Programmable Diffraction Gratings And Their Uses in Displays, Spectroscopy, and Communications

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ABSTRACT

Microelectromechanical Systems ("MEMS") and optics are a natural match. There are several reasons: MEMS devices have dimensions and achievable actuation distances comparable to the wavelength of light; smooth-surfaced dielectrics, semiconductors, and metals can be used in various combinations; and, photons don't weigh anything, so relatively feeble MEMS actuators can easily manipulate them. Many optical MEMS devices are based on mirror arrays that can be tilted using electrostatic actuation. This paper, however, focuses on programmable diffraction gratings and their uses for projection displays, spectroscopy, and wavelength management in modern optical telecommunication systems.

Keywords: MEMS, diffraction, actuators, displays, spectroscopy, optical communications

1. Introduction

MEMS and optics are a natural match. There are several reasons: MEMS devices have dimensions and achievable actuation distances comparable to the wavelength of light; smooth-surfaced dielectrics, semiconductors, and metals can be used in various combinations; and, photons don't weigh anything, so relatively feeble MEMS actuators can easily manipulate them.

2. The Programmable Diffractive Display

Moveable and tiltable mirrors and pop-up structures have held center stage in optical MEMS for several years, with uses in displays, micro-optical benches, scanners, and a variety of optical telecom switching applications. Less noticed, but perhaps equally important in the long run, is a family of diffractive MEMS structures that represent paradigm shifts in display technology, infrared spectroscopy, and optical telecom. The first such device was the Grating Light Valve Display from David Bloom's group at Stanford [1], subsequently commercialized by Silicon Light Machines (see Figure 1) [2].

The initial version was a binary-switched pixel of several parallel reflecting ribbons, with alternate ribbons initially displaced by a half-wavelength in the unactuated state. When actuated to pull-in, the spacing is reduced to a quarter-wavelength, turning a specular reflector into an efficient diffraction element. The diffracted light is collected and projected to create a display.

Figure 2 shows a close-up of one version of the Silicon Light machines grating light valve display chip. In this commercialized version, the control of the deflecting grating elements is analog, providing continuous control of displacement and corresponding diffraction intensity, as shown schematically in Figure 3 for a simulated model of the pixel response function.

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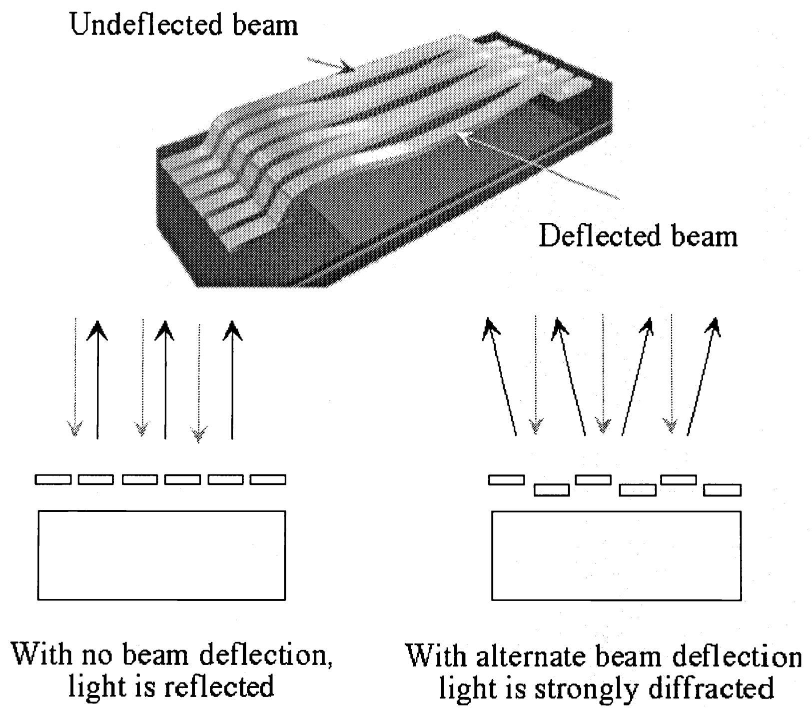

Figure 1. Schematic illustration of the Silicon Light Machines grating light valve pixel. [2]

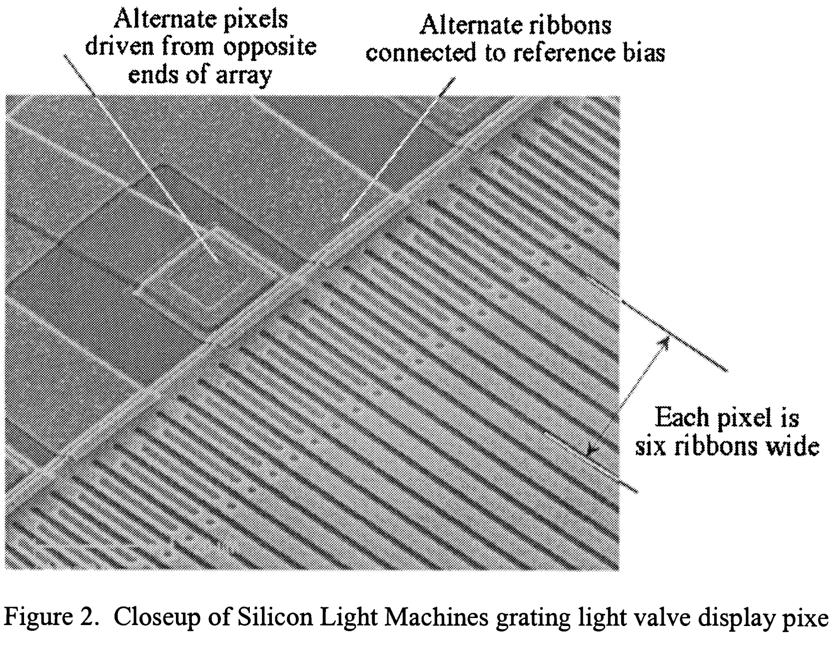

Figure 2. Closeup of Silicon Light Machines grating light valve display pixel. [2]

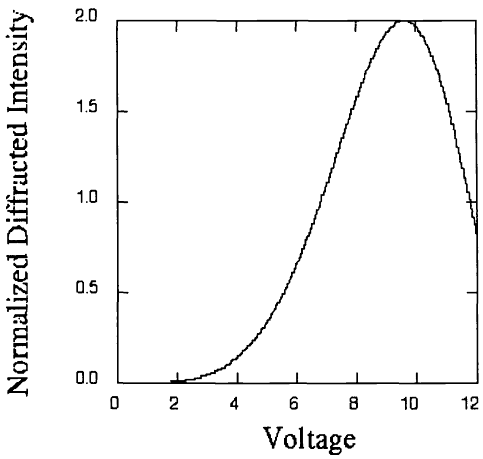

Figure 3. Diffracted intensity vs. voltage for a simulated grating light valve display pixel [2].

3. The Polychromator Applied to Correlation Spectroscopy

The *polychromator* [3] is a MEMS-based electrically programmable diffraction grating that has application both in chemical detection and in the creation of wavelength-management products for modern optical telecommunication systems. Unlike Bloom's initial grating light valve device, the polychromator uses a set of parallel mirror elements, each one of which is individually actuatable with an analog signal, achieving continuous rather than binary control of the mirror element position, a feature that was subsequently incorporated into the commercialized grating light valve display for intensity control. (Analog control has other advantages, notably, the absence of any artifacts due to contact of actuated surfaces.) In the case of the polychromator, with individual control over each grating element, an aperiodic diffraction grating is realized with a fully programmable optical transfer function. When illuminated with white light, the spectral content at a fixed viewing angle can be controlled by adjustment of the various mirror-element positions.

The original motivation for building the polychromator was to enable a new form of correlation spectroscopy, as explained in [3]. Conventional correlation spectroscopy requires a reference cell containing the target species as well as the ability to modulate the spectrum of the target species with pressure or other means. The polychromator, because of its programmable optical transfer function, replaces the reference cell. This not only simplifies the construction and operation of a correlation spectrometer, but it also creates powerful new tools to enhance the versatility and performance of such instruments. Specifically, the programmable feature makes it possible to select only those features of the reference spectrum that are free of interferences when making a chemical identification. Further, the programmable transfer function can be modulated directly using the same actuation and control lines that are used to set the reference spectrum. Programmability also allows the target species to be changed quickly under program control, and even allows the search for highly toxic or labile species that would pose problems in a conventional correlation spectrometer. Finally, the correlation can be performed using the emission spectrum rather than the absorption spectrum of the target species, meaning that the field against which the correlation is performed is a dark field, hence, reducing the background detector current and associated shot noise. This type of spectroscopy is referred to as "dark-field infrared spectroscopy."

A team from MIT, Honeywell, and Sandia Labs has been developing polychromator technology for the past five years under DARPA sponsorship. Initially targeting the 3-5 micron near-infrared band, more recent efforts have focused on devices designed for the 8-12 mid-infrared band. This poses a significant challenge in device design because, in order to create the programmable transfer function, it is necessary to create an array of 512 thin (20 microns wide) and long (1 cm) long mirror elements that can be actuated vertically by distances approaching a half-wavelength, or 4-6 microns, all the while remaining flat and parallel to all the other mirror elements. The successful design of this actuator is the recent work of Erik Deutsch of MIT working in collaboration with Dan Youngner of Honeywell [4]. The process pushes the state of the art in thick sacrificial layers, stress control, and support design to achieve balanced stress transfer between segments of the long mirror elements. Further, a two-layer nonlinear spring design allows the mirror element itself to remain flat while the underlying support structure is actuated, and simultaneously provides robust protection against pull-in. The net result has been a device that, in its first prototype versions, achieves a full 4 microns of vertical travel on each of 512 individually controlled mirror elements at high yield. Figure 4 shows the double-level goal-coated polysilicon device structure. Device uniformity and repeatability are quite good.

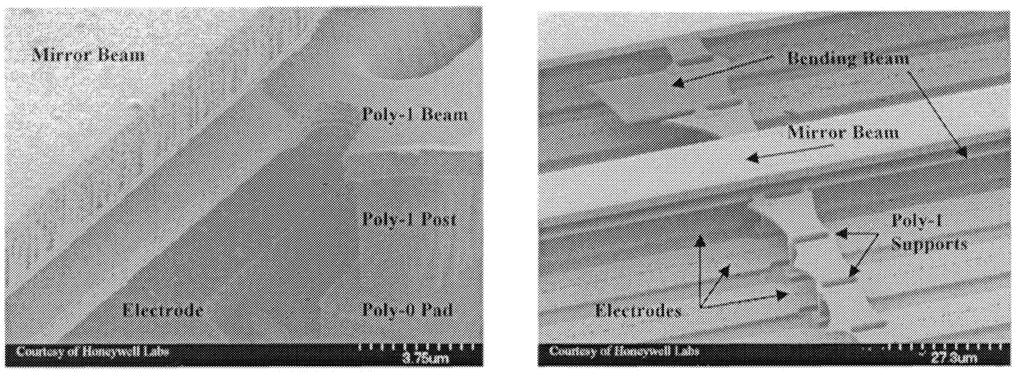

Figure 4. Left: lower beam support of polychromator. Right: broken away structure showing both lower beam support and double-layer structure with mirror beam on top [4].

The team at Sandia Labs has designed a benchtop correlation spectrometer that incorporates the polychromator along with a cooled broadband detector. Examples of spectral detection include carbon dioxide, and the detection of both toluene and hexane with a single optimized modulation scheme. More recently, the polychromator team has adopted the Polychromix optical telecom architecture (explained below) for spectroscopy. Details on this approach are being presented in another paper at this conference [5].

4. The Polychromator Adapted for Optical Telecom

Modern Dense Wave Division Multiplexed (DWDM) optical telecommunications systems carry many closely-spaced optical carriers or "channels" on a single optical fiber, each one of which may be modulated with information at 10 Gbit /sec rates. At various places in the network, this complex optical signal must be amplified and, because optical amplifiers are nonlinear in their operation and non-uniform with respect to wavelength, the channels entering the amplifiers must have their power profile optimized in order to obtain uniform power in each channel at the amplifier output. Present network architectures are migrating from the use of fixed filters to achieve this power adjustment toward the incorporation of programmable dynamically operable power compensation devices.

The Dynamic Channel Orchestrator^{TM} from Polychromix (Figure 5) provides a good example of this type of product. The core technology is based on the polychromator, but its structure and use is modified and optimized for the constraints of the optical telecommunications market.

Figures 5 and 6 show the Polychromix Dynamic Channel Orchestrator^{TM} and a schematic rendering of what it contains. The function of this product is to selectively and controllably attenuate each wavelength in a DWDM optical telecommunications signal. Such devices are needed to compensate for power nonuniformity in the performance of optical amplifiers and to control network power at add/drop ports. The product operates over the telecommunications C-band (wavelengths near 1.55 microns), controlling the power in 100 channels spaced 50 GHz apart over a 40dB dynamic range under program control. It contains one polychromator chip (see Fig. 7) modified and optimized for this wavelength range plus a fixed grating to disperse the individual wavelengths such that each wavelength hits a different portion of the polychromator. The details of the MEMS chip are intimately linked to the free-space optical design, the selection of fixed grating and lenses and the mounting and alignment procedures of all components on the optical bench. By varying the actuation signal reaching the chip, the device can either reflect all the light in any channel back into the output fiber, corresponding to the minimum attenuation state, or can diffract the light toward an absorber, resulting in controllable attenuation of that wavelength.

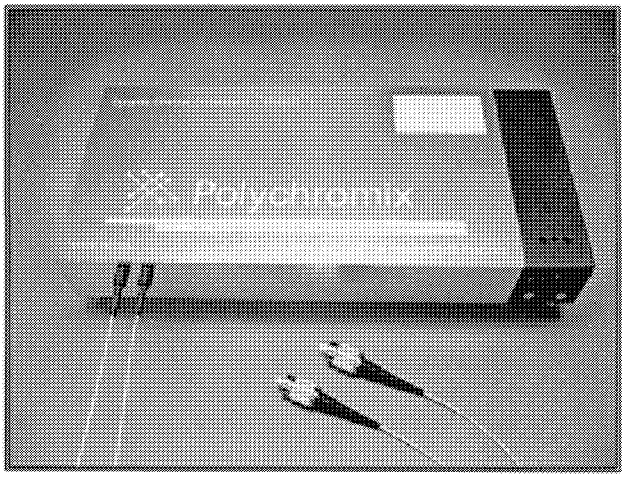

Figure 5. The Polychromix Dynamic Channel Orchestrator^{TM}.

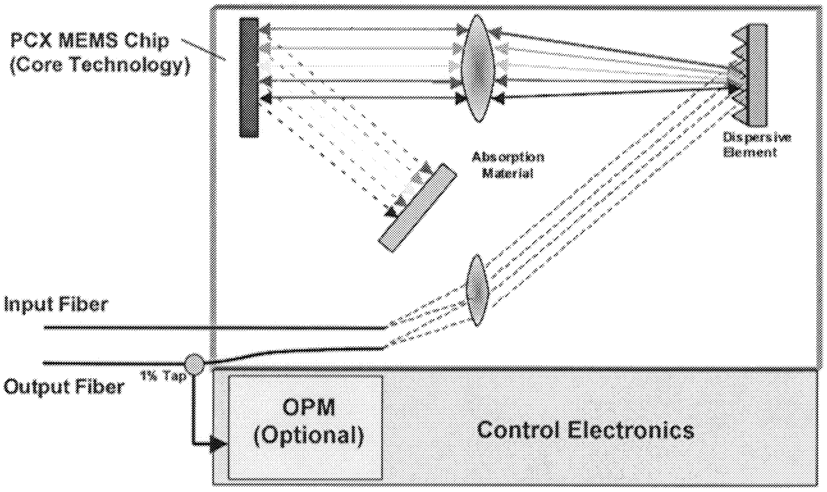

Figure 6. Schematic of the Polychromix Dynamic Channel Orchestrator^{TM}.

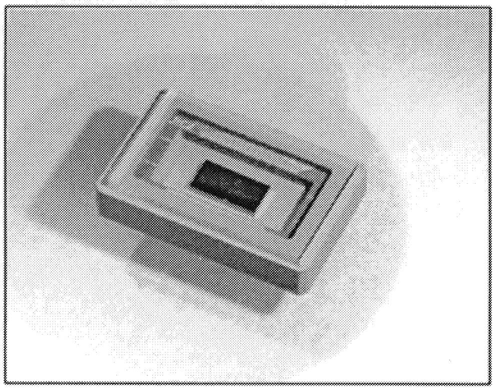

Figure 7. MEMS Chip used in the Polychromix Dynamic Channel Orchestrator^{TM}.

As mentioned earlier, the Polychromix product architecture turns out to be very relevant to spectroscopy applications. Recent results from this approach are being presented by Sinclair at this meeting [5].

5. Conclusion

Dynamic programmable diffraction devices have an important role in display devices, optical spectrometers, and wavelength-management products for optical telecommunications. Prototype versions of products for each of these applications already exist, and the optical telecom product is now commercially available. It is anticipated that many more applications for dynamic diffraction devices will be found as the commercial infrastructure for this type of device becomes fully established.

Acknowledgement

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