High-contrast ferroelectric liquid-crystal spatial light modulator

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The spatial light modulator based on total internal reflection at the ferroelectric liquid-crystal–glass interface has a 10^7:1 contrast ratio, a 250-μs response time, and a $\lambda/8$ transmitted wave-front uniformity. These properties make the spatial light modulator well suited to provide frequency-band excision in acousto-optic spectrum analyzers.

Acousto-optic spectrum analyzers offer an attractive way of processing wideband rf signals.[1] In these analyzers an acousto-optic crystal diffracts light through an angle corresponding to the input-signal frequency with an efficiency determined by the input-signal amplitude. A lens following the acousto-optic crystal focuses the light to a position corresponding to the input frequency. The addition of a spatial light modulator (SLM) in this focal plane permits the excision of unwanted frequency components of the input signal, with the completeness of the excision limited by the extinction or contrast ratio of the SLM.[2] Previous excision systems have achieved 30–40-dB excision ratios with acousto-optic[3] or multipass nematic liquid-crystal[4] SLM's. We report here a ferroelectric liquid-crystal (FLC) SLM developed specifically for excision applications to have a very high contrast ratio.

Optical modulation in our SLM is based on switchable total internal reflection at an FLC–glass interface,[5] as shown schematically in Fig. 1. A 3.5-μm-thick film of FLC Felix-008 (Ref. 6) is confined between two glass prisms whose refractive index of $n = 1.62$ nearly matches the extraordinary index of the FLC. Each prism carries an indium tin oxide transparent electrode coating on its inner face. On the bottom prism this coating is photolithographically patterned into a 1×200 array of pixel electrodes, 3 mm high, on 125-μm centers. The unpatterned indium tin oxide on the upper prism is overcoated with a chromium layer patterned into 3-mm-high, 15-μm-wide segments that are aligned with the lower prism to block light leaking through the gaps between the pixel electrodes. Voltages applied between the pixel electrodes and the upper common electrode switch the FLC optic axis between two orientations, both nearly parallel to the prism face, one perpendicular to the plane of incidence and one approximately 45° to the plane of incidence. The FLC alignment is determined by a rubbed polymer coating on both prism faces. Light incident normal to the upper prism's angled face strikes the pixel with an angle of incidence $\theta = 78°$. When the FLC axis is switched to be perpendicular to the plane of incidence, the $\hat{s}$-polarized component of the incident light is coupled to the index-matched extraordinary wave in the FLC and is nearly completely transmitted into the lower prism to leave from its angled face. With the FLC axis state reversed, the effective index for both ordinary and extraordinary modes is low enough that the incident light is beyond the critical angle, so it is totally reflected. Incident $\hat{p}$-polarized light is coupled only to the ordinary mode and is totally reflected by either FLC state.

We measured the performance of our SLM, using the test bed shown in Fig. 2. A 63-mm focal-length achromat (L1) focuses an 8-mm-diameter expanded, chopped beam from a 5-mW He–Ne laser to a spot in the plane of the SLM pixels. A 4× microscope objective (L2) imaged the pixels onto an aperture (I4) nearly 1 m away. I4 was adjusted to a diameter just slightly smaller than the image of a single pixel. Light transmitted through the aperture was focused by 100-mm focal-length lens (L3) onto a silicon photodiode (PD) whose amplified output was fed to a lock-in amplifier. We checked the test bed performance with the SLM removed by recording the detected intensity while translating a razor blade through the light spot. The spot profile obtained this way is shown in Fig. 3. As the blade began to traverse the spot, the intensity fell rapidly, reaching $1/e^2$ of the incident value with the blade 5 μm past the spot center and reaching 10^{-5} of the incident value with the blade 34 μm past the spot center. At larger diameters, however, the intensity dropped off much more slowly than expected for a Gaussian beam, not reaching 70 dB below incident intensity until the blade was

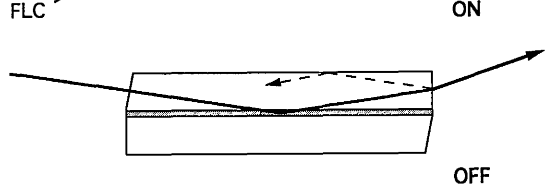

Fig. 1. Total-internal-reflection principle and prism cross section. In the on state incident $\hat{s}$-polarized light is transmitted; in the off state all light is totally reflected.

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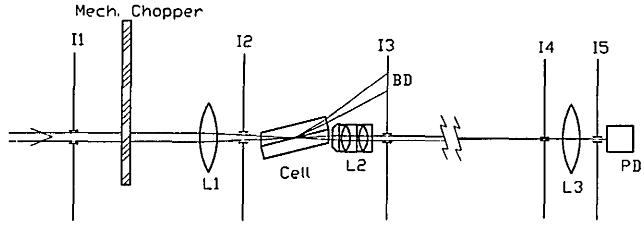

Fig. 2. SLM test bed: I1–I5, apertures; BD, beam dump.

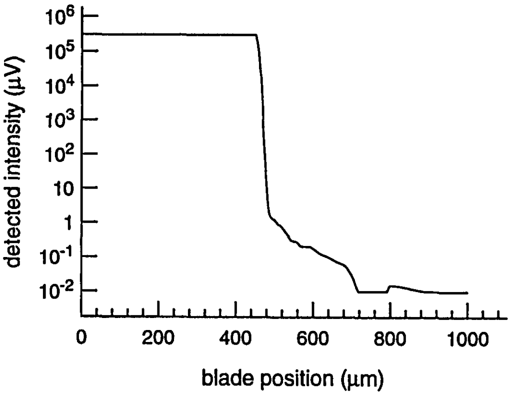

Fig. 3. Test bed spot profile: intensity versus razor blade position.

260 μm past the spot center. Further blade motion reduced the photodetector output to the system noise floor of 10 nV, or 75 dB below incident intensity.

With the SLM placed in the test bed so the focused spot was centered on a single pixel, we measured the transmitted intensity as the chosen pixel and the pixels adjacent to it were turned off. As the chosen pixel was turned off, the intensity dropped 47 dB (a factor of 4.5×10^4); also, turning off the two neighboring pixels increased the SLM attenuation to 61 dB (1.4×10^6). Finally, turning off the next two pixels out from the center, for a total of five, brought the attenuation to 68 dB (6.3×10^6). With all 200 pixels off we scanned the spot across the array and were unable at any location to detect transmitted light intensity above our -75-dB noise floor. The less-than-complete extinction when only one pixel is turned off results both from the wings on the incident spot that extend past the pixel and from light, reflected by the pixel, that strays back into the transmitted beam by multiple reflections within the prisms.

Figure 4 shows the photodetector output as a function of time as the pixel was switched on and off in response to a ± 15-V square wave. In both directions the optical response exhibits overshoot and ripple. When the pixel is switched on the transmitted intensity settles to 10% of it final value within 170 μs of the voltage reversal, whereas when the pixel is switched off the 10% settling time is 250 μs. In the on state 37% of the incident $\hat{s}$-polarized light was transmitted. Other devices that we have made showed a strong dependence of on-state transmittance on indium tin oxide thickness and FLC thickness, with the best device having an on-state transmittance of 86%. To us this indicates that the on-state transmittance is affected by multiple-beam interference across the FLC layer; the ripple evident in Fig. 4 arises from the same mechanism as the effective FLC refractive-index changes during the switching transient. Interferometric observation showed the wave front transmitted by the SLM to be flat to $\lambda/8$.

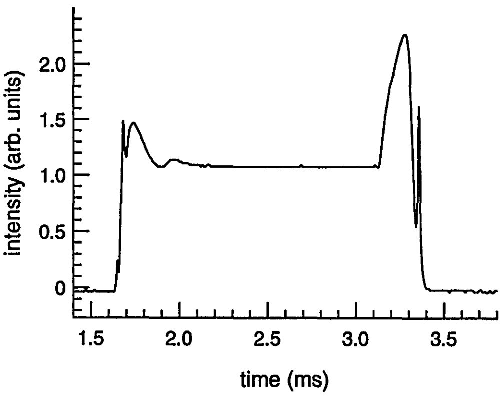

Fig. 4. SLM transmitted intensity versus time.

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