Improvement of spatial light modulator optical input/output performance using microlens arrays

H. Chase, M. A. Handschy, M. J. O'Callaghan, and F. W. Supon

Displaytech, Inc., 2200 Central Avenue Boulder, Colorado 80301

Received March 6, 1995

Advanced spatial light modulators both detect incident light and modulate reflected light. Each pixel may contain multiple photodetectors, a modulator, control circuitry, and signal-processing circuitry. Because each detector and modulator occupies only a fraction of the area of a pixel the optical efficiency of these devices suffers. We have experimented with improving optical input/output performance by integrating a microlens array with a ferroelectric liquid-crystal VLSI spatial light modulator. We have studied the microlens VLSI spacing accuracy that must be achieved to yield minimum distortion of reflected wave fronts and the best optical efficiency for Fourier-transform applications.

Spatial light modulators (SLM's) are being developed for a variety of optical information processing, wavefront manipulation, and display applications. The pixels of advanced SLM's envisaged for some of these applications may contain multiple photodetectors, a modulator (reflective, transmissive, or emissive), control circuitry, and signal-processing circuitry. Because each detector and modulator occupies only a fraction of the area of a pixel (the element's fill factor), the optical efficiency suffers. Furthermore, to take full advantage of the SLM's capabilities, images simultaneously incident from various directions should be guided selectively onto separate detectors or modulators within the pixels (angular multiplexing). To address these issues, we have carried out experiments involving the placement of microlens arrays on top of ferroelectric liquid crystal (FLC) VLSI SLM's. Microlens arrays also offer a solution to the problem of nonplanar VLSI surfaces. Many VLSI processes produce a surface that is bumpy; thus the VLSI surface performs poorly as a mirror and interferes with attaining high-quality FLC layers. However, it is generally possible to ensure that at least some fraction of the area within a pixel is smooth. By using the focusing properties of a microlens, one can confine light to be modulated in reflection to this smooth region within the pixel. Microlens arrays also have been investigated for use in improving the optical performance of deformable mirror SLM's.[1]

An FLC-VLSI SLM[2-5] consists of a specially designed integrated circuit, a layer of FLC (~1 μm thick), and a window with a transparent conductive coating (Fig. 1). The FLC modulates the polarization state of reflected light, and the state of the FLC is switched by voltages applied to metal pads on the VLSI surface. Each pixel of the SLM that we used contains a modulator (reflective electrode) and four photodetectors. The pitch of the 12×12 array of square pixels is 200 μm. The modulator pad within each pixel is approximately octagonal in shape, with an area of 4450 μm^2 and a width of 70 μm; its fill factor is $4450\ \mu m^2/(200\ \mu m)^2 = 0.11$. The detectors within each pixel also are approximately octagonal in shape but with an area of 772 μm^2, a width of 30 μm, and a fill factor of 0.019.

Microlens arrays are available from several vendors. We chose to use one manufactured by Adaptive Optics Associates,[6] because it was available with suitable parameters and could be placed on a glass window compatible with construction of an FLC-VLSI SLM. The specified fill factor is greater than 99%, the pitch is 200 μm, and the focal length in air is 1.0 mm. The focal length of a microlens within the glass used for the FLC-VLSI window is 1.47 mm at a wavelength of 633 nm.

Figure 2 shows photographs of two FLC-VLSI SLM's taken through a polarizing microscope. One SLM has only a standard window, and the other has a window with a microlens array formed on its surface. In the left photograph the modulator electrodes clearly occupy only a small fraction of each pixel (11% fill factor), whereas in the right photograph the modulator appears to have a fill factor of nearly 100%.

Because of its small size, each photodetector receives only 1.9% of all light incident upon a pixel when a microlens array is not used. When a microlens array is used, light falling upon the pixel is focused to a spot with a diameter of approximately $2.44\lambda f/n_G w = 8\ \mu$m, where $\lambda = 633$ nm, $f = 1.47$ mm, $n_G = 1.47$, and the pixel width is $w = 200\ \mu$m. Because the spot width is approximately one fourth the photodetector width, essentially all light incident upon the pixel should

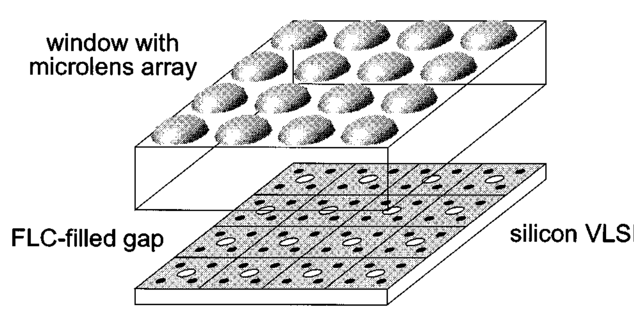

Fig. 1. Illustration of the structure of an FLC-VLSI SLM with a microlens array (not to scale).

0146-9592/95/121444-03$6.00/0

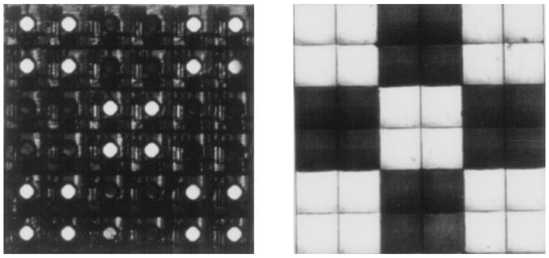

Fig. 2. Left: 6 × 6 portion of a SLM with no microlenses in which the FLC modulators have been turned on (the bright circular regions) in a checkerboard pattern of 2 × 2 groups. Right: otherwise identical SLM that has a microlens array attached.

be detected, resulting in a sensitivity gain of 100%/1.9% = 53. We observed that the SLM with a microlens array produced photodetector signals 46 times greater than the SLM without a microlens array. The factor of 46 compares favorably with the expected factor of 53.

When a SLM with microlens array is used in an image plane we must also ensure that the optical wave front at the microlens array is planar (parallel to the SLM surface to target a modulator or tilted to target an off-center detector), so that light is focused to the correct spot within every pixel. Consider an imaging system in which U_o and U_i are the object and image plane electric fields and d_o and d_i are their distances from an imaging lens of focal length f_L. Using Fourier optics (for infinite lens diameter) the relationship between the input and output electric field amplitudes (neglecting a constant phase factor) is given by the following expression[7]:

$$U_i(x_i, y_i) = \frac{d_o}{d_i} \exp\left[i \frac{\pi}{\lambda d_i}\left(x_i^2 + y_i^2\right)\left(1 + \frac{d_o}{d_i}\right)\right] \times U_o\left(-x_i \frac{d_o}{d_i}, -y_i \frac{d_o}{d_i}\right). \quad (1)$$

On inspection of the complex phase factor, it is apparent that the image wave front has a radius of curvature $r = d_i - f_L$ (assuming that $r \gg \sqrt{x_i^2 + y_i^2}$). Because of wave-front curvature, the spot of light formed under a microlens will be shifted from the center of the underlying pixel by an amount approximately equal to $\sqrt{x_i^2 + y_i^2} f / n_G r$, where f is the focal length of the microlens. Consider, for example, the case $r = 10$ cm, $f = 1.47$ mm, and we look at a point 10 microlens widths from the center ($\sqrt{x_i^2 + y_i^2} = 2$ mm). The calculated spot offset of 20 μm is 2.5 times the 8-μm spot diameter and is large enough to cause focused light to miss its intended detector (30 μm wide).

The image plane phase curvature can be eliminated by placing a lens of focal length $f_c = d_i/(1 + d_o/d_i)$ in the object plane (e.g., the object is placed against this lens), as we have done in our own work. Alternatively, the corrective lens could be placed at the output plane.

Ideally, a normally incident plane wave should be reflected by the SLM as through it were reflected off an ordinary flat mirror. Collimated light would enter each microlens, be focused to a diffraction-limited spot at the SLM's reflective surface, and then be recollimated as its emerges from the microlens. If the reflective surface is not exactly at a distance f behind the microlens, the outgoing wave front from each microlens will be curved rather than planar (Fig. 3). This issue is especially important for Fourier-transform-(FT-) based applications such as correlators, because wave-front curvature causes light to be wasted in unused spatial frequencies.

It is important to known how strongly the central spot (zero-frequency) intensity of the FT depends on the accuracy of the microlens-to-SLM spacing, because this will determine the efficiency of FT processing operations. We have determined this dependence experimentally and have used simple imaging formulas combined with the mathematics of Fourier optics to calculate the dependence. Collimated light enters a microlens and is reflected from the underlying SLM surface. Light emerging from the microlens will appear to come from a point a distance $-z$ behind the microlens, where z is given by $n_A/z + n_G/(2T - f) = n_G/f$, T (the window thickness) is the distance from the microlens surface to the SLM, n_A is the refractive index of air, and n_G is the refractive index of the glass. We must compute the FT of this two-dimensional array of virtual spherical light sources.

Using the approximations of Fourier optics, and assuming an infinitely large lens aperture, we obtain the electric field U in the FT plane by[7]

$$U(f_x, f_y) = \frac{1}{i\lambda f} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} u(x_o, y_o) \times \exp[-i2\pi(f_x x_o + f_y y_o)] \mathrm{d}x_o \mathrm{d}y_o,$$

$$u(x_o, y_o) = \frac{A}{w^2} \mathrm{rect}\left(\frac{x_o}{W}, \frac{y_o}{W}\right)\left(\mathrm{comb}\left(\frac{x}{w} + \frac{1}{2}, \frac{y}{w} + \frac{1}{2}\right) * \left\{\mathrm{rect}\left(\frac{x}{w}, \frac{y}{w}\right)\exp[i\phi(x, y)]\right\}\right). \quad (2)$$

The function $u(x_o, y_o)$ is the outgoing electric field at the outer surface of the microlens array, $f_x = x_f/\lambda f$, $f_y = y_f/\lambda f$, A is the electric-field amplitude, and $*$ is the convolution operator. The functions rect and comb have their usual meaning,[7] although here we use them in a two-dimensional form. The quantity W is the width of the array, and w is the width of an individual square microlens. With no loss of generality, the number of microlenses in a row is assumed to be even. The function $\phi(x, y)$ describes the phase of the outgoing wave front across the aperture of a microlens. Equation (2) can be rewritten as

$$U(f_x, f_y) = \frac{AW^2}{i\lambda f} \mathrm{sinc}(Wf_x, Wf_y) * \left\{\exp[i\pi d(f_x + f_y)] \times \mathrm{comb}(wf_x, wf_y) H(f_x, f_y)\right\}. \quad (3)$$

Here $H(f_x, f_y) = \mathcal{F}\{\mathrm{rect}(x/w, y/w)\exp[i\phi(x, y)]\}$ and $\mathcal{F}$ is the FT operator. Equation (3) describes an infinite rectangular array of spots with a spacing $1/w$. As long as the width of the sinc function is small compared with the spacing of the comb function ($2/W \ll 1/w$),

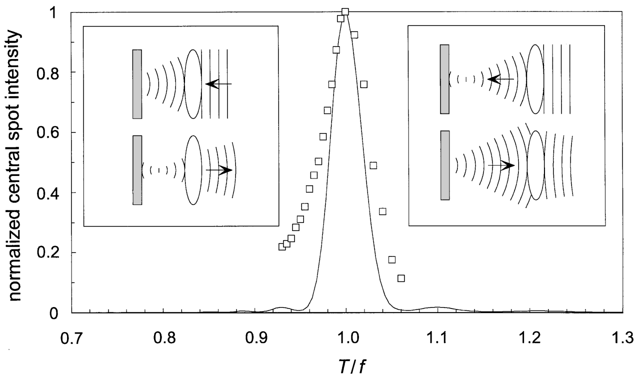

Fig. 3. Comparison of the calculated central FT spot intensity (solid curve) with the measured intensities (squares).

the amplitude of the central spot of the FT is

$$U_0(f_x, f_y) = \frac{AW^2}{i\lambda f w^2}\,\mathrm{sinc}(Wf_x, Wf_y)H(0,0)\,. \tag{4}$$

To compute $H(0,0)$, we approximate the wave front to be from a point source a distance $-z$ behind the microlens. The phase of light emitted from this source is $\phi = 2\pi\sqrt{x_o{}^2 + y_o{}^2 + z^2}/\lambda$. Because $(x_o{}^2 + y_o{}^2)/z^2 \ll 1$ ($x_o \sim 100\ \mu$m, $z \sim 1470\ \mu$m), we can use a series expansion to approximate $\phi = 2\pi z[1 + (x_o{}^2 + y_o{}^2)/2z^2]/\lambda$. Using this expression for the phase, we obtain

$$H'(0,0) = \left(\int_{-1/2}^{1/2} \exp\left\{ i\,\frac{n_G}{n_A}\,\frac{2\pi\tilde{x}^2 w^2}{\lambda f}\left[\frac{(T/f) - 1}{2(T/f) - 1}\right]\right\}\mathrm{d}\tilde{x}\right)^2 . \tag{5}$$

Here $\tilde{x} = x/w$ and H' has been normalized so that its maximum value is 1. We have omitted a constant phase factor of $\exp(i2\pi z/\lambda)$ since it does not affect the light intensity.

When the exponential is rewritten as a sine and cosine sum, the integral of Eq. (5) is seen to be the sum of two Fresnel integrals that cannot be evaluated analytically. To obtain a plot of the intensity of the central FT spot $|H'|^2$ versus window thickness T, we have computed the integral numerically (Fig. 3).

In addition to calculating the sensitivity of H' to the microlens–mirror spacing, we also assembled an optical system designed to determine this dependence experimentally. For this test, the microlenses were formed on a glass substrate thin enough that the front and back focal planes lay outside the glass. The microlenses were then plano–convex lenses with a 1-mm focal length. A flat mirror was placed behind the array (planar side) to simulate a reflective SLM surface. The microlens array was illuminated with collimated, normally incident laser light ($\lambda = 633$ nm) that passed through the array and was reflected off the mirror. The reflected light again passed through the microlens array, and the outgoing wave front was then passed through a FT lens. The microlens array was mounted on a translation stage that could vary the microlens-to-mirror distance, and a photodetector was positioned to detect the intensity of the central FT spot. Figure 3 shows that the normalized intensity measurements agree fairly well with the calculated values and that the FT efficiency depends very strongly on the microlens-to-mirror spacing. We do not expect the calculation to be accurate for values of T/f that are much different from 1 because light reflected by the mirror will tend either to underfill the microlens ($T/f < 1$) or to spill over into adjacent microlenses ($T/f > 1$).

The sensitivity of the FT performance to the microlens-to-VLSI spacing sets a high standard for device assembly. Figure 3 shows that we need $T/f = 1.00 \pm 1\%$ to achieve 90% or better of the maximum achievable FT performance. Manufacturers typically specify focal lengths to no better than ±1%. When this is added to the tolerance with which the window thickness can be adjusted to match the focal length (in our case ±1 mil, equivalent to ±2%), it is apparent that achieving $T/f = 1.00 \pm 1\%$ can be difficult. Another practical concern is the use of microlenses with SLM pixel pitches much smaller than the 200 μm used here. For example, if we were to use a 20 μm pitch and require a 4-μm diffraction-limited optical spot size ($d = 2.44\lambda F/n_G$), then the microlens F-number ($F = f/w$) would have to be 2.6 or less at $\lambda = 633$ nm. The microlens focal length given by $f = Fw$ would be 52 μm and would require a 52-μm-thick window, which is much too thin for a conventional SLM window. Consequently, a different method for placing the microlenses in proximity to the pixels would have to be devised. As a final comment, note that we have not addressed the question of the maximum achievable FT efficiency. What fraction of the energy of a plane wave incident upon an ideal microlens SLM will emerge as a plane wave and thus appear in the central spot of the FT? We need to consider influences such as spherical aberrations and diffractive effects; e.g., some fraction of the light that has entered one microlens inevitably will exit through neighboring lenses after reflection. We have not attempted to determine fundamental performance limits established by these mechanisms.

This research was supported by contracts from Rome Laboratory, Hanscom Air Force Base.

References

1. A. D. Kathman, M. L. Temmen, and M. L. Scott, Proc. Soc. Photo-Opt. Instrum. Eng. **1544,** 58 (1991).
2. L. K. Cotter, T. J. Drabik, R. J. Dillon, and M. A. Handschy, Opt. Lett. **15,** 291 (1990).
3. M. A. Handschy, D. B. Banas, and S. D. Gaalema, in *Spatial Light Modulators and Applications*, Vol. 6 of 1993 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1993), pp. 62–65.
4. M. A. Handschy, H. Chase, L. K. Cotter, J. D. Cunningham, A. M. Pattee, T. J. Drabik, and S. D. Gaalema, Proc. Soc. Photo-Opt. Instrum. Eng. **2237,** 432 (1994).
5. K. M. Johnson, D. J. McKnight, and I. Underwood, IEEE J. Quantum Electron. **29,** 699 (1993).
6. Micro-Optics Group, Adaptive Optics Associates, Inc., 54 Cambridge Park Drive, Cambridge, Mass. 02140-1348.
7. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1968).