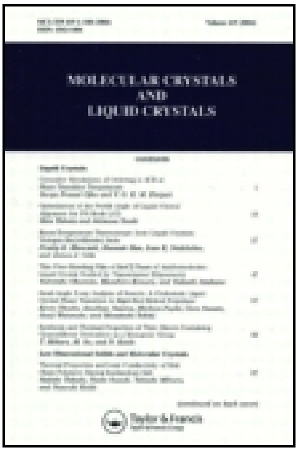

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Realisation and Characterisation of a Ferroelectric Liquid Crystal Bistable Optical Switch

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Abstract A bistable optical switch using a ferroelectric liquid crystal (FLC) layer sandwiched between two glass optical waveguides is reported. Input light can be switched from one waveguide to another one by changing electro-optically the FLC refractive index. Optical waveguides were made by ion-exchange in BK7 glass. On top of them indium tin oxide was deposited and lithographically patterned. Mixture FELIX-M4851-025 fills a 1.8 μm gap between the two optical waveguides. Such a thin cell gap and teflon film as alignment layer provides the switch with optical bistability which is its unique feature among waveguided FLC optical switches. The prototype can be driven by square monopolar pulses of 200 μs width and 20 V amplitude. It shows a maximum extinction ratio of 15 dB and becomes about 9 dB because of relaxation of FLC molecules after removing driving voltage. Switching time of the device is about 300 μs.

Keywords: optical switches; surface stabilised ferroelectric liquid crystals.

INTRODUCTION

Communication systems employ photonic signals travelling through optical fibers in order to exploit their large bandwidth which provide high information capacity. Optical transport networks require large switching systems to route and process photonic signals. Available technologies based on inorganic materials, such as $LiNbO_3$ do not allow for many inputs and many outputs, because they are paid in terms of too high insertion losses, crosstalk and too large dimensions in the order of several mm^2 per device [1]. Micro-electro-mechanical switches based on vertical torsion micro-mirrors on Si substrate can be a good solution to implement large switching matrices but this advantage is often paid in terms of high driving voltages of about 80 V and switching times of about 1 ms or longer [2]. Recently ferroelectric liquid crystals (FLC) have become interesting materials to make optical switches mainly because of their bistability in surface stabilised cells, relatively short switching times in the range of microseconds and because of easy fabrication due to mature flat panel display technology. Furthermore FLC optical switches have potentially low losses due to molecular order of smectic phases [3]. Ferroelectric liquid crystal spatial light modulators were proposed and demonstrated, to route optical beams in free-space between input and output optical fibers, with excellent low crosstalk in wavelength division multiplexing optical communication systems [4] [5].

Integrated optics devices using ferroelectric liquid crystals and optical waveguides were proposed [6][7][8][9]. All of them perform amplitude modulation of light at low frequencies, in the range of few kHz. These devices use a simple structure consisting of an FLC layer path between input and output slab waveguides as in [6] and [7], or they employ an FLC overlaying an optical waveguide as in [8] and [9].

In this paper we report the fabrication and the characterisation of an integrated optical switch based on a surface stabilised ferroelectric liquid crystal (SSFLC) layer sandwiched between two single mode optical waveguides. This approach can be easily extended by using display technology to make large switch matrices for cross-connects in optical networks. Switching of light between the two waveguides can be performed with about 20 V, and less then 300 μs switching time.

Clark and Handschy demonstrated a device with a similar structure by using multimode waveguides, FLC aligned by shearing technique and ITO electrodes deposited on external surfaces of only 150 μm thick glass substrates used as buffer. Such thin substrates were used to reduce high driving voltage due to external electrodes. Nevertheless light could be switched from one waveguide to another with no less than 1 kV [10]. Among lightwave FLC switches a unique feature of the switch presented in this work, is the bistability of its optical response which reduces even further its driving power.

DEVICE FABRICATION

The device structure which has been made is sketched in Figure 1.

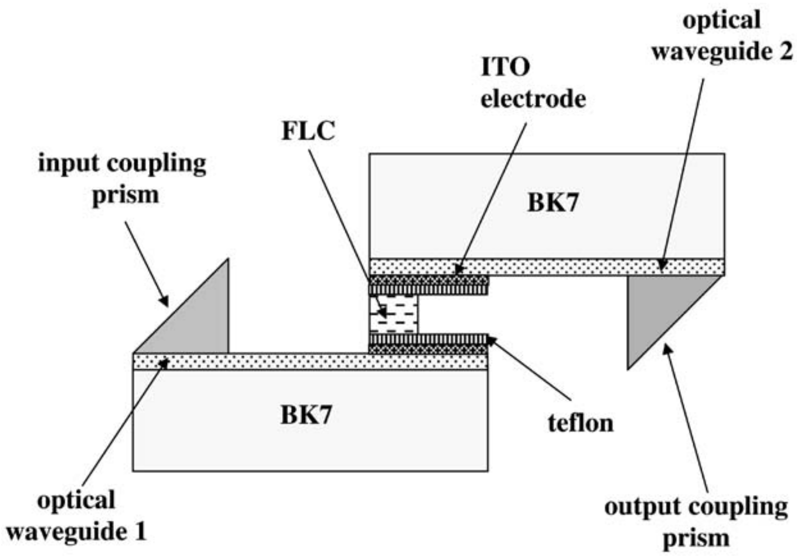

FIGURE 1. Realised device with input and output coupling prisms.

It consists of an SSFLC cell made of two BK7 glass substrates. Two single mode optical waveguides have been obtained on the inner surfaces of the cell by using ion-exchange process. Indium tin oxide electrodes with a thickness of 200 Å and 4 mm^2 have been deposited by electron-beam vacuum evaporation and covered by a 400 Å layer of teflon, as alignment layer, deposited by hot friction. The cell was assembled with 1.8 μm gap filled with ferroelectric liquid crystal M4851-025.

In the optical switch of Figure 1, laser light coupled to the optical waveguide 1 by a coupling prism is transferred to the optical waveguide 2 when FLC refractive index, n_{FLC}, is higher than that one of the optical waveguides n_w. In this case the switch is in the cross-state. When n_{FLC} is lower than n_W light remains in the input waveguide and the switch is said in the bar-state. Only TE polarised light can sense a change of n_{FLC} since it is due to electro-optical in-plane switching of FLC molecules.

Beam propagation calculations have been carried out to find out the values of n_w and n_{FLC} to get maximum optical power transferred from one waveguide to another in the cross-state [11].

In particular an optimum effective refractive index n_w = 1.528 at the wavelength of 0.6328 μm was obtained by performing ion-exchange at 385 °C for 10 min in a salt mixture made of an initial mixture of $NaNO_3$:KNO_3 50% weight/weight and adding 0.7 mole % of $AgNO_3$.

The corresponding optimum value of n_{FLC}= 1.533 in the cross-state was obtained by choosing an orientation of teflon deposition of 19° respect to the direction of propagation. This optimized alignment orientation was computed for FLC extraordinary refractive index 1.611, ordinary refractive index 1.466 and tilt angle of 26° at temperature of 25°C.

Since the smectic cone axis coincides with the normal to the smectic planes, given by the teflon deposition direction (as in the device of ref. [10]), FLC director in the two stable states is at 26° respect to teflon orientation. The correct orientation was also verified in the sample by using a polarizing microscope. The two stable states can be initial states indifferently, depending on last memorized state, because of bistability due to surface stabilization. Moreover TE polarized light vector in the FLC layer forms an angle of 45° with molecule director for one state and 97° for the other state due to switching along the entire smectic cone surface as a further consequence of chosen alignment direction. Finally it was assumed about 0° the pretilt of FLC molecules, i. e. the angle between director and cell plane, as previously measured for our teflon alignment layers. This feature of teflon alignment layers was also found by other authors [12][13].

OPTICAL MEASUREMENTS AND DISCUSSION

Characterisation of the realised prototype was carried out by using a setup schematically drawn in Figure 2.

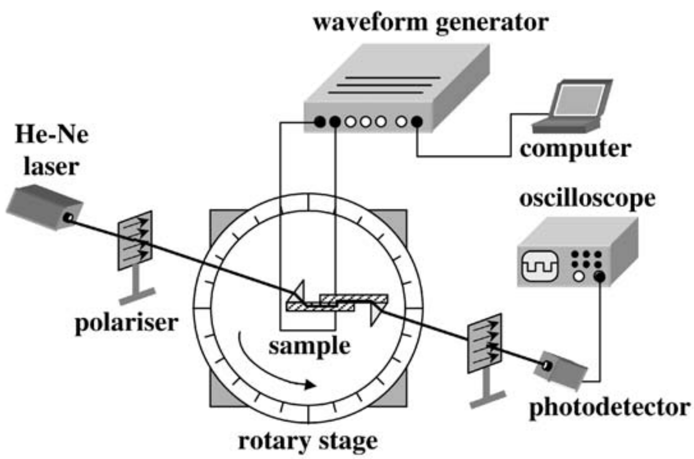

FIGURE 2. Optical measurement setup to characterise the switch.

An He-Ne laser is used as optical source whose output passes through a first TE polariser before impinging on the surface of SF6 coupling prism mounted on the input waveguide of the device.

The optical switch was positioned on a rotary stage to easily determine coupling angle. Output light comes out from another prism, identic to the input one, when the switch is in the cross-state. It crosses through a second TE polariser and hits a Si photodetector whose electrical output is captured by an oscilloscope to visualise the optical response.

The second polariser was used to check that signal output is TE polarised as expected. The switch was driven by an arbitrary waveform generator capable to produce any driving voltage waveform by using a dedicated computer software.

Optical bistability of the switch was observed by looking at its optical response to simple monopolar pulses as shown in Figure 3.

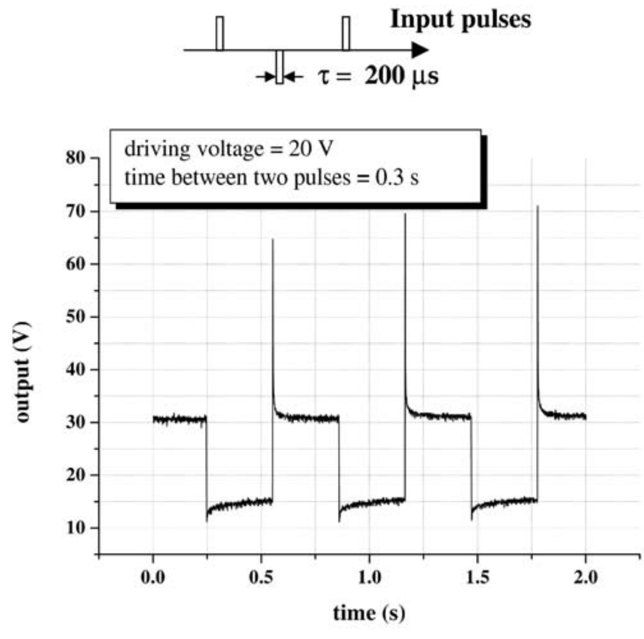

FIGURE 3. Bistable optical response of the switch by applying monopolar pulses schematically drawn in the upper side.

Input pulses of 20 V amplitude and 200 μs width were applied with a period of 0.6 s to allow for complete relaxation of liquid crystal molecules. They pass from their forced position corresponding to maximum optical response intensity, as the driving pulse is applied, down to the final equilibrium state. Asymmetry of the optical response is due to the asymmetric position of the smectic cone respect to the propagation direction and hence the asymmetry of the molecule positions in the two states of the switch. In the bar state light extinction is not very good, as it can be observed in Figure 3, because a simple sequence of monopolar pulses is not the best driving waveform to force FLC molecules to the position corresponding to the lower refractive index.

In order to get a better bar state a more complex bipolar driving waveform was chosen and was used to measure the switching time and the contrast ratio. Figure 4 shows the optical response to a DC-compensated three-pulse driving waveform, whose intensity is reported on the left-end side y-axis.

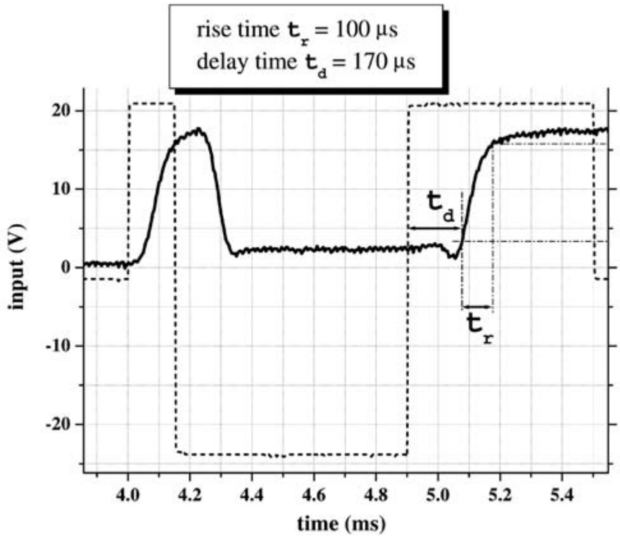

FIGURE 4. Delay and rise times read on the optical response (solid line) to a three-pulse driving waveform (dashed line).

The first two driving pulses allow for writing the cell in the same state and the third pulse is the actual switching pulse. The switching time was measured on the optical response to the last pulse and defined as delay plus rise time. The delay time, t_d, is the time employed by the switch optical response to reach 10% of its maximum value starting from the instant in which the third impulse is applied. The rise time, t_r, is the time employed by the switch optical response to pass from 10% to 90% of its maximum value. Input voltage intensity of about 23 V gives a delay time of about 170 μs and a rise time of 100 μs for a total switching time less than 300 μs.

Two different values of contrast ratios were defined because of relaxation phenomena observed in the electro-optical response as shown in Figure 5.

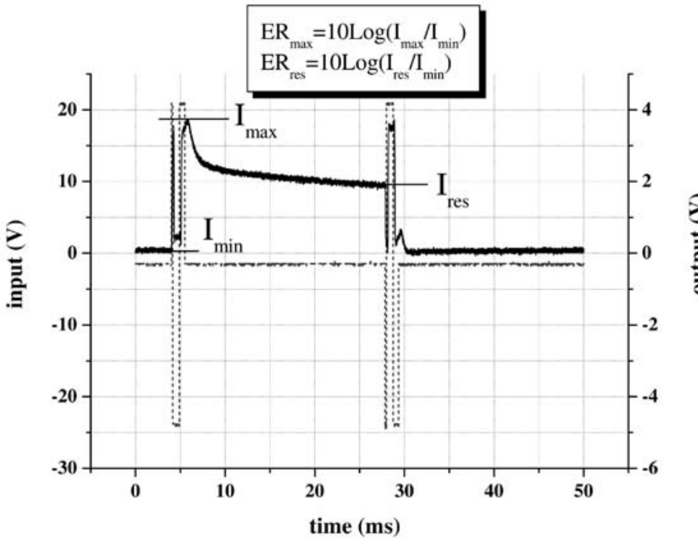

FIGURE 5. Driving waveform (dashed line) and corresponding optical response (solid line) with definition of measured contrast ratios.

The complete relaxation and the definition of the two contrast ratios are reported. The maximum contrast, ER_{max}, is defined as the ratio in dB between maximum optical response intensity I_{max} in the cross-state of the switch and the minimum output value I_{min}. The residual contrast, ER_{res}, is defined as the ratio in dB between final relaxed output intensity I_{res} and I_{min}.

The applied three-pulse waveform improved contrast of the optical response of the switch respect to simple monopolar pulses because of a better stabilisation given by the first two pulses. In particular a better minimisation of output optical power was observed during bar-state of the switch.

A value of ER_{max} over 15 dB and ER_{res} of 9 dB was measured for input peak voltage of about 23 V. A value of ER_{max} over 14 dB was measured even for input peak voltage of just 5 V. Furthermore such values of contrast ratios can be greatly improved by obtaining a better alignment uniformity. In fact an optical inspection of the SSFLC cell revealed small domains which were not able to switch because of poor alignment. The complete switching area is less than 4 mm long which is nevertheless shorter than coupling length of commercial electro-optic coupler-based switches made of $LiNbO_3$ [1]. Coupling length of the SSFLC optical switch can be further reduced by using a photolithographic mask to pattern the electrodes with better resolution. Simulations of the device by beam propagation method indicates that coupling length as short as 60 μm can be obtained [7].

CONCLUSIONS

The first to our knowledge FLC waveguided bistable electro-optical switch has been experimentally demonstrated. It was realised by using an SSFLC layer sandwiched between two ion-exchanged glass waveguides on BK7 substrates. Optical power can be transferred from one waveguide to another with a maximum contrast ratio of over 14 dB by applying only 5 V. Because of FLC relaxation, residual contrast ratio of 9 dB can be obtained after applying about 23 V peak voltage. Such a voltage is far below 1 kV applied to the device in which electrodes are external to substrates. Furthermore the device proposed by Clark is not bistable [10]. Bistability in the prototype presented in this paper reduces even further its overall driving power. Complete switching is accomplished within 300 μs time with a coupling length of less than 4 mm which can be potentially reduced down to less than 100 μm according to device simulation by using beam propagation method [11]. Since such a device is basically a single pixel SSFLC cell fabricated by using standard flat panel display technology, a large bistable photonic multiple inputs multiple outputs switch/router matrix containing lots of such switches can be designed and fabricated to be used in optical networks.

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