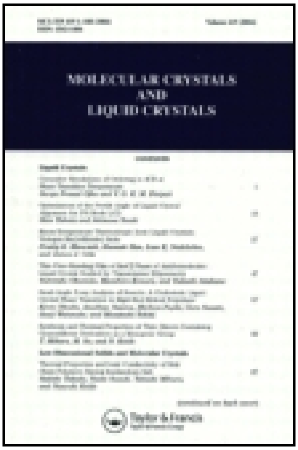

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In this work, V-shaped liquid crystals are proposed for phase modulation optical devices. The aim is to measure the relationship between phase shift and the applied voltage by an experimental set-up based on an interferometer. The optical retardation of the liquid crystal medium could then be determined simply by measuring the phase difference of the waves of the two arms. By supplying a voltage, the liquid crystal molecules are reoriented and the effective refractive index of the liquid crystal changes. Preliminary results show that the devices may be used such as phase modulators, but the phase modulation is polarization sensitive.

Keywords: electrooptic; interference; liquid crystal; modulation; phase shift; V-shaped

INTRODUCTION

Liquid crystal based phase modulators are useful in many applications for photonic devices (tunable grating, prism, lens), in optical communications, optical data and image processing and in diffractive optics. Their advantages of low cost, low power consumption, small weight and size and non-mechanical parts may be promising their integration such as encapsulated birefringent components in optical systems. Particularly, phase-only modulation is desirable for laser applications and adaptive optics. On the one hand, modulators based on nematic liquid crystals are slow (miliseconds) to operate at the fast frame rates

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of optical data processing. On the other hand, mass fabrication processes of ferroelectric modulators lack of efficiency due to a large fail rate.

Some proposals of liquid crystal phase modulators are non-sensitive to the state of polarization of light. Modulators based on polymer dispersed liquid crystal mixtures require high working voltages and power consumption and, in despite of showing low phase shifts, they are useful in microdevices for adaptative optics, such as microlenses or microprims [1]. Excellent phase shifts (8π) are showed in new attractive configurations with double-layered structures based on nematic liquid crystals. They are also polarization-independent phase modulation systems [2]. Amplitude-only or phase-only modulations have been verified, placing optical elements, such us retarder wave plates and polarizers, in front and behind the liquid crystal devices. Optimum configurations results from the design of the right angular position of the optical components [3].

V-shaped liquid crystals are ferroelectric liquid mixtures capable of grayscale generation, excellent contrast ratio and reduced switching voltages (<5 V) [4]. In addition, the response time of these compounds is two orders lower than that of nematic liquid crystals. In the following work, V-shaped liquid crystals are proposed for phase modulation optical devices.

DESCRIPTION OF THE SYSTEM

The experimental set-up consists of a whole controlled system of two main parts (Fig. 1). Optical part comprises a polarized laser beam, a Mach-Zehnder interferometer, a classical large area photodiode and a CCD image sensor. LC device is placed in a branch of the interferometer. On the other hand, the whole adquisition is controlled by a PC. Driving waveforms applied to the LC device are generated with a waveform generator via GPIB. Image adquisitions are obtained with a camera controller via a frame grabber board. An external tunable synchronism circuit has been design to control the CCD adquisition. An oscilloscope shows simultaneously the applied electrical signals and the optical transmission of the device.

Some experiments have been checked to evaluate the phase modulation in V-shaped liquid crystal cells. By applying low frequency triangular waveforms, the angular position between the liquid crystal molecular director and the reference of the laser polarization is easily found. Test cells have been driven with video rate optimized waveforms [5,6], that is, electrical signals that erase the liquid crystal memory, to check the phase modulation. Data pulses are 14.5 ms long and

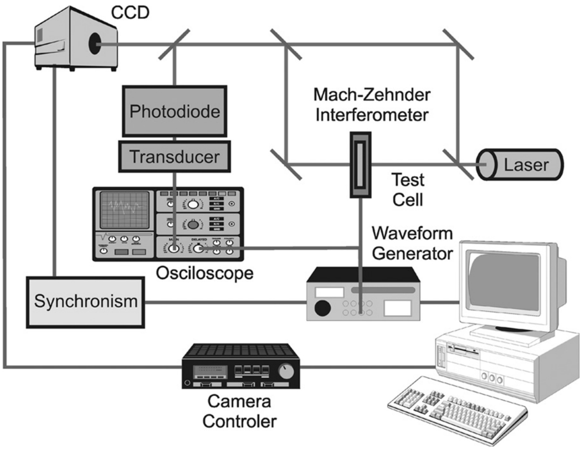


FIGURE 1 Experimental set-up to characterize the phase response in V-shaped devices.

from 0 to 10 V amplitude. Some intermediate voltage levels have been applied and the interference pattern registered. The visibility was measured as the maximum and minimum fringes intensities ratio. Phase modulation measurements [7,8] were based on the theory of interferometry.

PHASE MEASUREMENT METHOD

The experimental set-up to measure the phase modulation of a transmissive LC device is based on a Mach-Zehnder interferometer (Fig. 2) built on a floating optical table. A polarized He-Ne laser beam ($\lambda = 632.8$ nm), was used as a light source followed by a lineal polarizer

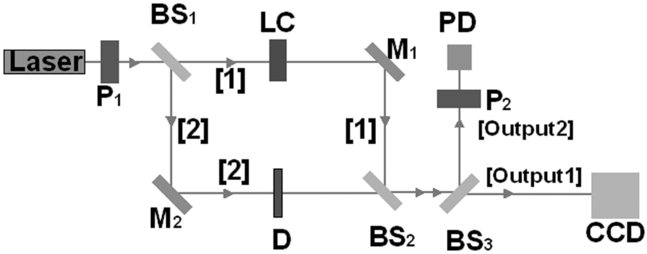


FIGURE 2 A Mach-Zehnder interferometer for measuring the total phase shift induced by a birefringent device.

(P1). The input beam is split into two beams, beam 1 and beam 2, by the first beamsplitter (BS1). LC device is placed in the reference arm (beam 1). Beam 1 and beam 2 are reflected in mirrors M1 and M2, respectively, and joined in the second beamsplitter (BS2). The interference pattern generated in BS2 contains information about the phase delay change introduced by the effective birefringence of the device. Interferometer output beam is split into two beams by a third beamsplitter (BS3). Output 1 is projected at the CCD image sensor. CCD records the fringe displacements and the intensity profiles obtained from them. Total phase shift is measured as LC device is driven with design waveforms. Output 2 travels towards a lineal polarizer (P2), which axis is crossed with polarizer P1, and then it is sent out a large area photodiode (PD). It checks amplitude modulation in real time blocking beam 2 by a diaphragm (D). A transducer circuit based on a transimpedance amplifier translates the intensity into voltage.

Fringe Displacement Measurement

A Mach-Zehnder interferometer uses a technique for measuring total phase shift induced by a birefringent device due to the optical path difference [9]. As a liquid crystal cell is placed in an arm of the interferometer, the interferometer fringes produced by the recombination of beams can be recorder.

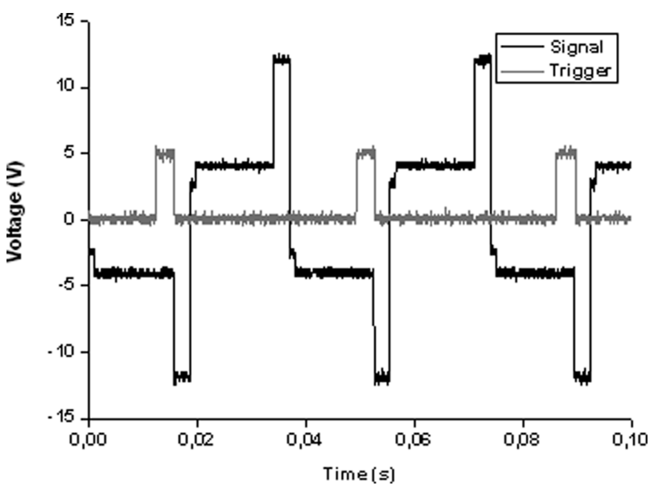
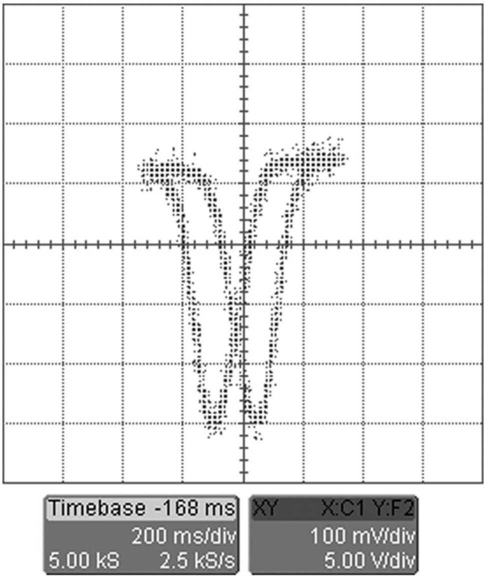
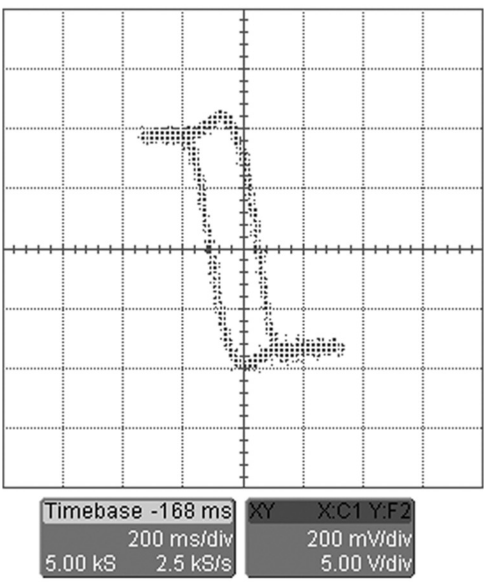


FIGURE 3 Optimized waveform at video rate for driving to the device and a trigger signal for controling the adquisition time.



(a)



(b)

FIGURE 4 Electrooptic response at 1 Hz triangular waveform. (a) Balanced hysteresis. (b) Unbalanced hysteresis.

The two beams of the interferometer join in the output beamsplitter (BS2) and the interference pattern is generated. Only those optical components of the output beams with the same state of polarization interfere. The theoretical profile of the interference fringes can be written as,

$$I = 4I_0 \cos^2\left(\frac{\delta}{2}\right); \quad \delta = k \cdot (r_1 - r_2) + \varepsilon$$

where δ is the phase difference arising from a combined path length of the two arms $(r_1 - r_2)$, and an initial phase difference, ε. Two consecutive peaks of the profile are spaced for $\delta = 2\pi$ and fringe displacements are translated into phase shifts.

Phase delay between the two arms of the interferometer, depends on the birefringence for every voltage applied to the device. It can be written as,

$$\phi(V) = \frac{2\pi}{\lambda} \cdot [\mathit{neff}(V) - 1] \cdot d + \alpha$$

where λ is the light wavelength and α the residual phase difference originated by the optical path difference in the air. Phase reference is set at a zero angular position for a known data voltage. No polarizers are used in phase characterization, unlike modulation characterization.

RESULTS AND DISCUSSION

A set of measurements has been carried out in order to characterize the phase response in V-shaped devices. Optimized waveforms at

FIGURE 5 CCD image of the interference fringes registered for a V-shaped liquid crystal device.

video rate with data voltages from −10 V to 0 V have been applied to the device (black line, Fig. 3). A trigger signal fixed the adquisition time at every frame. The synchronism has been defined by a positive edge during the negative data voltages (gray line, Fig. 3).

Firstly, cell was placed so that the molecular director aligned parallel to the entrance polarizer, when the waveform generator supplied zero data voltage (Fig. 4b). In that arrangement, LC device worked as a non-retarder waveplate. It is known that optical transmission of

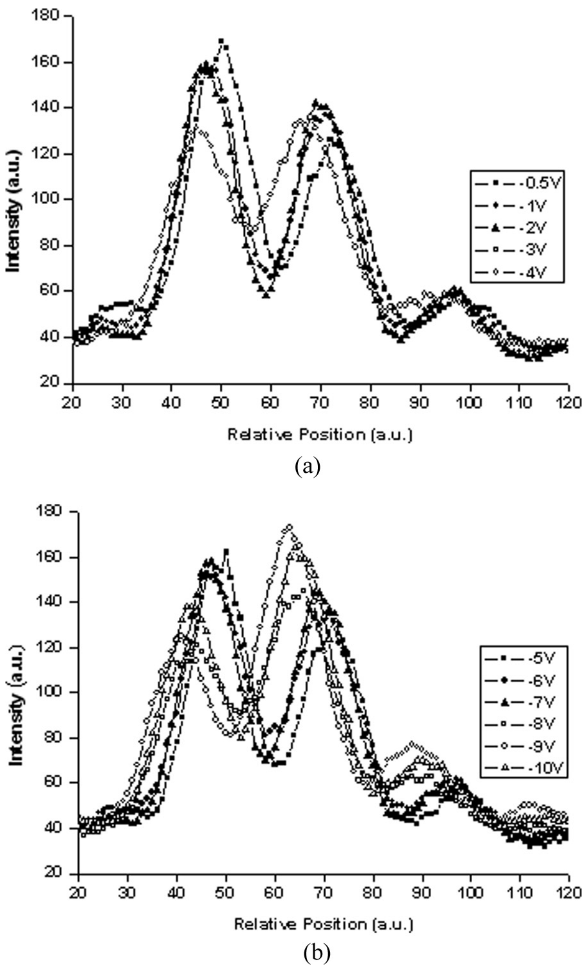


FIGURE 6 Interference fringes profile obtained for a V-shaped device for the whole data range. a) From −0.5 V to −4 V. b) From −5 V to −10 V.

a V-shape device, as 1 Hz triangular waveforms are applied, shows a hysteresis cycle centred at 0 volts (Fig. 4a). Finally, driving waveforms were applied and interference patterns registered (Fig. 5).

Reported movies in working conditions indicates that the absolute position of the fringes peaks remains rough stable, as well as the distance from peak to peak. An example of the most representative results is shown in Figure 6. Interference fringes displace towards left if the data voltage is in the range -0.5 V to -3 V (Fig. 6a). Phase reference, was set at -0.5 V data voltage, $\phi(-0.5V)$. Total phase shift is about 0.5π in this interval. At -5 V, interference fringes almost overlap the fringes of the phase reference and displace again from -6 V to -8 V, with a total phase shift nearly π (Fig. 6b). The maximum fringe displacement, $\phi(V_F)$, is obtained near the extreme ferroelectric state. Total phase shift, $\Delta\phi = \phi(V_F) - \phi(-0.5V)$, is graphed in Figure 7. Test cells show a nearly linear phase shift in every voltage interval. Phase shift profile obtained suggests that the projection of the molecular director on the cell plane does not follow an increase in a monotonous way.

Visibility measurements versus data voltage have been obtained in a V-shaped device (Fig. 8). The results show that the visibility value changes slightly in a range between 2 and 4.

The phase decrease and the contrast ratio leakage, near -4 V and -9 V, suggests that phase shift is not pure; that means phase changes happen together with significant variations in the state of polarization.

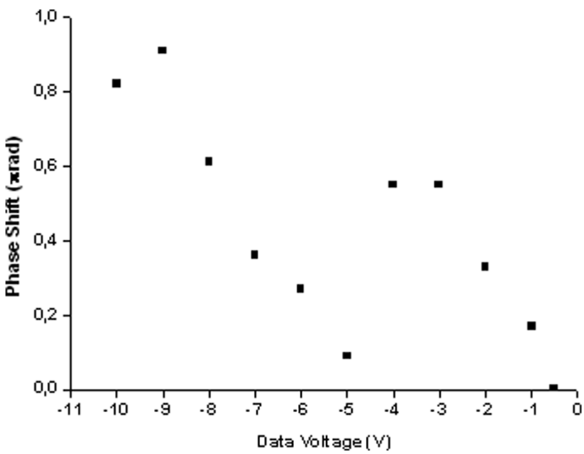


FIGURE 7 Total phase shift versus data voltage in a V-shaped device.

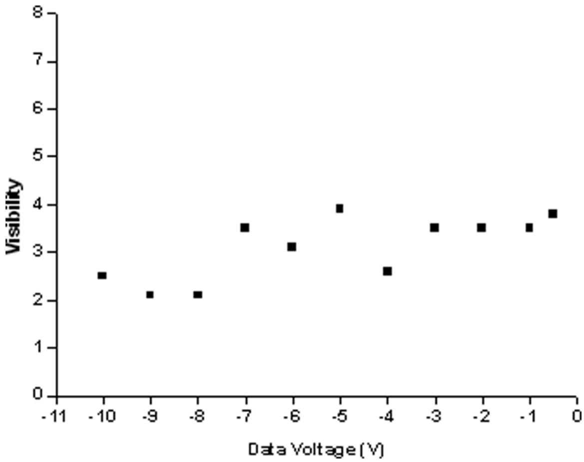


FIGURE 8 Visibility versus data voltage in a V-shaped device.

CONCLUSIONS

The purpose of this work was to measure the phase modulation characteristics, namely the relationship between the phase shift and the applied voltage. The way used to measure the phase shift was based on a Mach-Zehnder interferometer. Optical retardation of the LC medium could then be determined simply by measuring the phase difference of the waves of the two arms. Optimum driving signals have been used as driving schemes. The liquid crystal device has a nearly linear voltage dependent phase change response. It can provide from 0 to π phase modulation at $\lambda = 632.8$ nm but, usually, with a certain amount of amplitude modulation which is inherent to the in plane switching of the ferroelectric liquid crystals modulators; that is, the phase modulation is polarization sensitive.

V-shaped liquid crystals may be used as an interesting alternative to the nematic liquid crystals in new proposed configurations. Those structures are based on double-layered structures, or new set-ups with external optical components added.

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