High-reflectivity patterned metal mirror used in an optically addressed spatial light modulator

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Abstract. We demonstrate an a-Si:H/surface-stabilized ferroelectric liquid crystal (FLC) optically addressed spatial light modulator (SSFLC OASLM) incorporating a reflecting patterned metal mirror. The mirror, made using standard photolithographic techniques, has a three-layer structure containing two metal-matrix layers with an insulating layer between. Compared to a single metal-matrix layer, the gaps between the edges of pixels can be greatly reduced. With two metal-matrix layers, the principle advantages of a metal mirror over a dielectric stack reflector in FLC OASLMs are the metal layer's high capacitance and relatively achromatic reflectivity. A consequence of the metal-matrix pattern is that the effective reflectivity of the mirror is a function of the *f*/# of the read-beam-imaging optics. With $f=1/6$, the theoretical maximum effective reflectivity is 0.91 R_{metal} where R_{metal} is the reflectivity of the metal. Our device has measured reflectivities as high as 0.52. The transmission coefficient of the mirror is measured to be as low as 0.017.

Subject terms: reflectivity; mirror; metal-matrix layers.

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1 Introduction

Ferroelectric liquid crystal optically addressed spatial light modulators (FLC OASLMs) have applications in a number of optical technologies: optical signal processing,[1] optical computing,[2] and high-resolution projection TV[3] among others. The basic structure of an FLC OASLM is shown in Fig. 1. The device consists of two optical flats, both of which are coated with a transparent conducting oxide (TCO). One optical flat has a photosensor deposited on it, which may be either a photoconductor or, as is the case with the devices we fabricate, a photodiode.[4] On top of the photosensor a reflective layer can be deposited that serves both to increase the amount of light reflected from the device and to optically isolate the write side (photosensor side) from the read side (FLC side) of the device. The isolation is important to prevent the read light, which may be much more intense than the write light, from writing. Both the reflective layer and the TCO on the other optical flat are coated with an alignment layer, which orients the FLC between them.

A typical experimental configuration in which FLC OASLMs are used is shown in Fig. 2. A write-beam image is incident on the photosensor side of the device while a read beam passes through a polarizing beamsplitter (PBS) and is incident on the FLC side of the device. The spatially varying intensity of the write beam is converted to spatially varying polarization rotations in the read beam. On passing through the PBS a second time, these polarization variations in the read beam are converted to intensity variations. In this way, the image carried by the write beam is imposed on the read beam. The details of this process have been described many times in the literature.[4–6]

Much attention has been paid to the choice of liquid crystal and alignment layer material and structure. Although many applications for FLC OASLMs require both high read-light intensity and good optical isolation between the read and write sides of the device, little has been published about the design and performance of reflective layers. This paper first discusses the performance requirements of FLC OASLM reflective layers. Then the design and fabrication of a novel patterned metal mirror is described. Finally, we report the experimentally measured performance.

2 Requirements of FLC OASLM Reflective Layers

The reflective layer in an FLC OASLM serves two important functions. It provides high reflectivity for the read beam, important for applications where strong output intensities are needed, and it provides isolation between the photosensor and the modulator. Good isolation is necessary to prevent the read beam from falling on and writing to the photosensor, thus reducing the contrast ratio of the output image. A com-

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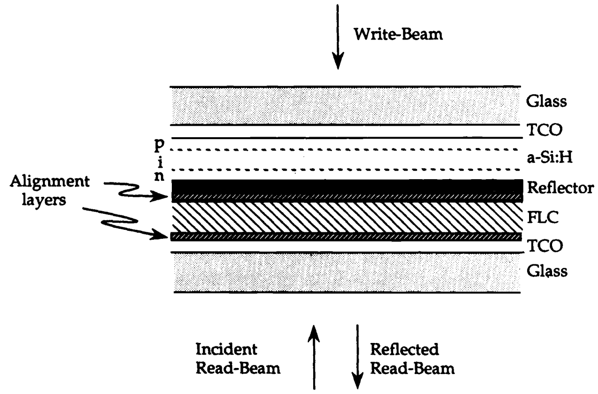

Fig. 1 Structure of an a-Si:H FLC OASLM.

mon application of FLC OASLMs is that of an image intensity amplifier.[3] When used as an image amplifier, the FLC OASLM has a low intensity write beam and a high intensity read beam incident on it. A highly reflective layer is required for the desired high-intensity output, and good optical isolation would ensure that the strong read beam did not overwrite the write-beam image.

Unfortunately the reflective layer in an FLC OASLM also has two important drawbacks. First, the layer acts as a series capacitor between the photosensor and the FLC. Consequently, some fraction of the externally applied voltage drops across the reflective layer leaving a weaker field to drive the FLC. This results in longer device switching times,[7] lower device sensitivity,[8] and reduced bistability.[9] A high-capacitance reflective layer is desired to increase the fraction of the voltage that is dropped across the FLC. Second, the inclusion of a reflective layer reduces the device resolution because of field spreading and transverse conduction in the layer itself. A good reflective layer must not only provide high reflectivity and good optical isolation, but also have a large capacitance and low transverse conductivity.

We used FLC as the modulating material in our devices. FLC has certain advantages over nematic liquid crystal (NLC), such as fast switching speed and high bistability. However, FLC is typically used in a layer 1 to 2 μm in thickness, whereas NLC layers typically are 6 to 7 μm in thickness. The thinner FLC layer results in a higher series capacitance for the layer, which reduces the driving voltage appearing across the liquid crystal.

3 Types of FLC OASLM Reflective Layers

There are two fundamental types of reflective layers: dielectric stacks and patterned metal mirrors. Dielectric stacks offer high reflectivity and low transverse conductivity, but also introduce a small series capacitance, the drawbacks of which have already been discussed. Dielectric stacks are sometimes used in conjunction with light-blocking layers,[10] which are placed between the stack and the photosensor, to provide very high ($\geq 10^5$) optical isolation. Materials used for light-blocking layers are highly absorbing at the read-light wavelength, allowing thin layers to be made that have a large series capacitance. The series capacitance of a dielectric stack and light-blocking layer can also be increased by choosing materials that have high dc dielectric constants.

Metal mirrors[11] are also highly reflective, provide relatively achromatic reflections, and introduce a desirable in-

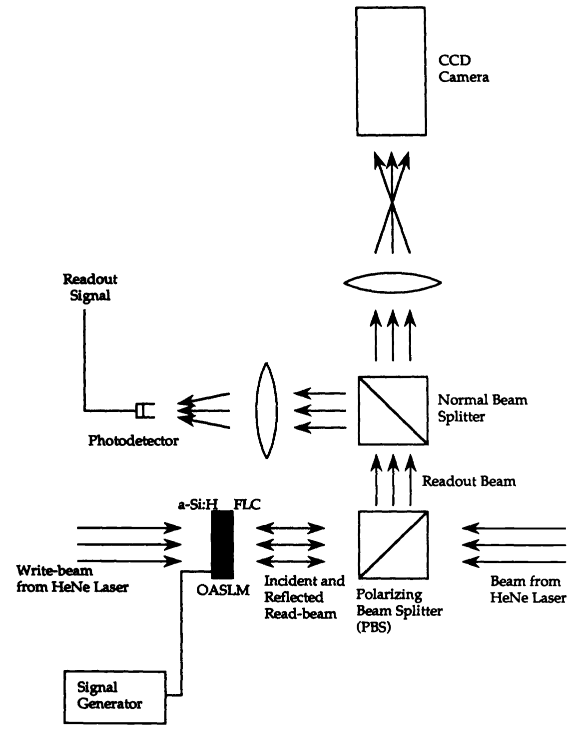

Fig. 2 Experimental setup used to test FLC OASLM performance.

finite series capacitance (i.e., a shunt), but they also have a large transverse conductivity. This problem can be avoided by designing the mirror as a matrix of metal squares (pixels) that are electrically insulated from each other (see Fig. 3). With this arrangement, the device's spatial resolution is limited by the size and spacing of the pixels, but the high reflectivity and large series capacitance of the layer make for a worthwhile trade-off.

Patterned metal mirrors with the common structure just described have a further disadvantage. Read light incident on the gaps between pixels sees no reflective layer at all. Therefore, the photosensor adjacent to these regions is always illuminated by the read light and the readout image always has imposed on it the mesh pattern formed by the gaps (see Fig. 3). In addition to the problems associated with the presence of unwanted structure on the readout image, the image quality is further degraded by field spreading and transverse conductivity in the photosensor, which cause the FLC near the edges of the pixelated regions to switch on as well. Our three-layer design of a patterned metal mirror eliminates most of the light leakage through the mesh of gaps between pixels and reduces the associated read-beam signal degradation. It also increases the reflectivity of the mirror by covering more surface area of the FLC OASLM with metal than would a one-layer metal reflector.

4 Three-Layer Patterned Metal Mirror

The improved design of the patterned metal mirror involves three layers instead of one: two metal-matrix layers and an insulating layer between them. Each of the metal layers consists of a square matrix using alternate squares with 50% coverage, as shown in Fig. 4(a). The corners of the squares are beveled to avoid contact with adjacent pixels. The front metal layer is translated by one unit square with respect to

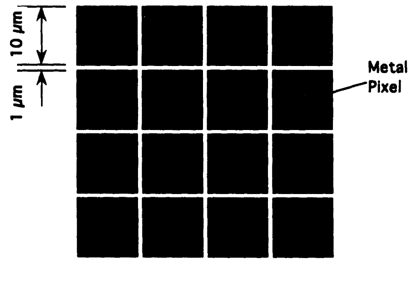

Fig. 3 Metal mirror is patterned into square pixels to suppress transverse conduction over large areas. The resolution of the FLC OASLM is limited by the density and spacing of the pixels. The gaps between pixels are responsible for a permanent mesh structure in the readout image.

the rear metal layer, as shown in Fig. 4(b). In this way, the three-layer mirror is optically continuous except for the nonmetalized regions at the pixel corners.

We compare the relative reflectivities of the one and three-layer designs by calculating the percentage of the total area covered by metal. Assuming a pixel size of 10 μm a side with 1-μm gaps between pixels, the three-layer design has 99% area metal coverage of the device surface, whereas the single-layer device has only 82% coverage. Using R_{int} to represent the reflectivity of the unmetalized photosensor-FLC interface, with the single-layer reflector a factor of $0.18\ R_{\text{int}}$ of the incident read light is present in the readout light as part of a permanent mesh structure, whereas in the triple layer structure only $0.01R_{\text{int}}$ is present in the readout light as an array of dots. The smaller amount of light leakage past the three-layer reflector also results in less field spreading and consequently signal degradation than in the one-layer reflector.

In addition to the increased complexity of fabrication, the three-layer design has another drawback. As mentioned earlier, one of the strongest assets of a metal reflective layer is its high (infinite) series capacitance. The three-layer design incorporates an insulating layer, which reduces the reflector's overall series capacitance. The extent to which this is a problem depends on the insulating material selected and layer thickness.

5 Device Fabrication

To explore the feasibility of the three-layer patterned metal mirror, we chose a pixel size of 25 μm on a side with 1-μm gaps between the beveled corners. Our device resolution is therefore limited to 20 lp/mm in the horizontal and vertical directions. Suitable choices for the reflective metal include aluminum and silver. For ease of fabrication both metal-matrix layers were made with aluminum using lift-off photolithographic procedures and a positive photoresist. (The lift-off lithographic procedure allowed us to use the same mask for both layers.) The aluminum film was deposited by thermal evaporation at high vacuum and its thickness was controlled to 60 to 100 nm.

Although tantalum oxide would be a better material to use for the insulating layer because of its high dc dielectric constant ($\varepsilon_r = 42$), for ease of fabrication we chose silicon monoxide. An insulating layer of ~100 nm was deposited by thermal evaporation. The resistivity of the insulating layer was measured to be $5 \times 10^{12}\ \Omega$ cm, which is large compared to the resistivity of the a-Si:H *p-i-n* photodiode used as the photosensor. The combined transmittance of the three-layer reflector and a-Si:H photodiode was measured with a Varian Cary 2400 spectrophotometer to be <0.2%, limited by the spectrophotometer's maximum sensitivity. The reflectance of the mirror before affixing it to the other optical flat and filling the device with FLC was measured to be ~80% using the spectrophotometer with a specular reflection accessory.

The photosensor in the FLC OASLM was a *p-i-n* diode, having *p, i,* and *n* layers of thickness 10 nm, 2 μm, and 10 nm, respectively. The FLC layer was 3 μm thick, and the FLC material was CS1014 from Chisso Company, Japan. The alignment layers were rubbed nylon. The optical flats used were 25.4 mm in diameter. For our devices we use indium tin oxide as the TCO. After fabrication, the device had an effective aperture of diameter 19 mm.

6 Experiment and Results

Two devices were characterized in an experimental setup similar to the one shown in Fig. 2. The three-layer patterned metal mirror acts as a two-dimensional phase grating. On reflection from the device, the initially collimated read beam diffracts in various directions corresponding to the different

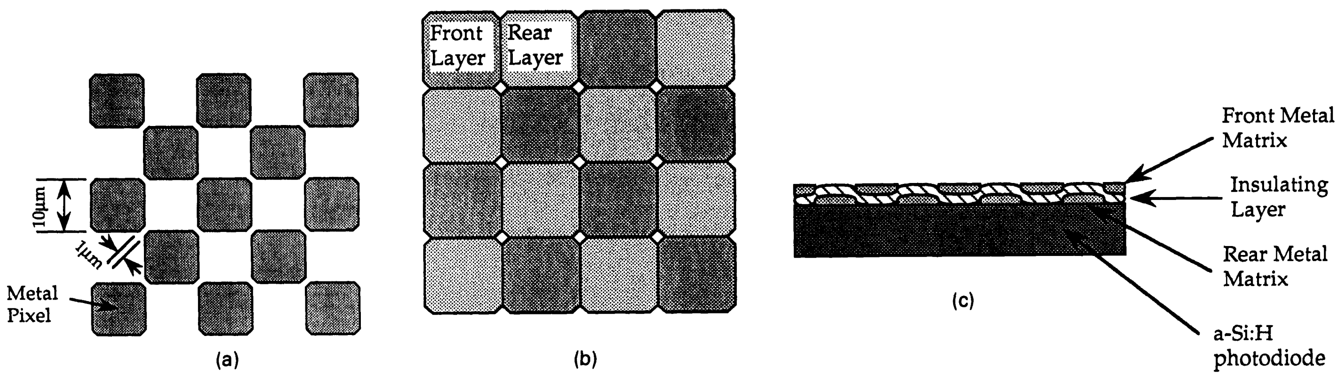

Fig. 4 (a) Metal mirror is patterned into a checker board of square pixels. (b) Back mirror is shifted by one square to reflect the light that passes through the holes of the front mirror. The only gaps in the mirrored surface occur at the corners of the pixel elements. (c) Side view showing the three-layer structure. The insulating layer prevents the two metal-matrix layers from making electrical contact.

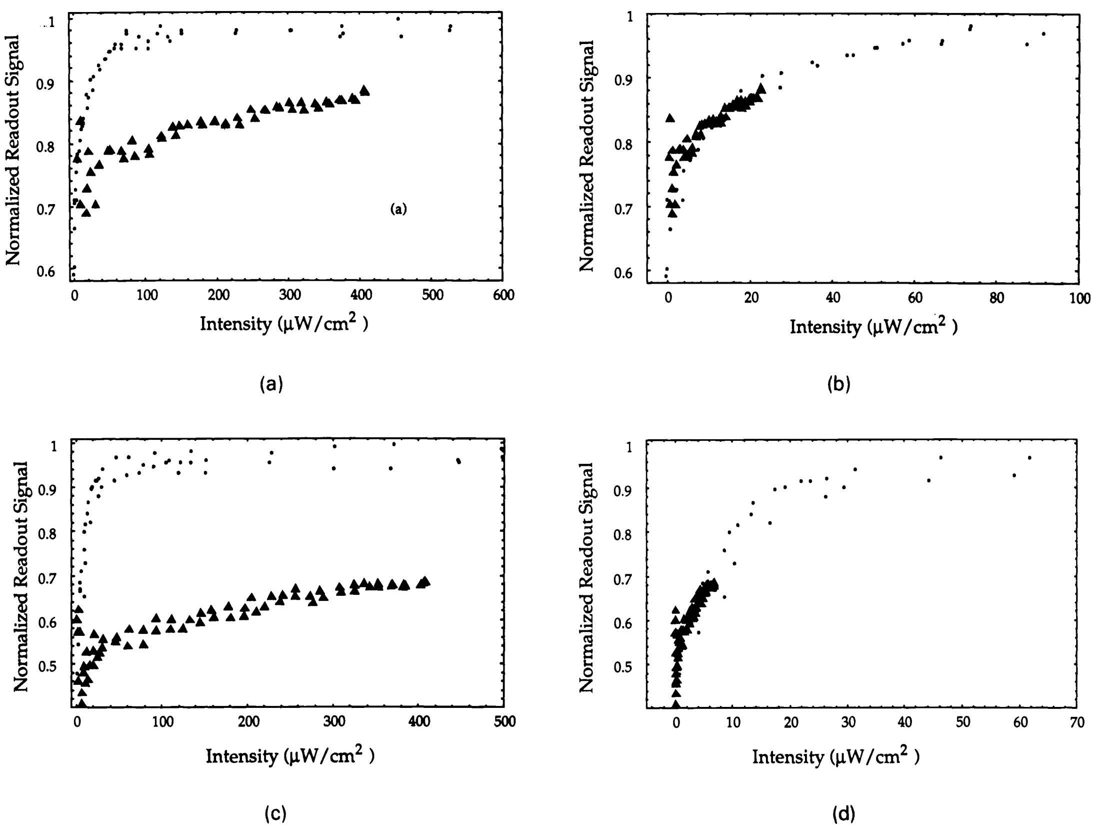

Fig. 5 From these curves we infer the effective transmission of light through the reflective layer to the photosensor. The triangles correspond to the optical response of the FLC OASLM as the intensity of the read beam is scanned with no write light. The circles correspond to the optical response as the intensity of the write beam is scanned with very weak read light (> 10 μW/cm^2). The horizontal scaling factor needed to make the triangles fall on the curve defined by the circles can be thought of as an effective transmission coefficient. (a) Normalized readout signal versus both read-beam intensity and write-beam intensity for the first device made. (b) Same data as shown in (a) but with the horizontal axis of the read-beam intensity scan multiplied by a factor of 0.056. (c) Normalized readout signal versus both read-beam intensity and write-beam intensity for the second device made. (d) Same data as shown in (c) but with the horizontal axis of the read-beam intensity scan multiplied by a factor of 0.017.

diffraction orders. The effective reflectivity, therefore, increases with increasing $f/\#$ of the read-light-imaging optics. Although the positions of the diffracted orders correspond well with the predictions of diffraction theory, because of nonuniformities in the reflectance and orientation of individual pixels, as well as the phase modulation caused by the nonphase flat reflecting surfaces, the intensity profile of the diffraction pattern does not fit any simple model. Using a read-light imaging system with $f = 1/6$ optics, the two devices show reflectivities of 45 and 52%. The dramatic reduction in reflectivity from the bare mirror cannot be explained by diffractive loss alone. It is likely that there is additional loss associated with passage through the FLC. The reflectivity of devices made with no reflective layer, i.e., with reflectivity resulting solely from the a-Si:H/FLC interface, is ~20%. Thus devices made with a three-layer patterned metal mirror can have reflectivities up to 2.5 times that of devices with no reflective layer at all.

The transmission coefficient of the reflective layer alone, i.e., without the photosensor, could not be measured directly. Instead we compared the OASLM optical response versus read-light intensity, with no write light, to the optical response versus write-light intensity, with a weak read light. By optical response we mean the intensity of the reflected read beam after passing through the PBS (see Fig. 2). The intensity scaling factor needed to make the optical response versus read-light curve fall on top of the optical response versus write-light curve can be thought of as an effective transmission coefficient. To minimize the difference in optical response resulting from illumination of photosensor from two different sides, HeNe lasers (633 nm) were used for both the read and write beams. Red light is weakly absorbed by the a-Si:H photosensor, which is thus illuminated approximately uniformly throughout its thickness. The curves of optical response versus both read-light and write-light intensity as well as the former curve scaled horizontally for both devices appears in Fig. 5. The results of these tests show that the two devices have effective transmissivities of 5.5 and 1.7%. The results from similar experiments conducted on comparably designed devices with no reflective layer correspond to an effective transmittance through an a-Si:H/FLC interface of ~80%. Therefore, our results show that devices made with a three-layer patterned metal mirror can be read with intensities up to 50 times larger than those used for a device without a reflective layer.

A lower bound on the resolution of the two devices was determined by imaging an Air Force resolution target onto the write side of the devices and imaging the resulting output image onto a CCD camera. The maximum resolvable spatial frequency was ~15 lp/mm in the direction of the rows and columns of the pixels. This corresponds reasonably well to a pixel size of 25 μm.

Finally, we measured the FLC switching times. For one device the 0 to 90% rise time and 100 to 10% fall time were 360 and 250 μs, respectively. For the other device the rise and fall times were 530 and 510 μs, respectively. These times are comparable to switching times for comparably fabricated devices without a reflective layer. The series capacitance of the insulating layer does not seem to be significant.

7 Conclusions

We have demonstrated the feasibility of a three-layer-structure patterned metal mirror incorporating an a-Si:H surface stabilized (SS) FLC OASLM. The layer is patterned using standard lift-off photolithography. The mirror can give FLC OASLMs reflectivities of over 50% and effective transmittances of under 2%, providing strong reflected signals and good optical isolation between the read and write sides of the device. The inclusion of the mirror does not introduce a significant (low) series capacitance, which would adversely affect the FLC switching speed. The devices we fabricated had pixel sizes of 25 μm on a side, limiting the spatial resolution to a maximum of 20 lp/mm. The pixels could be scaled down to at least 5 μm on a side, allowing for a spatial resolution limit of 100 lp/mm.

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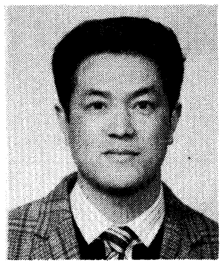

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