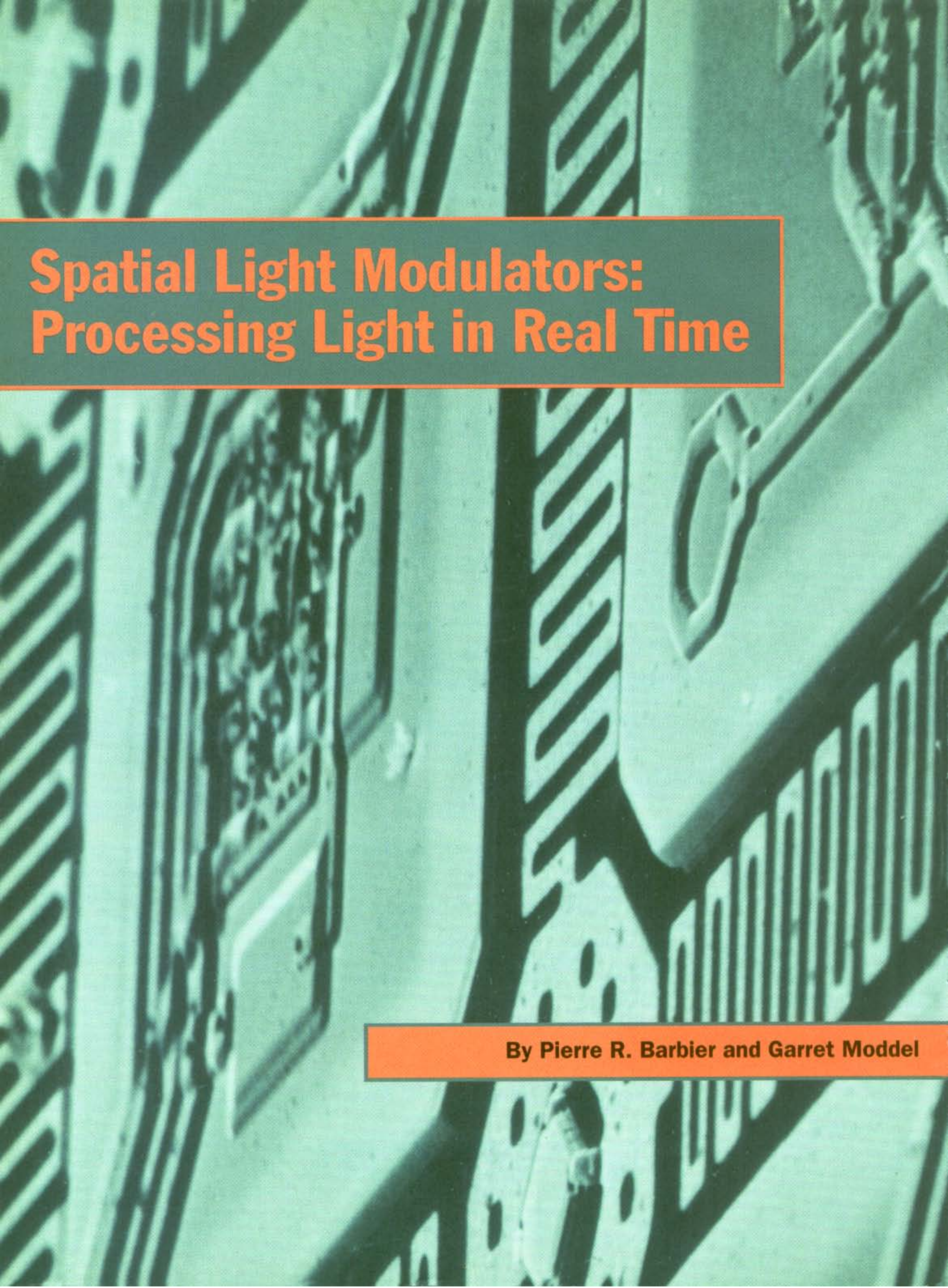
Spatial Light Modulators: Processing Light in Real Time

By Pierre R. Barbier and Garret Moddel



Improvements in spatial light modulators (SLMs) are expanding their applications. Barbier and Moddel describe how SLMs work and provide insight into the latest SLM applications.

Spatial light modulator (SLM) is the inscrutable name for a device that is making its quiet, yet steady entrance into our daily lives. Also called light valves, SLMs are essentially time-varying masks. An example of their function can be seen in an optical crossbar switch. It can be visualized as a bar consisting of a linear array of light emitters, and another bar consisting of a linear array of light detectors crossed with respect to the first one and at some small distance from it. Each emitter illuminates all of the detectors. As described, the crossbar switch does not appear interesting. If we now insert a mask between the emitter array and the detector array, only those parts of the mask that are transmissive will provide a connection between specific emitters and selected detectors. The mask is an SLM. The selected interconnects that have been formed may be reconfigured by changing the pattern on the SLM.

SLMs include a large range of devices whose primary function is to spatially modulate a readout beam. The image can be input either electrically or optically. Electrically addressed spatial light modulators (EASLMs) can be distinguished from optically addressed spatial light modulators (OASLMs). Liquid crystal displays (LCDs) are a type of EASLM, and photographic film and low-light image intensifiers are types of OASLMs (see Fig. 1).

The dividing line between display technology and SLM technology is vague. Generally SLM devices provide higher frame rates or resolution than display devices. In many applications, SLMs must exhibit other properties, such as phase flatness and small size (to be compatible with available optics), which are not required of displays. In this article, we include high performance LCDs as SLMs. Because so many different types of SLMs have been developed over the years, we must limit our discussion to some new SLM technologies that have the potential to provide superior performance over video displays, and to recently developed and new potential SLM applications. Although linear arrays may use the same SLM technology, we will limit this discussion to two-dimensional arrays.[1]

Two prominent display applications of SLMs that are starting to affect our everyday lives are in the entertainment industry. They consist of large screen video projectors[2] and virtual reality, head-mounted displays. Even though these applications were originally developed around the traditional cathodic ray tube (CRT), recent breakthroughs in SLM technology have increased their performance dramatically.

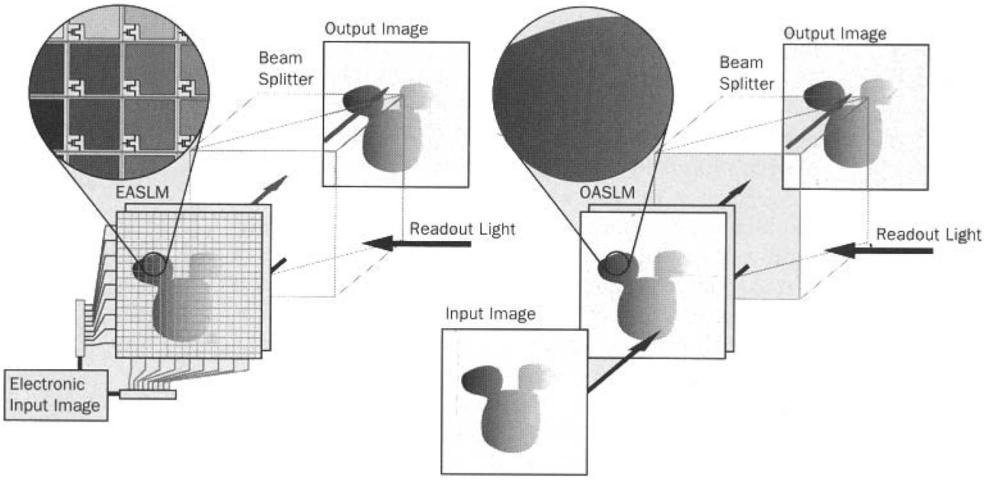


Figure 1. Electrically addressed spatial light modulators (left): individual pixels are addressed electrically. Optically addressed spatial light modulator (right): an input image is sent onto the device, which forms a replica in the modulating medium. Both devices are read out with an external light beam, which is modulated and reflected by (as shown here) or transmitted through the device. Note that OASLMs may also be pixelated.

CRT-based video projectors were limited by the brightness of the image formed onto their phosphors and projected onto the screen, restricting the use of these devices to dimly lit rooms. In contrast, in an SLM-based video projector, the image is formed by the SLMs and read out by a high-power lamp or by laser beams before being projected onto a screen. Consequently, much

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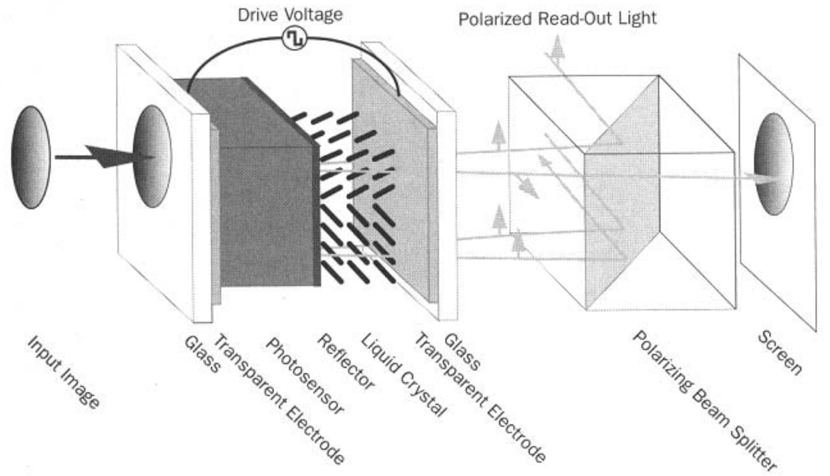


Figure 2. Diagram of the operation of a liquid crystal optically addressed spatial light modulator: the input image is absorbed in the photosensor. The photogenerated charges cause the liquid crystal molecules to rotate, which in turn affects the polarization—in this example—of the polarized readout light. This polarization replica of the input image is transformed into an intensity replica by filtering through a polarizing beam splitter.[3]

brighter and larger images can be projected, and are limited mainly by the intensity of the light source. With current video projectors, images that have a diagonal dimension of a few meters are perfectly visible in a normally illuminated room. Applications of these systems in entertainment include network or traffic-control monitoring rooms. These systems are manufactured by several companies including Ampro Greyhawk Division, Hughes-JVC, In Focus, Sharp, and Texas Instruments.

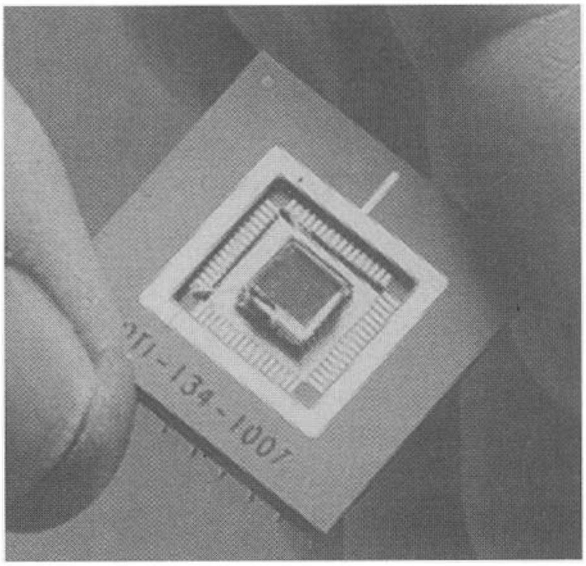
Head-mounted displays used to be bulky because of the electronics and the high voltages required to control the small CRTs. New liquid crystal SLMs, which are much smaller and require only a few volts, have reduced these constraints considerably, yielding light-weight head-mounted displays that produce a striking stereoscopic effect. Along with applications in 3-D video games, these devices can be used in virtual reality applications. Such devices are manufactured by Kaiser Electro-Optics, Virtual Research Systems, Liquid Image, and so on.

Addressing

The light-modulating medium modifies the readout light using an electro-optic effect. The most practical and common approach to make an EASLM is to apply matrix-addressing electrodes to a substrate. The pixels are formed at the intersection of the electrodes, which modulate the voltage dropped across the sandwiched light-modulating medium. To make it possible to address a large number of rows sequentially, a transistor at each pixel transfers and stores the electrical information for that pixel. Therefore, the addressing of the device can be carried out rapidly while the reading can be done more slowly in the remaining frame period. For example, EASLMs used in head-mounted displays incorporate an integrated circuit (IC) silicon substrate addressing matrix, and a liquid crystal light-modulating medium. The pixel size in these active backplane SLMs is limited to that which can be formed by very large-scale integration (VLSI) IC fabrication. For some coherent optical processing applications, the current state of the art is not sufficiently small. Technical challenges include increasing the maximum number of pixels, frame rate, fill factor (fraction of an area that is optically usable), number of distinct gray levels, and contrast ratio.

In optically addressed active backplane devices, a photodiode, which replaces the control electrode matrix, can be incorporated into each pixel. The optical write-image is directly sensed by the photodiodes and the image is transferred to the modulating layer. Some "smarts" can be built into this OASLM in the electronic circuit between the photodiodes and the pixels, implementing some specific optical image processing functions such as edge detection or human retina simulation. This forms one type of smart pixel SLM.

Often such optical image processing is not necessary, and the substrate can be coated with a uniform film of photosensing material that absorbs the write-image photons and converts them to electron-hole pairs. These carriers locally alter the electric field across the electro-optic material modulating the readout light. The light modulating medium may be adjacent to the photosensor film forming a hybrid OASLM. This is the case in liquid crystal-amorphous silicon OASLMs, represented in Figure 2.[3] Alternatively, a single material can act as both photosensor and light-modulating medium, forming monolithic OASLMs. This is the case in multiple-quantum-well (MQW) self-electro-optic devices (SEEDs) where the effect is two-dimensional,[4] and photorefractive crystals OASLMs that form volume holograms. The resolution of OASLMs can be quite high, above 100 linepairs/mm, limited only by the physical properties of the photosensing and modulating layers. In addition to spatial resolution, performance limitations of these devices include



Courtesy of Displaytech Inc.

Figure 3. Integrated circuit backplane spatial light modulator incorporating a ferroelectric liquid crystal. The 256 × 256 array of pixels can be driven at frame rates of up to 3 kHz.

response time, contrast ratio, write-light sensitivity, and linearity. (SLM resolution is usually quoted in linepairs per millimeter (lp/mm) and display resolution in lines per millimeter. Therefore, the resolution in linepairs per millimeter of a display used as an SLM is twice that of its resolution expressed in lines per millimeter.)

Devices

As shown in Figure 1, the output pattern of an SLM is imposed onto the readout light, which may be a coherent laser beam or an incoherent filtered or unfiltered white light. SLMs may reflect or transmit the readout light, and modulate its intensity, phase, polarization, or angle depending on the light modulating medium. We discuss four types of SLM light modulation approaches: liquid crystal, SEED, digital micromirror device (DMD), and photorefractive crystal. Note that other devices not discussed in this article have been developed, such as the charge-transfer-plate membrane-mirror OASLM, the magneto-optic OASLM, and the Si/PLZT OASLM.

How they work

The application of an electric field across a liquid crystal (LC) film causes the molecules to rotate. The refractive index along the optic axis parallel to the long axis of the liquid crystal is significantly different from the index along a perpendicular short axis. This difference, the birefringence, is quite substantial for liquid crystal molecules, typically about 0.2. By an appropriate choice of the twist of the liquid crystal axis or the thickness of the material, and of the polarization of the readout light, the polarization of the light may be rotated or its phase modulated. Polarization rotation can be converted to intensity modulation by filtering through a polarizer, as is done in most laptop computer screens or in LC SLM-based video projectors (see Fig. 2). Phase modulation can be used for adaptive optics applications or to create thin-film holograms for optical image processing applications. Two main types of liquid crystal materials have been used in SLMs:

- Nematic liquid crystals (NLCs) provide analog response, but are limited by the natural relaxation of the material, to a response time of approximately 10 msec.
- Surface-stabilized ferroelectric liquid crystals (SSFLCs) switch much faster (10 μsec), but are inherently binary in their response.

Both types of material have been incorporated into EASLMs, using IC backplanes to provide the drive circuitry (see Fig. 3), and OASLMs, using thin film photosensors such as hydrogenated amorphous silicon,[3] polycrystalline silicon thin film transistors (TFTs), or crystalline silicon photodiode arrays.[4] LC SLMs were pioneered by Hughes and are now manufactured by several companies, including Hughes-JVC, CRL, Displaytech (see Fig. 3), and Hammamatsu.

Glossary

Active backplane SLM: A spatial light modulator in which a silicon integrated circuit addresses each pixel individually (predominantly implemented with liquid crystal technology).

Contrast ratio: The on-to-off ratio of the output light intensity (ideally infinity).

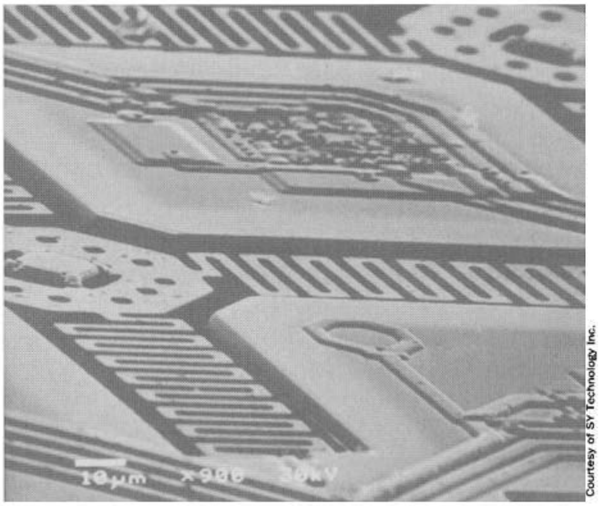
Modulation transfer function (MTF) curve: The curve corresponding to the contrast ratio versus the spatial frequency of a periodic one-dimensional pattern expressed in linepairs per millimeter (lp/mm).

Pixel: The minimum addressable area as defined by patterning.

Smart pixel SLM: A spatial light modulator in which a silicon VLSI circuit performs an image processing operation and addresses each pixel.

Spatial resolution: The spatial frequency expressed in linepairs/millimeter (lp/mm) at which the MTF reaches 50% or 10%, depending on the definition. The inverse of the spatial resolution is equivalent to pixel dimension for an unpatterned OASLM. The spatial resolution is simply the inverse of the pixel dimension divided by two for a patterned SLM.

Thin film transistors (TFT): Transistor fabricated in thin semiconductor films, such as hydrogenated amorphous silicon, to drive the pixels of an active matrix liquid crystal display.



Courtesy of SY Technology Inc.

Figure 4. SEM photograph of a phase-modulating micromirror and its electronic driver. Drive electronics controls the vertical position of the micromirror with an electrostatic field. The silicon micromirror array is micromachined on cantilevers. Using a separate microlenslet array, light is focused onto each micromirror to modulate the phase.

Amplitude modulation may be achieved in a SEED through the modulation of the excitonic absorption edge by an electric field (quantum-confined Stark effect) applied across a multiple quantum well (MQW) structure.[5] OASLMs have been formed by depositing photodiode films on top of the MQWs and by making them semi-insulating. A modified version of this technology is the bonding of a GaAs/AlGaAs MQW chip with photodetectors and modulators onto a VLSI silicon chip to improve switching performance.[6] Because they switch rapidly (on the order of 1 GHz), MQW SLMs are used predominantly in photonic switching such as in the crossbar switch described earlier.

DMDs are fabricated by micromachining a silicon wafer.[7] Tiny (16 μm × 16 μm) suspended mirrors are micromachined on cantilevers. The mirrors are rotated by an electrostatic field to one of two stable positions. The reflection angle modulation is converted into an intensity modulation after spatial filtering through an aperture. DMDs, with 400 × 600 pixels, can be fabricated with their addressing circuitry into a single chip. Their response time is short (0.3 msec), but they are inherently digital, and require multiplexing to achieve grey levels. Texas Instruments has fabricated and incorporated DMDs into commercial TV projection systems. SY Technology is developing a new generation of micromirrors that can modulate the phase only and could be used in adaptive optics applications (see Fig. 4).

Photorefractive crystals use an effect that results from a local modulation of the index of refraction of the crystal after illumination with a write light.[8] The photorefractive effect can be used for phase conjugation, which is described in the following section. This effect is usually relatively slow (10-100 msec) and requires a single wavelength. To this category belongs the Pockels Readout Optical Modulator (PROM), which uses the longitudinal electro-optic effect and is commonly made from a $Bi_{12}SiO_{20}$ (BSO) crystal, and the Russian PRIZ (a Russian acronym for "image transformer"), which uses the transverse electro-optic effect.

Applications and trends

Video projection

The most apparent applications of SLMs have been in displays. Liquid crystal EASLMs and OASLMs, as well as DMDs, are at the heart of new video projectors. They are used to modulate a bright white light for projection of video or computer images onto a screen. The picture is sent electronically to the EASLMs, or to CRTs that are imaged onto the photosensor of the OASLMs, which then modulate the readout light. Red, green, and blue images must be generated and combined to reconstitute color images. Video projectors are presently limited by the brightness of the readout source and the insertion loss of the light modulating scheme. Refinements may improve this projection efficiency and larger pixel numbers should be soon possible to accommodate high definition television.

Image processing

Correlators aid machine vision and pattern recognition. Specific optical image processing operations necessary in machine-vision applications include image correlation using LC or fast MQW OASLMs at the Fourier plane as an intensity sensor. Image correlation consists of image recognition using Fourier transform processing. This can be achieved in real time by using an OASLM-based image correlator, which may be much faster than processing the images numerically on a desktop computer. Image correlators can be used for pattern recognition such as for finger print identification. With the development of smart pixel OASLMs other specific machine vision applications may be expected.

Image conversion

Optical computing applications also take advantage of SLMs when an incoherent scene needs to be converted in real time to a coherent monochromatic image. This is done using LC OASLMs, or MQW OASLMs. Other applications include wavelength conversion where a visible scene is converted into an infrared image for simulation purposes, and conversely, for image amplification.

Interconnects

EASLMs may be applied to optical interconnects where it is necessary to rapidly interconnect a matrix of different processors to one another. This can be done by using a crossbar switch described in the introduction incorporating a fast MQW SLM. The SLM acts as a switch matrix that rapidly controls the interconnection between the outputs and inputs of all the processors.[6]

Phase conjugation

Phase conjugation can be accomplished using OASLMs, such as photorefractive crystals and liquid crystal/amorphous silicon devices. In phase conjugation, the exact complex conjugate of a laser beam is redirected precisely along the incoming path. A plane wavefront that passes through a distorting medium will return as an unaberrated plane wave after reflection from the phase conjugate mirror and propagation through the same medium. Applications for this include imaging or laser beam propagation through a turbulent medium such as the atmosphere.[10]

Optical compensation

Photorefractives have found applications as optical compensators where there is a need to clean up a laser beam that is distorted by a mechanism whose characteristic time is slower than the photorefractive effect. The Hughes Compensated Laser Ultrasonic Evaluation (CLUE) system employs a $BaTiO_3$ (barium titanate) crystal double-phase conjugate mirror to clean up the spatial information of a laser beam reflected and distorted from the rough surface of a metal part.[11] The metal part is excited by ultrasound vibrations and modulates the phase of the reflected laser beam. The double-phase conjugate mirror transfers the energy of the distorted reflected beam to a clean reference beam. The ultrasonic response of the part is recovered by heterodyne detection of the cleaned beam and recorded. After raster-scanning a welded metal part, an image of the quality of the weld joint can be obtained in the industrial environment.

Adaptive optics

Phase-modulation EASLMs can be used in adaptive optics to compensate for phase distortions of an arriving light wavefront after propagation through a distorting medium.[9, 10] This can be used for imaging through the atmosphere in astronomical or terrestrial applications or to precompensate a laser beam before sending it through the atmosphere and achieve diffraction-limited performance, *i.e.*, the smallest possible spot size.

Turbulence simulation

Finally, an unusual application of SLMs that was developed at the Army Research Lab is in an atmospheric turbulence simulator.[12] This system uses EASLMs and OASLMs in a close-loop configuration. By adjusting the characteristics of the input phase screen generated by the EASLM, the system can be set to a chaotic behavior with characteristics similar to atmospheric turbulence.

Future developments

In addition to previously mentioned applications, the next few years will see other emerging applications made feasible by the appearance of new material systems. In particular, for some photorefractive applications, photopolymers will be more practical than photorefractive crystals, and biological material, in particular bacteriorhodopsin, may also be used to form practical OASLMs.

The commercially driven applications that are more likely to make an immediate entrance are machine vision applications, optical correlators for pattern recognition in machine vision and security applications, and the use of SLMs as page formatters in holographic storage. With improvements in OASLMs, there may be wider application of SLMs in adaptive optics and in optical crossbar switches. Finally, like other technologies, SLM technology might exceed our current expectations with regard to potential applications.

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Garret Moddel is a professor in the Electrical & Computer Engineering Department and Optoelectronic Computer System Center at the University of Colorado, Boulder, Colo., and Pierre R. Barbier is assistant research scientist in the Laboratory for Physical Sciences and Electrical Engineering Department, University of Maryland, College Park, Md.

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