High-speed analog spatial light modulator using a hydrogenated amorphous silicon photosensor and an electroclinic liquid crystal

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A high-speed optically addressed spatial light modulator is described which uses the electroclinic effect in chiral smectic *A* liquid crystals with a *p-i-n* photodiode of hydrogenated amorphous silicon (*a*-Si:H). The near microsecond response time is a function of the liquid-crystal mixture and temperature. We present and analyze optical modulation measurements of a device which exhibits a response time of 40 μs at 29 °C and 4 μs at 50 °C. The optical response is continuous and linear with electric field and write-light intensity, allowing for grey level applications.

Interest in the development of optically addressed spatial light modulators (OASLMs) has grown recently due to their potential applications in optical data processors, displays, image amplifiers, incoherent-to-coherent image and wavelength converters, associative memories, spatial filtering, optical correlators, and neural net computers.[1] In an OASLM, an incident write beam is absorbed in a photosensor, producing spatial variations in the modulating layer which modulates a read beam. The design of an OASLM requires choosing a suitable photosensor and electro-optic modulator. For nematic liquid crystals which have a response time in the milliseconds regime, photosensors of CdS and crystalline Si have been utilized.[2] With the advent of the ferroelectric liquid crystal in the surface stabilized geometry,[3] which can switch with a response time of 50–100 μs, a need arose for a high-speed photosensor. This was achieved recently using a hydrogenated amorphous silicon (*a*-Si:H) photodiode,[4–7] since its response time is ~ 100 ns.

In this letter we incorporate an *a*-Si:H *p-i-n* photodiode as the photosensor in an OASLM with a higher speed electroclinic liquid crystal. The electroclinic effect exists[8] in the chiral smectic *A* (SMA*) liquid crystalline mesophase, usually obtained by heating the chiral smectic *C* ferroelectric phase (SMC*) above a transition temperature T_C. The electrically addressed electroclinic spatial light modulator was recently demonstrated by Andersson *et al.*[9] The response is faster than in the SMC* phase and is continuous and linear with the field allowing for grey level applications. An optically addressed device was also reported by Collings *et al.*,[10] utilizing a bismuth silicon oxide photosensor which limited the response time.

In our geometry the smectic layers are perpendicular to the substrates and in the SMA* phase the molecular director (optic axis) is along the normal to the layers. By applying a field between the substrates the molecules tilt and the optic axis rotates in the plane of the substrate by an angle θ in a direction which depends on the sign of the applied field. When the voltage is changed from V_+ to V_- the induced rotation is $\alpha = \theta_+ + \theta_-$.

The change in the transmittance between the ON and OFF states ($T_{ON} - T_{OFF}$) $\propto \sin^2 2\alpha$. The term T_{OFF} accounts for the nonzero transmittance in the OFF state, due to nonuniformities in the structure of the cell like the chevron defect,[11] the existence of splayed states,[12] and light scattering.[13] The intensity of the ON state depends on the tilt angle. In the SMC* case, α is close to 45° at room temperature and a very intense state can be obtained. In the SMA* phase, the induced tilt changes with temperature and field. It has been shown that to a first approximation, $\theta \propto E/(T - T_C)$, where E is the applied electric field.[8,9]

The OASLM is composed of several layers. An *a*-Si:H photodiode in a *p-i-n* configuration deposited on a transparent conducting oxide (TCO) coated glass plate, with a sheet resistance of $\sim 200\ \Omega/\square$ forms the photosensor. The diode consists of an ~ 100-Å-thick boron-doped p^+ layer, an intrinsic region of $\sim 2\ \mu$m, and a phosphorus-doped n^+ layer which is ~ 100 Å thick. The sheet resistance of the n^+ layer is $\sim 10^{10}\ \Omega/\square$. The active area of the OASLMs is a 1.27-cm-diam circle. The liquid-crystal (LC) material was filled by capillary suction from the isotropic phase between the *a*-Si:H thin film and an indium tin oxide (ITO) coated glass plate with a sheet resistance of $\sim 14\ \Omega/\square$. Both surfaces were treated using a conventional polymer rubbing alignment technique.[14] The material used in our device is M764E, produced by the British Drug House,[15] which transforms from SMC* to SMA* at 28 °C, and to the chiral nematic phase at 73 °C. The thickness of the LC layer is ~ 1.5–2.0 μm, achieved by spreading polystyrene microspheres between the plates.

To operate the OASLM, a square-wave clock voltage is applied between the TCO and the ITO. Ideally, when the voltage is high (V_+) and the photodiode is forward biased, all the voltage drops across the LC, switching it to what we define as the OFF state. Ideally, when the voltage is low (V_-) in the dark all the voltage drops across the reverse-biased photodiode; the LC remains OFF. If a write beam illuminates a region of the photodiode during this period, the LC is switched to an ON state.

The real response differs from the ideal response because of the capacitances associated with the photodiode and the LC.[4,7] In the transition from V_+ to V_-, the difference V_{pp} is divided between the two elements. For the dimensions in our devices, $\sim 40\%$ of V_{pp} is dropped across the LC, modulating it even with no write beam. Because the trans-

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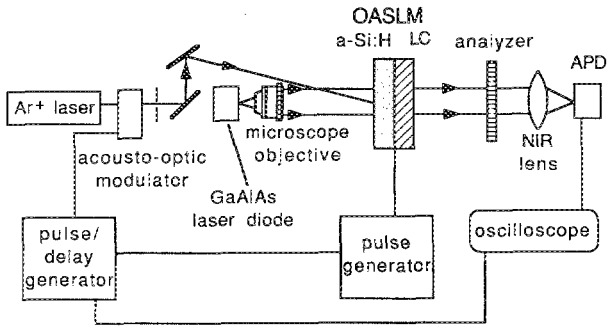

FIG. 1. Experimental apparatus for the measurement of the device response.

mittance change ($T_{ON} - T_{OFF}$) varies as $\sin^2 2\alpha$, the 40% voltage modulation modulates the transmission by a much smaller fraction.

A diagram of the experimental setup used to measure the response characteristics of the OASLM is shown in Fig. 1. The 514.5 nm line of the Ar^+ laser is used as the write beam, which is incident at a small angle from the normal on the *a*-Si:H side and absorbed by the photodiode layer. This results in an electric field across the LC during the negative part V_- of the applied voltage. The 830 nm read beam from a GaAlAs laser diode is incident normally on the *a*-Si:H side. This wavelength was chosen such that it is not absorbed by the *a*-Si:H. The read beam is transmitted through crossed polarizers and measured with a high-speed avalanche photodiode. For the optical response measurements, the write light is modulated using an acousto-optic modulator with a transition time of < 200 ns. A delay/pulse generator is used to synchronize the write light and the applied voltage so that the write light is ON only during a portion ($100\,\mu$s) of the V_- period, allowing the measurement of the optical switching time of the device in response to the write light pulse. The OASLM was held in a hot stage, which controlled its temperature to within ± 0.1 °C.

Figures 2(a)–2(d) show the optical signal modulation at two different temperatures, along with the applied voltage and the write-light pulse. In Fig. 2(a) the polarization of the incident read light is oriented along the optic axis in the stabilized state that the SMC* phase assumes during the V_+ period. Figure 2(b) shows the optical response at $T = 31.5$ °C, where the LC is in the SMA* phase. Since the SMA* induced tilt angle is lower than the spontaneous tilt angle in the SMC* phase and is a function of temperature, for each measurement we rotated the cell such that the transmittance with no write light was the same during the V_+ and V_- periods. We estimated the induced tilt angle from the amount of rotation which is the difference between the tilt angle in the SMC* phase and the induced tilt angle. The tilt angle decreases with temperature from 16° at 28.5 °C to 3° at 50 °C for $V_{pp} = 30$ V. It increases with applied field from 3° for 6 V to 10° for 30 V at 30 °C.

The optical modulation, defined as $M = (T_{ON} - T_{OFF})/(T_{ON} + T_{OFF})$, changes with both temperature and field. It is 74% at 29 °C and decreases to 5% at 50 °C with $V_{pp} = 30$ V, while with $V_{pp} = 6$ V it changes from 20% to 2%. For the optically addressed device, the dependence of the modulation on the ($100\,\mu$s duration) write-light intensity shown in Fig. 3 is of importance for grey level applications. The difference between the nonlinear response of the SMC* phase and the linear response of the SMA* phase at different temperatures is apparent. In the SMC* there exists a threshold above which the optical response increases rapidly and saturates due to the existence of ferroelectric domains, which switch by nucleation and growth. In the SMA* phase no threshold exists, the modulation grows linearly with I, and the saturation is due to the saturation of the tilt angle with the applied field. This explains why for small intensities the modulation in the SMA* phase may exceed that of the SMC* phase.

The dependence of the response time on temperature is shown in Fig. 4. The delay time is the interval between the beginning of the write-light pulse and the time when the optical modulation changes by 10% of its maximum. The

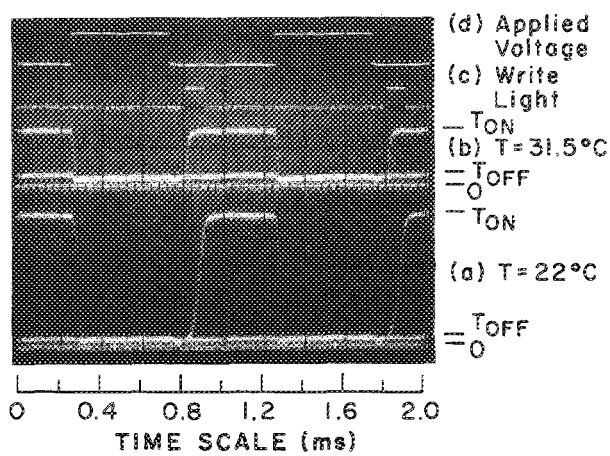

FIG. 2. Oscilloscope traces showing the optical response of the OASLM in (a) the SMC* phase at 22 °C and (b) the SMA* phase at 31.5 °C. Levels for maximum (T_{ON}), minimum (T_{OFF}), and zero (0) transmission are indicated. The T_{OFF} levels which appear during the V_- periods are the transmittance when the write light was blocked. Traces (c) and (d) are the write-light modulation with a pulse width of 100 μs and the applied voltage square wave ($V_{pp} = 30$ V, $V_- = -2$ V), respectively. The write-light intensities are 5.5 mW/cm^2 for (a) and 7.4 mW/cm^2 for (b). The vertical scale is arbitrary.

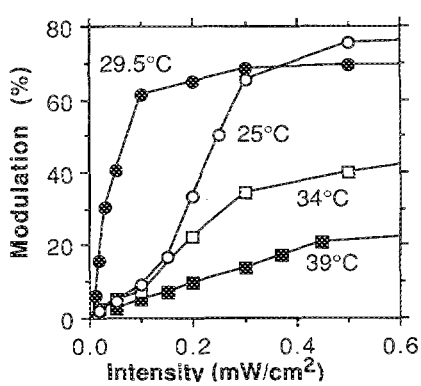

FIG. 3. Optical modulation as a function of write-light intensity for different temperatures. The other conditions are similar to those of Fig. 2.

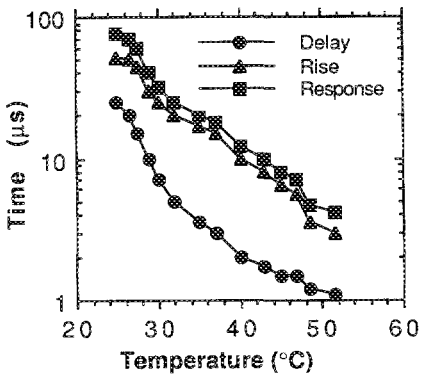

FIG. 4. The delay, rise, and response times as a function of temperature, for conditions similar to those of Fig. 2. The write-light intensity was set at every temperature such that the optical response just saturated.

rise time is the interval between 10% and 90% modulation and the response time is the sum of the delay and rise times. In the SMC* phase there is a strong dependence of the response time on the field, while in the SMA* phase there is no field dependence to a first approximation. To confirm that the response time is not limited by the RC time constant of the TCO electrode with resistance R and liquid-crystal capacitance C, we note that there is a continuous decrease of the response time with temperature. In addition, we measured a similar response time in an electrically addressed device having low resistance ($\sim 14\ \Omega/\square$) ITO-coated glass plates.

In conclusion, we have demonstrated an optically addressed spatial light modulator using an a-Si:H photodiode and the electroclinic effect in chiral smectic A liquid crystals. As the temperature is raised from 29 to 50 °C, the response time drops from 40 to 4 μs and the modulation drops from 74% to 5%. This device is useful where both high speed and a linear response are required.

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