seems likely that the tools now available from optical systems with micromachined static or moving parts, discussed in this report, will be useful for molecular biology.

Optical MEMS might also prove valuable for cellular biology. A method of identifying individual living cells is being developed at Sandia National Laboratories [Lewotsky 1997]. The optical cavity region of a VCSEL was used as a sample chamber for unknown biological cells. These cells are largely transparent to the laser wavelength and act as intra-cavity waveguides. Each type of cell has a characteristic internal configuration, and will affect the cavity mode in a specific way. Since the length of the cavity is on the order of a few microns, individual cells can be sampled. This is a unique method of sampling cellular material, and does not depend on the typical absorption and fluorescence techniques. It could lead to sampling rates as high as 20,000 cells per second. The initial demonstration did not involve mechanically-tunable VCSELs, but it seems likely that a configuration to exploit such optical MEMS could be employed. The added spectral flexibility might permit optimization of the flow cytometry.

One medical application of MEMS to test an optical device, the human eyeball, has been prototyped. An opthalmic tonometer for measuring the pressure within an eye was developed. It included a silicon micromachined pressure sensor with a piezoresistive readout [Hachol et al. 1996]. Of course, an optical readout could have been employed, as discussed above in the section on pressure sensors.

Other medical uses of optical MEMS are possible, especially techniques using compact spectrometers for measurement of light transmitted or scattered by living tissue. Figure 55 shows the absorption

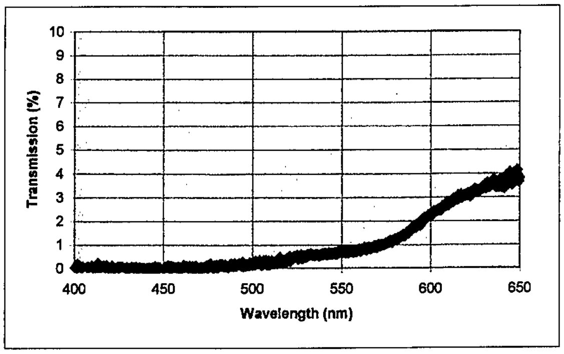

Figure 55. Light transmission percentage as a function of wavelength through a human ear lobe.

spectrum of one of the author's ear lobes . It turned out to be relatively featureless, and hence useless for blood chemistry analysis. However, the use of absorbed or scattered light from high-resolution, tunable lasers, as measured by compact spectrometers with micro-optical components, might yield more spectral detail and permit useful assays.

17. New Optical Materials and Associated Processes

Silicon has historically been the material of choice for optical MEMS. Its extensive use in the semiconductor industry provides a strong database for its electrical properties. These data are not especially relevant to its optical characteristics. Silicon is also an outstanding mechanical material [Peterson 1982]. The doping of silicon with materials like boron is an effective way to create etch-stop layers. Such layers are key to multidimensional micromachining processes. However, doping silicon with high levels of impurities affects its mechanical properties [Cabuz 1996, Cabuz 1997]. This can sometimes interfere with the intended application of the device.

Indium phosphide may be suitable for some optical applications [Hjort et al. 1997]. It can be etched with RIE and other wet or dry processes [Greek et al. 1997]. However, the mechanical strength of InP limits its use. Some work has been done recently on the physical characteristics of InP [Greek et al. 1997] as they relate to micromechanical structures. InP optical filters have been made and exhibit promising optical properties [Le Dantec et al. 1997]. These filters employ the movable mirror methods for tuning a Fabry-Perot cavity. High reflectivity (>95%) Bragg mirrors may be made with just three pairs of InP/air interfaces [Le Dantec et al. 1997]. More conventional devices will use InAlGaAs/InP and InGaAs/InP pairs that have Bragg characteristics closer to GaAs/AlAs.

In addition to inventive uses of familiar materials for optical MEMS, there are three other opportunities for materials innovations. The first is the use of currently available materials for optical MEMS. Nanostructured materials, especially semiconductor quantum dots, which have already been made and tested fall into this category. Such materials should offer the designer of optical MEMS new properties and functionality. Secondly, totally new materials can be developed to provide greater flexibility for optical MEMS design and manufacture. That is, it is possible that the attraction of optical MEMS will drive the development of new photonic materials with particularly desirable properties.

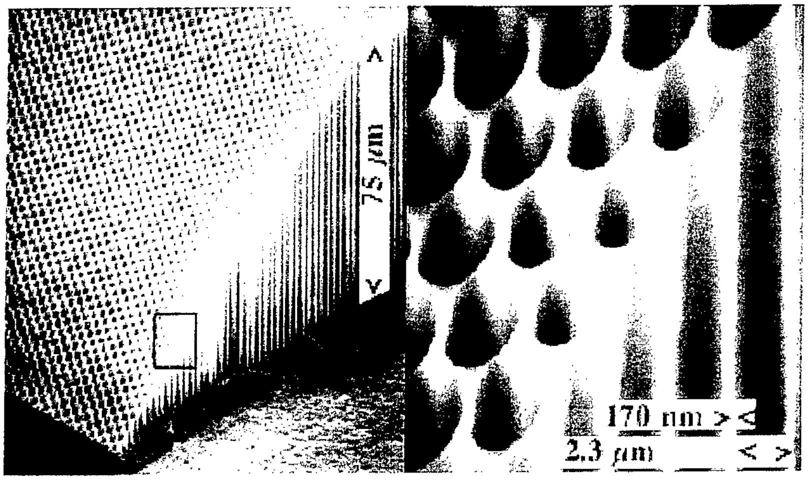

Figure 56. Photonic bandgap material made from macroporous silicon.

The third frontier for materials in MEMS involves structuring of materials to produce desirable optical properties. Included here are familiar processes such as the controlled smoothing or roughening of surfaces. Of greater interest and possibility, however, are methods to produce photonic bandgap materials in MEMS. Such materials have structures on the order of optical wavelengths. Hence, their dispersion relations as a function of optical wavelength are strongly modulated. The situation is very analogous to the influence of atomic scattering on the propagation of electrons in crystals. It is fortuitous that some of the same patterning and etching processes commonly employed in MEMS production are needed for the production of some photonic bandgap materials. Figure 56 contains micrographs of silicon, which has been structured to modulate its optical properties [Gruning et al. 1996]. Figure 57 shows a photonic bandgap material made by the successive buildup of silicon structures with cross sections about 1 micrometer square [Lin et al. 1998]. Micro-structured photonic materials offer two kinds of useful properties. They can modify the spectral character of incident radiation, and redirect both monochromatic and colored light.

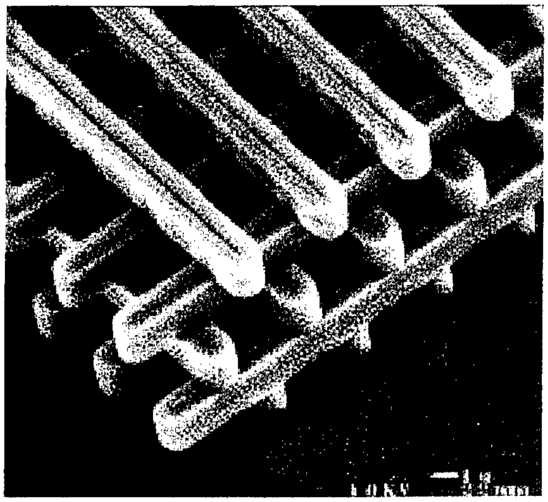

Figure 57. Photonic crystal developed at Sandia National Laboratory. Each element is 1.2μm wide.

Particular attention has to be paid to the processes associated with each type of new materials. This is true whether the material is produced in separate processes and subsequently incorporated into optical MEMS, or whether the new materials are grown in place during MEMS production. Materials and processes simply go hand in hand, with specific materials requiring any one of a limited set of processes, and any process applying only to a range of materials.

Many examples of recently developed and emerging processes germane to production of optical MEMS could be given. A process with great overall promise for MEMS, in general, involves pulsed laser deposition (PLD) of thin films [Chrisey and Hubler 1994]. It requires the straightforward preparation of a target of the material to be made into the thin film. A pulsed laser, usually a KrF laser operating at about 10 Hz, is focussed onto the target. This produces a plasma with temperatures in excess of 10,000 K, high enough to evaporate any material, no matter how refractory it is. The vapor falls on the substrate of interest, usually a few centimeters from the focal spot. The trump characteristic of PLD is the ability to make multi-element films with compositional fidelity. Complex materials, with five and more elements, have been made by PLD, including high temperature superconductors, ferrite, ferroelectric and piezoelectric materials and bio-materials, among others. PLD can also produce films with well-controlled structure, if the substrate is heated.

Thin films of polymers have many uses, so it was desirable to develop a method to produce them by PLD in order to exploit the flexibility and rapid cycle time of the method. Recently, a method of embedding the polymer of interest in a matrix, especially dissolving it in a solvent and freezing the solution, has been used to produce targets for PLD. The laser pulse is absorbed dominantly by the solvent matrix, with the polymer molecules being thrown toward the substrate intact. The smaller solvent molecules are pumped away, leaving a functional film of the polymer of interest. The technique, shown schematically in Figure 58, has been dubbed MAPLE for Matrix-Assisted Pulsed Laser Evaporation [McGill et al. 1998].

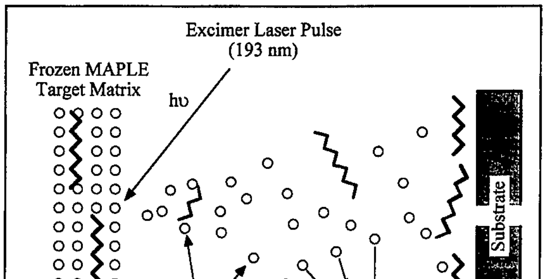

Figure 58. Schematic of the Matrix Assisted Pulsed Laser Evaporation (MAPLE) process.

Other processes to produce micro-scale structures in polymers with useful optical properties have been demonstrated. LIGA was already discussed as a microstructuring process based on x-ray optics. It has been used also to produce plastic parts up to 1 cm in width by exploiting the penetrating power and collimation of synchrotron x-radiation [Guckel 1993]. The micro-scale metal molds, which result from electroplating LIGA resist structures, can be employed for molding or embossing plastic parts. So-called "soft lithography", or microcontact printing, with microstructured poly(dimethy siloxane), could be applied to the production of surfaces with useful optical reflection characteristics [Xia and Whitesides 1998]. In short, there are many opportunities for introduction of both new materials and new processes to the field of optical MEMS.

18. Conclusion

The past four decades have produced two technological revolutions, one in computing and information handling and the other in photonics and communications. These converge in optical MEMS, as indicated in Figure 59. The addition of mechanics to electronics and optics is both exciting technology and very important for commercial applications.

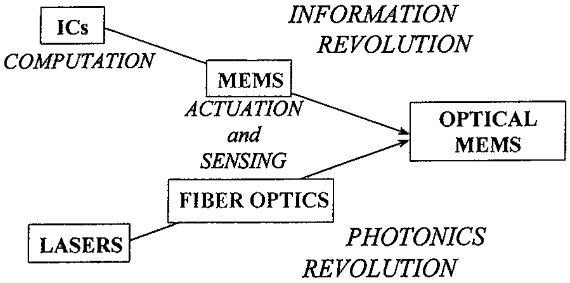

Figure 59. The information and photonics revolutions come together in optical MEMS.

The material presented in this review should make clear that optical MEMS is a field which has "taken off" recently and definitely. The ordinary literature, evidenced in the bibliography, and the patent literature, discussed in the appendix, both support this contention. So also do the variety of optical MEMS devices and the range of their applications. Commercial production of Digital Mirror Devices by Texas Instruments exceeds ten thousand units annually. Fiber optic crossbar and other switches, especially reconfigurable MEMS devices for wavelength division multiplexing, are poised for large-scale production and use in communications networks. Optical MEMS are projected to be a quarter-billion industry annually in the next five years [Detlefs 1999].

For all of the progress made in recent years, it is clear that optical MEMS exhibit great potential for growth. Facile methods for their design are only now getting serious attention. New materials and associated processes will be employed to improve demonstrated devices and enable new optical MEMS. The considerable creativity already exhibited in the design of the devices discussed above, and many others not reviewed, will undoubtedly be surpassed in the future. Creative alternative uses of available optical MEMS, and focussed development of new devices for particular applications, are both expected. Optical MEMS technology, now far from maturity, is poised to grow in both diversity and utility for many years.

NOTE ADDED IN PROOF:

Since completion of this report, a conference on optical MEMS was held in Paris, France. The proceedings contain numerous review and research papers germane to the topics contained herein. Conference proceedings were published as proceedings of the SPIE and are referenced as follows:

> "Design, Test and Microfabrication of MEMS and MOEMS", B. Courtois, S.B. Crary, W. Erhfeld, et.al., *Proceedings of the SPIE – The International Society for Optical Engineering*, vol. 3680, 1999.

Acknowledgments and Figure Credits

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Figure 52.	Robert Corrigan, Silicon Light Machines Inc.
Figure 53.	Larry Hornbeck, Texas Instruments
Figure 54.	Larry Hornbeck, Texas Instruments
Figure 56.	Stefan Ottow, University of Kiel
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Appendix A: Design of Optical MEMS

This appendix outlines some aspects of the design phase of optical MEMS. It should, in principle, include three sub-phases, as indicated in Figure 60. While they can be considered and performed separately, these phases are interactive and should be performed iteratively. The first phase is *optical or functional design.* It involves choosing the geometry and optical characteristics (especially materials) for the MEMS, so that it will perform the desired function. This phase is the focus of this appendix. The primary issue to be addressed is whether or not any of the commercially available optical design codes are useful for the design of optical MEMS. If so, can they be used with the other codes needed to design MEMS? Examples of how some commercially available optical codes perform for the design of MEMS are included at the end of this appendix.

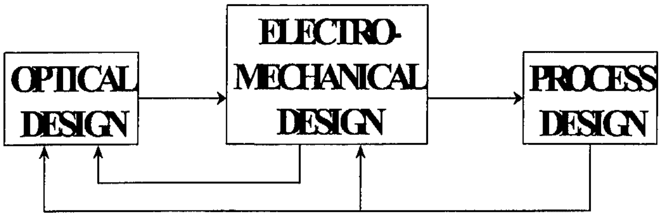

Figure 60. Each sub-phase of the design process has individual components that can be performed separately but each is inherently interrelated with the others.

The second process is the *electro-mechanical design* of the MEMS device. This, in itself involves iterative, detailed and self-consistent calculations of the electronics and the mechanics of the device. It requires consideration of many germane bulk characteristics of materials, such as stiffness, that are far beyond the optical properties of their surfaces. There are a few companies that now offer design codes for MEMS in general. They include, to varying degrees, material parameters and physical characteristics, such as electrostatics, mechanics, thermal processes, fluidics, and others [Nagel 1999].

The third phase is *process design.* Here, the patterning, material deposition and etching steps, which must be done sequentially to produce the desired devices with the needed performance, are laid out in enough detail for the fabrication personnel to make the devices. While there are several codes for process design of integrated circuits, process design of MEMS is at a more primitive stage. Some of the IC codes do apply, and there are codes for the orientation-dependent etching of silicon, for example. However, the development of process design codes for MEMS is an area rich with opportunity. This will be increasingly true as new materials are employed to develop new MEMS, which perform better or are cheaper. For example, compound semiconductors and plastics will be used increasingly in optical MEMS.

Returning to the optical design of MEMS, there is reason for hope that the codes developed to design macroscopic optics might also be good for the design of optical MEMS. This is because the wavelengths of light in and near the optical region of the spectrum are still short compared with the lateral dimensions of almost all of the optical MEMS devices reviewed earlier. The physical dimensions of MEMS optics often fall in the range of 10 to 100 micrometers. In this region, diffraction effects due to the clear-aperture size may be negligible. Of course, for some optical MEMS, smaller structures do bring diffraction effects into play. These might disqualify many of the commercial optical design codes from being useful for MEMS design.

This review of the design of optical MEMS was initiated by using a compilation of optical design software companies, which was published in a trade journal review article [Zankowsky 1997]. Twenty-five firms were listed. Of these, 21 companies were contacted in order to learn details of their codes, and 16 companies responded. The available material, much of it received by downloading trial codes over the internet, was examined to determine the characteristics of each code. These characteristics fall into two classes. The first involves the situations to which each of the codes applies, for example, refractive or reflective optics, or optical fibers. A major aspect for each involves how the surfaces being designed are input, modified and described. These solid model descriptions can have much in common with the descriptions that go into the electro-mechanical models ordinarily employed for MEMS. Such commonality could be important for the overall optical MEMS design problem. The second class of descriptors for each code involves its size, cost and the required platforms and performance to get results in reasonable times. Some of the codes are relatively small, so that they fit and run easily on ordinary personal computers. Others require workstations and much more extensive calculations.

Many simple optical codes, like AutoRay™ and Beam Four™, will perform a basic analysis of optical designs. These codes typically use ray tracing, gaussian ray propagation, ABCD methods, or rotationally-symmetric propagation algorithms. More robust codes use non-sequential ray-tracing to accommodate non-symmetric optical elements. Codes, such as GLAD™ and BPM Cad™, use complex amplitude distribution functions to represent optical beams. These programs will be better suited to some MEMS optical designs because they handle diffraction effects more rigorously. Design software for some optical MEMS must have the capability to model diffractive components, such as Fresnel zone plates, binary lenses, and binary grating structures. Fiber optics and 3-D waveguides also play an important role in some MEMS devices. Design codes, such as IFO_Gratings™, do an excellent job of modeling waveguide structures, but will need to handle waveguides in conjunction with standard lenses to increase their utility. Many optical design programs, such as CODE V™, have extensive catalogues of materials incorporated within the program. Optical MEMS devices will need a very different materials selection, and thus the ability to input custom materials parameters is mandatory. The usefulness of these optical codes will also depend on their ability to output standard file formats, such as IGES, DXF, and STEP, which can be used as input files for both design and fabrication software.

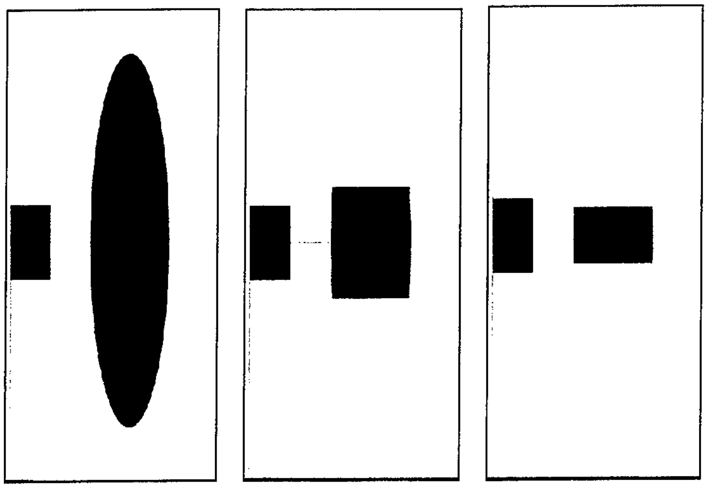

Figure 61. A Schematic top view of the three optical systems. The waveguide is represented by the element on the left of each illustration and the lens is the element on the right. The light propagates from left to right in the positive Z direction.

How a program that uses a complex amplitude distribution function is used to simulate an optical system is shown by a simple example. It illustrates how this method can show the true physics of a micro optical problem. A waveguide system was modeled using BPM Cad. The system contains two optical elements. The first is a square waveguide that confines a propagating wave. The wave profile is mode matched to the lowest order of the waveguide, so that it propagates unaffected by waveguide dimensions. The optical wave is launched into a vacuum from the flat face of the waveguide. The second optical element is a lens with positive curvature. The lens diameter was varied, so three different configurations were investigated. The width of the waveguide is 8 μm while the lens diameters are 40 μm, 12 μm and 6 μm. These different configurations will be referred to as Lens-1, Lens-2, and Lens-3, respectively. Figure 61 shows a schematic top view of the X-Z plane for each optical system. The aspect ratios of the figures are not 1:1, so the lenses look thicker than they should. The Z-axis is the propagation direction and runs from left to right. The right side of each schematic view has been cropped so the full propagation distance is not shown. All of the systems have the same initial conditions on the incoming wave. Each lens is 40 μm thick and positioned 20 μm from the end of the 20 μm long waveguide. The program calculates the electric field intensity out to z=300 μm. The free space propagation from the back of the lens is 220 μm.

Results for Lens-1 are not surprising and could probably be calculated using any good ray tracing program. However, as the lens diameter is reduced, diffraction begins to play an increasingly dominant role. Figures 62 through 64 show the data generated by the simulation software. The data are arranged in a quad-chart format for each lens simulation.

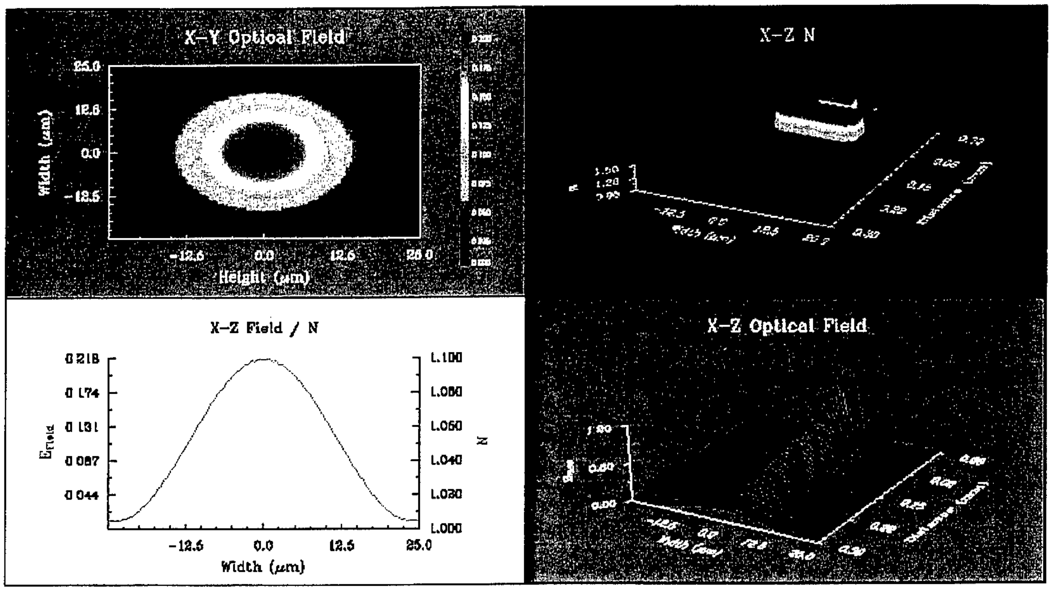

Figure 62. Data from the Lens-1 simulation.

The upper right graph shows index of refraction as a function of the X-Z plane. The waveguide is clearly visible in the back and the lens is in front of it. The simulation is run by letting the program calculate the electric field intensity as the wave propagates in the positive Z-direction. The data in the lower right corner shows the electric field intensity in a slice of the Y-axis (y=0) as a function of the Z-direction. Since this is a three-dimensional simulation, the electric field is calculated at every point in X-Y-Z space. However time is also represented as the wave propagates down the Z-axis. In order to display the data on paper, one or more dimensions must always be held constant. These data can be more easily understood if we look at the graph in the upper left corner. This graph shows the X-Y profile of the electric field at z=300 µm, the end of the simulation. If a slice is taken through the vertical axis of the graph, y=0 µm and its intensity (represented here in false color) is plotted against the X-direction, the resulting graph is identical to the last contour profile in the graph from the lower right corner. This data is also shown on the graph in the lower left corner of the figure. This graph has an additional feature as the index of refraction profile is shown on the right side vertical axis. During the calculation, the entire quad chart is updated for each time increment. Each graph changes, with the exception of the graph in the upper right, since it represents the index of refraction profile that stays constant throughout the simulation. The quad charts in Figures 62 through 64 are data from the end of the simulation and represent the electric field intensity at that point in time. It is clear from the Lens-1 data that the electric field distribution is relatively unaffected by diffraction.

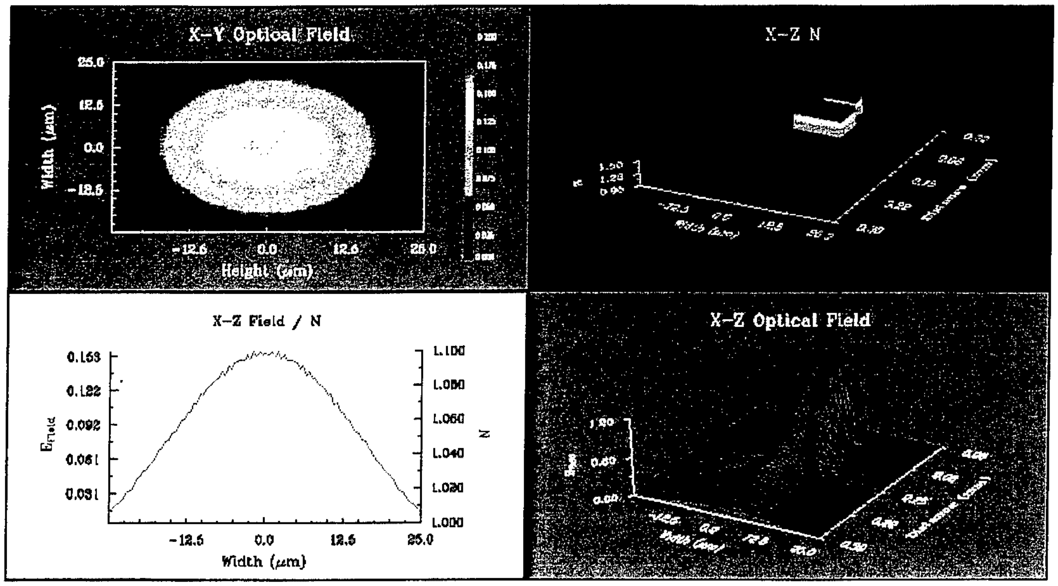

Figure 63. Data from the Lens-2 simulation

The second Lens-2 data is shown in Figure 63. The lens width is reduced to 12 μm and is now just a little larger than the waveguide aperture. The data shows a much different final energy distribution. The radial symmetry is unchanged but the energy is spread across a much larger area. The effects of diffraction can also be seen in the high frequency noise imposed on the energy distribution in the lower left graph. These subtle changes would not be reveled if a ray tracing approach were used.

The Lens-3 data is shown in Figure 64. The lens width is reduced to 6 μm and is now smaller than the exit aperture of the waveguide. The effects of this are dramatic. The energy is completely dispersed and very little remains at the end of the simulation. To illustrate the resolution of the simulation Figure 65 shows the electric field distribution 48 μm past the back surface of the lens. Diffraction effects are very clearly shown, as is the capability of the beam propagation method to handle this type of small optics problem.

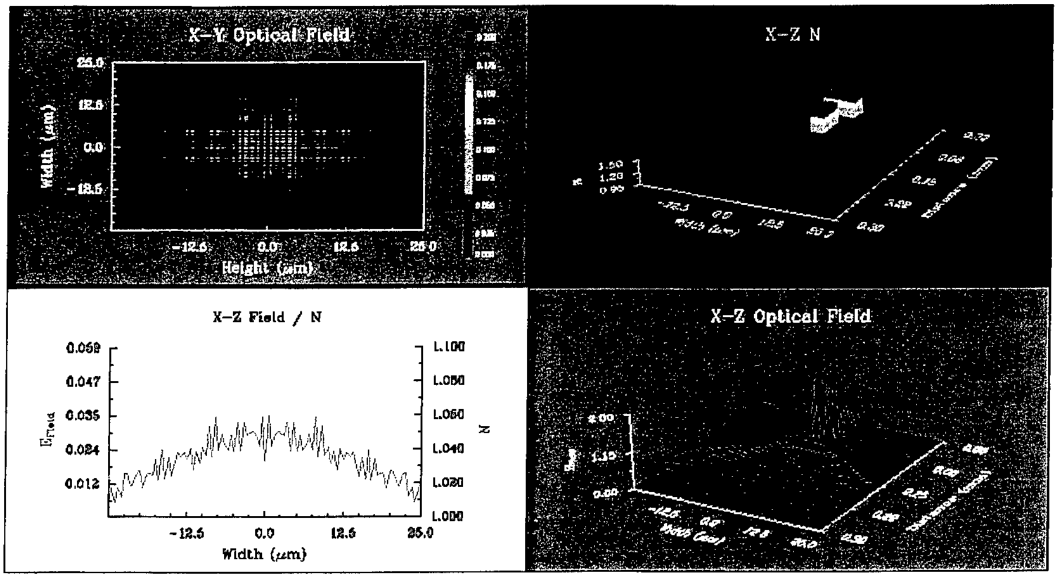

Figure 64. Data from the Lens-3 simulation

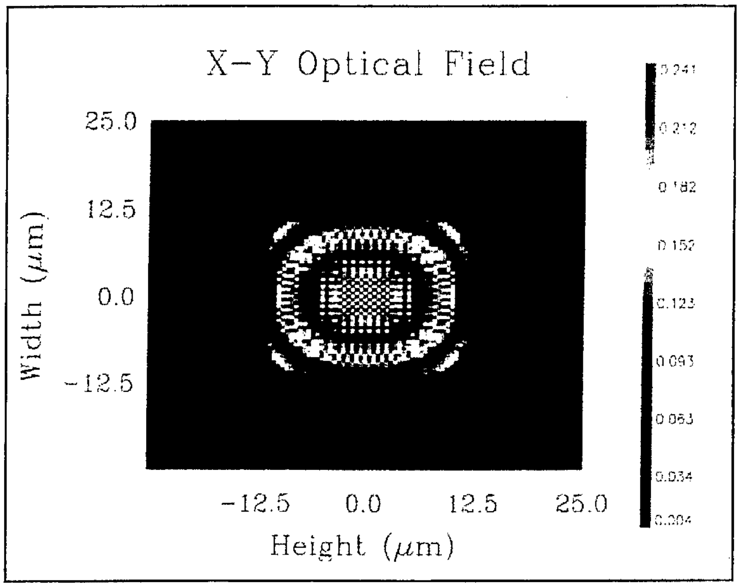

Figure 65. Electric field distribution for the Lens-3 simulation. This data is the X-Y optical field at Z=128 μm.

These data are an example of how well an optical design software package can handle the effects of diffraction and small optical devices. To contrast this, another simulation of a micro optical system was performed using Code V™, which is a ray-tracing based code. A lens pair was designed to couple two fibers together. The lenses were optimized for energy transfer, and a solid model and point spread function was generated. These are shown in Figure 66. To illustrate the inadequacy of the ray-tracing program to handle small optical designs, the original size of the device was scaled down dramatically. The fiber optic was originally designed to be 125 μm in diameter with an elliptical core. The lenses were on the order of 0.5 mm in diameter. The solid model depicted in Figure 66 shows the lens edges clipped, so the relative sizes in the figure are not representative. The entire system was scaled down so that the fiber diameter was 125 pm (a factor of 10^{-6}) and the point spread function, shown in the inset of Figure 66, was unaffected! This simple example shows that the ray tracing algorithms do not adequately reflect the physical world at submicron levels.

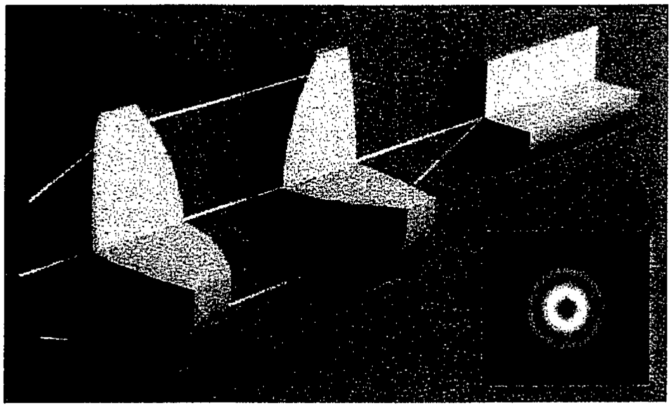

Figure 66. Solid model of a fiber coupler lens system. The source is an unseen fiber to the left edge of the figure and the point spread function is calculated at the face of the fiber on the right. The inset is the false-color contour plot of the point spread function.

Many commercial optical design programs have various features that can be used to simulate optical MEMS, but some programs will be worthless for the task. An effort must be made to do a detailed study of the available programs, including their applicability and efficiency. Later, the best features of each code, from a MEMS perspective, might be integrated into one code. Such software could then be utilized with the available MEMS CAD tools to create a complete, computer-based design capability.

This appendix has focused on commercially available software for design of optical MEMS. A university group has developed a design tool for simulation and analysis of free-space optoelectronic systems. Reference to this work can be found in: "Chatoyant: a computer-aided-design tool for free-space optoelectronic systems", S.P. Levitan, T.P. Kurzweg, P.J. Marchand, et.al., Applied Optics, vol. 37, No. 26, 10 September 1998.

Appendix B: MEMS Patent Analysis

There are three kinds of literatures for any area of technology. The first is the ordinary open literature. It is a good overall measure of the level of activity and the available funding in a field. The second is the thesis literature. It shows the extent to which graduate students and their advisors are willing to make a long-term commitment to advancing the field. The third is the patent literature. It measures the extent to which individuals and companies judge that some ideas are commercially valuable and worth the time and cost of legal protection.

Several projections of the level of commercial activity in the production of MEMS have been made and published [Detlefs 1999, Marshall 1997]. These are useful, but they vary widely in what they include and what they predict. By contrast, an assessment of commercial interest using the patent literature is straightforward. We present our methodology and results, and briefly discuss their implications.

Two patent databases, both searchable with key words for a fee, as part of the Dialog Information Services system, were used. They are claims/U.S. Patents and the Derwent World Patents Index. The key words used were "MEMS", "microelectromechanical systems", "microsystems" and "micromachines", with the search arranged to produce a "hit" for any of these words. The results of the searches were provided in tagged formats on diskettes for importation into the bibliographic software package EndNote™. The use of this program permits further key word searches and specific printouts, as well as the facile insertion of the individual records into the reference list of documents.

In order to examine the patent activity in optical MEMS, a further key word search was performed on the database resulting from the initial searches. The results of searching the two databases independently were compared to eliminate duplicate "hits" in the merged data base. Two data sets were then reduced from the overall database. The number of "basic patents" and the overall number of patents were each tabulated against the year issued. "Basic patents" are counted as individual ideas that are patented under various authorities in different countries. "All patents" represent the total number of patent numbers from the searches, independent of the content of the patents. The number of "all patents" is greater than the number of "basic patents" because the same disclosures are sometimes filed in multiple countries. The information was entered into an Excel™ spreadsheet for plotting.

The patent history for the overall MEMS field is given in Figures 67 and 68. There is "noise" of a few patents per year before the field took off about 1988. This increase lagged by only a year the initial investment in MEMS research and development by the National Science Foundation in the U. S. The stagnation in the 1990-2 time frame could be a statistical fluctuation. However, it might reflect the gap between the NSF program, and the initiation and increase in the funding of MEMS by the Defense Advanced Research Projects Agency in the U. S., mechatronics by the Ministry of International Trade and Industry in Japan, and microsystems technology by the ESPRIT program in Europe. These programs started in the early 1990s and have generally grown since then. Of course, governmental funding is only part of the story, since many of the patents are due to industrial initiatives. The integrated number of all MEMS patents is 726, while the integrated number of basic patents is 453.

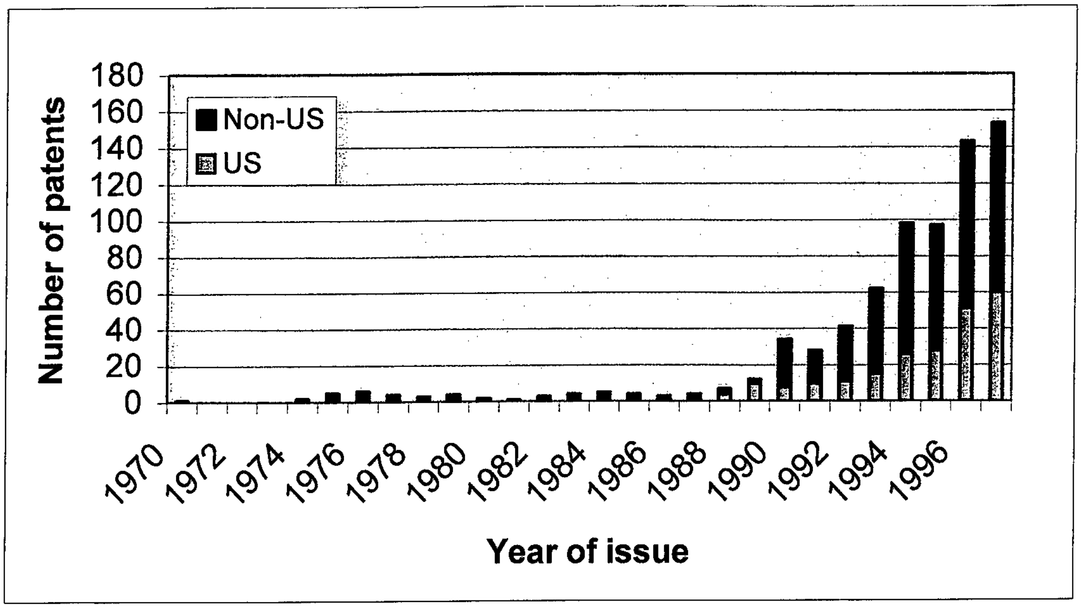

Figure 67. All MEMS patents.

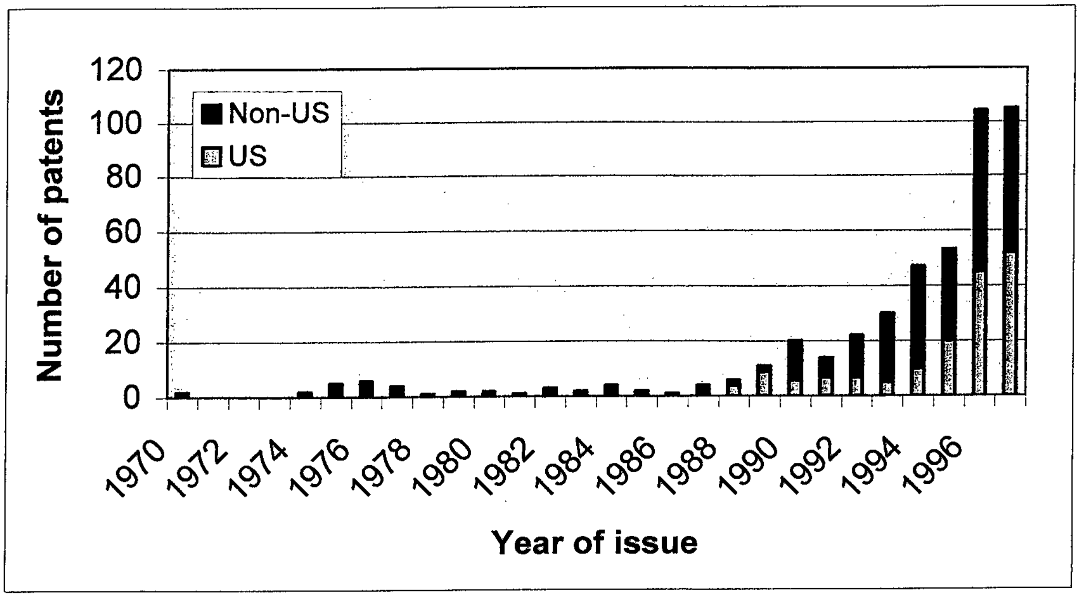

Figure 68. Basic MEMS patents.

The data for optical MEMS tends to mirror the general growth of the field and is shown in Figures 69 and 70, being about 10 to 15 % of the total. There is no clear reason, other than statistical fluctuation, for its somewhat erratic character. The integrated number of all optical MEMS patents is 135 while the integrated number of basic patents on optical MEMS is 83.

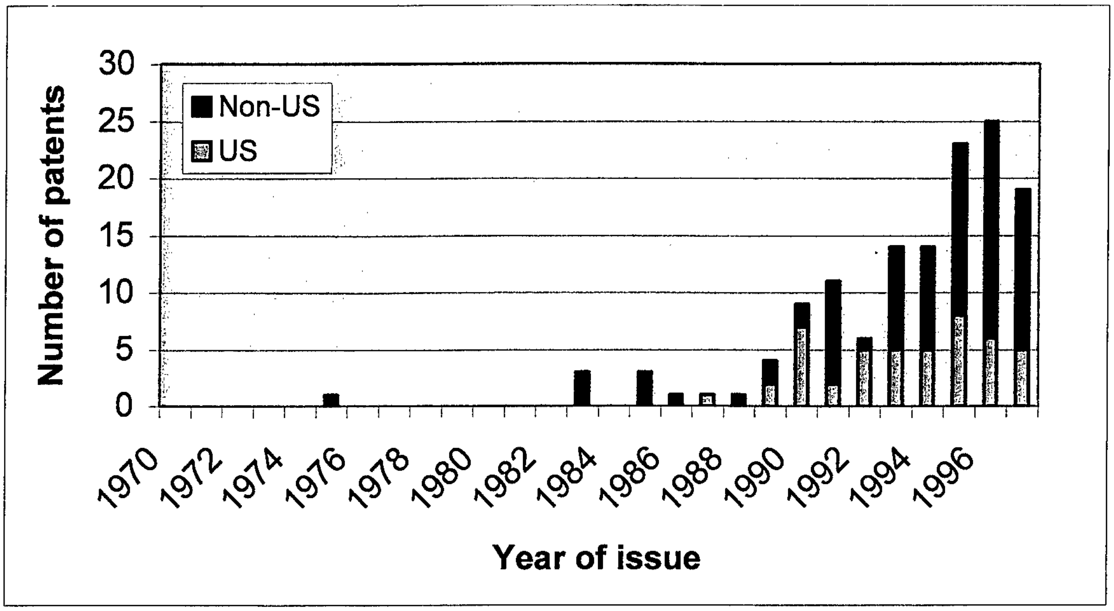

Figure 69. All Optical MEMS patents.

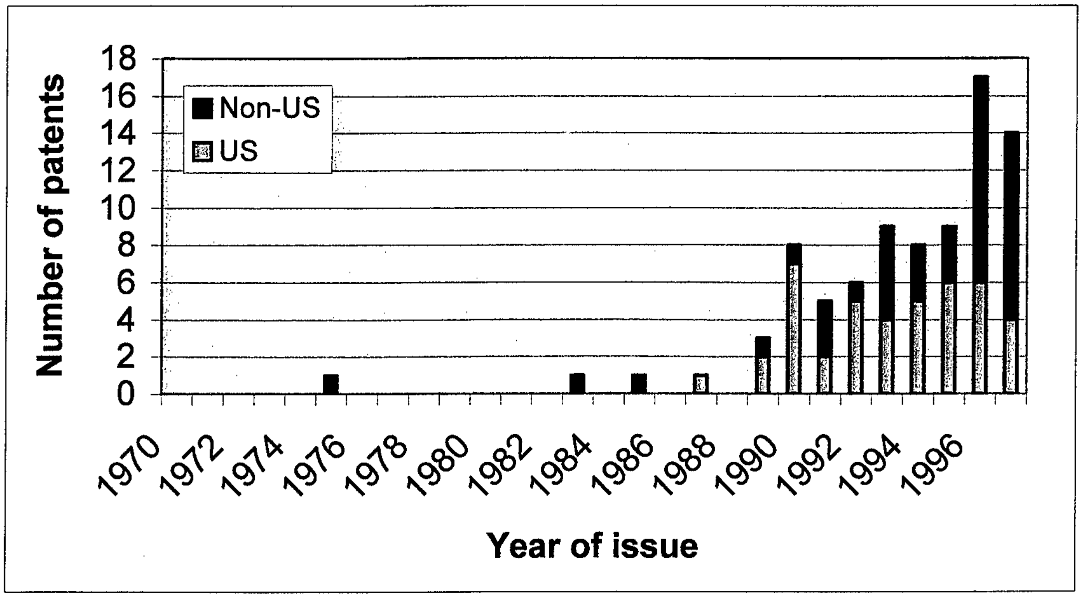

Figure 70. Basic Optical MEMS patents.

This study was meant to provide the overall picture on MEMS patents, and to focus on optical MEMS. It shows that the patents on MEMS in general have begun to exponentiate, with an annual growth rate around 35%, which is equivalent to doubling every two years. The patent activity for optical MEMS is more erratic, being only about one-eighth of the overall level. However, it clearly shows that the tempo of patenting ideas on optical MEMS has also increased significantly recently. The same methodology could be used to highlight the history of patents on other major types of MEMS. For example, a study of patents on MEMS pressure sensors or accelerometers would probably show an earlier and higher level of activity.

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This compilation of references was obtained from three sources, the bibliography collected by Robert Stroud prior to 1998, automated keyword searches of INSPEC and other databases, and references otherwise encountered by the authors. The bibliography was generated via the EndNote™ software package. The entire database of references is contained in an EndNote library file and is available from the lead author. Not all of the references below are cited it the text. The additional papers and reports are given to show related work by authors active in the field, as well as papers otherwise relevant to optics and MEMS.

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