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OPTICAL SWITCH USING TOTAL REFLECTION IN LIQUID CRYSTALS

Sergey DOVGALETS [1], Yulia SEMENOVA [2], Vasyl PRYSYAZHNYUK [1]
[1] *Department of Automatics & Information-Measuring Engineering, Vinnitsa National Technical University, Khmelnitske Shosse 95, 21021 Vinnitsa, Ukraine*
dovgalets@vstu.vinnica.ua
[2] *School of Electronic & Communications Engineering, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland*

Abstract. *Optical switch using electro-optical effect in liquid crystals is proposed and investigated for incorporation in a switch matrix for optical networks. This device employ total reflection at the border between glass and nematic liquid crystal. Prototype of the switch has been designed and its parameters have been investigated. Initial results show the switching contrast ratio of 42 dB, respectively, with insertion loss about 2.9 dB for polarized light.*
Keywords: *All-optical matrix switch, liquid crystal, total reflection.*

Introduction

All-optical switching fabrics will be a significant component in order to relieve the capacity limitation of electronic-switched networks. These devices allow to switch the traffic directly in the optical domain, avoiding the need of several optical↔electrical conversions.
Several technologies have been proposed as candidates for optical switching. The most common switching technology is based on optomechanical switches, where the path of light is switched by some form of mechanical movement of either fibers or mirrors. Such switches feature good scalability, however, this approach involves moving parts, and typically has a limited lifetime of up to 10^6 cycles. Some of the best developed types of optical switch employ liquid crystal (LC) materials due to their extreme sensitivity to applied fields, low power consumption, long lifetime and to their low cost.

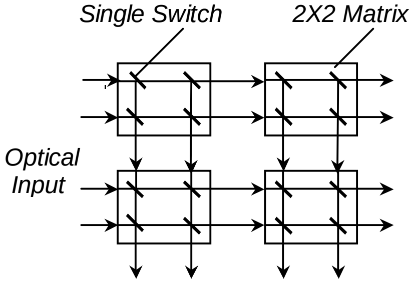

Figure 1. Matrix spatial switch.

Several different physical mechanisms for LC switches have been investigated and tested. One LC technology involves polymers containing nematic LC droplets [1]. Another approach involves chiral smectic A, which has a much faster response (10μs versus a few ms) [2]. Some ferroelectric liquid crystal switching technologies are based on the concept of total internal reflection [3, 4]. However, these approaches are characterized by a high energy loss and thus high insertion loss, which limits the practical applications of LC optical switches in optical networks.
The most popular form of switching technology is a so-called matrix switch. We have considered the matrix consisting of 2x2 single switches as a basic structure. This structure can be subsequently incorporated into a module containing N^2 basic matrices (Fig.1) [5].
In this paper the design of all-optical switching device based on total reflection in liquid crystals will be presented.

Principle of operation

Schematic diagram of the total internal reflection switch is shown in the Figure 2. Planar nematic LC layer is sandwiched between two glass prisms with transparent conducting and aligning layers.

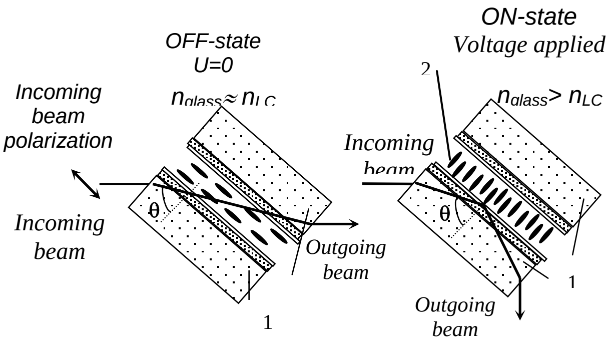

Figure 2. Total reflection switch structure: 1- glass prisms; 2- liquid crystal layer

The glass and LC material's refractive indices should be adjusted to maintain the switch transparency in the OFF-state and total reflection condition in the ON-state. The alignment layers should provide a homogeneous planar orientation with the director parallel to the incident light polarization direction. The required thickness of LC layer should be much greater than the decay distance for the evanescent wave. Without an applied voltage the nematic has a refractive index ($n_{LC\text{-}OFF}$) near that of the glass prisms (n_g), so the incident light passes through the liquid crystal layer. Liquid crystal molecules change their orientation while the switch is turned on by the applied voltage, so the LC refractive index becomes smaller than that of the glass ($n_{LC\text{-}ON} < n_g$) to satisfy the total internal reflection condition, so the input beam will be reflected.

Let's consider a monochromatic plane wave propagating in an arbitrary direction through nematic liquid crystal; two independent, linearly polarized, propagation modes can exist whose phase velocities are determined by the indices of refraction n_A and n_B along the each direction of polarization. The intersection of the material's index ellipsoid

$$\frac{x^2}{n_x^{\ 2}} + \frac{y^2}{n_y^{\ 2}} + \frac{z^2}{n_z^{\ 2}} = 1, \qquad (1)$$

and the plane normal to the direction of propagation produce an ellipse whose major and minor semi-axes determine the indices n_A and n_B. For nematic liquid crystal these indices depend on the surface alignment conditions (or the texture type) and on the strength and direction of the electric field applied to the electrodes. Without an applied electric field the nematic director is parallel to the electrodes surfaces and is modeled as a uniaxial crystal with a principal axis ellipsoid given by:

$$\frac{x^2}{n_e^{\ 2}} + \frac{y^2}{n_o^{\ 2}} + \frac{z^2}{n_o^{\ 2}} = 1. \qquad (2)$$

The intersection of the normal plane for an incident linearly polarized plane wave has indices of refraction given by:

$$n_A = n_z = n_o, \qquad (3)$$

$$n_B = \left\{ \frac{\cos^2\theta}{n_e^{\ 2}} + \frac{\sin^2\theta}{n_o^{\ 2}} \right\}^{-1/2}, \qquad (4)$$

where n_o, n_e – liquid crystal refracting indices, θ - angle between the light propagation direction and the crystal surface.

Thus, for the light with its **E** component lying in the plane formed by the **k** vector of the beam and the crystal optical axis, the refractive index is $n_{LC\text{-}OFF} = n_B$.

Under an applied electric field liquid crystal molecules change their orientation along the field, so the nematic layer becomes homeotropically aligned and the crystal axis is along the y-axis.

For a linearly polarized beam propagating through the cell in the ON-state the index of refraction is given by:

$$n_B = \left\{ \frac{\sin^2\theta}{n_e^{\ 2}} + \frac{\cos^2\theta}{n_o^{\ 2}} \right\}^{-1/2} \qquad (5)$$

for the case when **E**-component is lying in the plane formed by the **k**-vector and the LC optical axis.

In this way the LC optical axis changes its orientation depending on applied electric field value. It gives a possibility to vary the LC refractive index in the range from $n_{LC\text{-}OFF}$ to $n_{LC\text{-}}$

$_{ON}$. As can be seen from Fig.3, the difference between $n_{LC\text{-}OFF}$ and $n_{LC\text{-}ON}$ values depends on both the LC optical anisotropy and the angle of input beam incidence.

A planar liquid crystal layer may be considered as a conventional Fabri-Perot interferometer with a refractive index n_{LC} depending on applied voltage which light transmittance is given by the formula:

$$I = \frac{I_0}{1 + M \cdot \sin^2(\phi)}, \qquad (6)$$

where I is the intensity of the light transmitted by liquid crystal layer; I_0 is the intensity of the incident light;

$$\phi = k \cdot n_{LC} \cdot 2d \cdot \cos(\theta_R),$$

is the phase difference between two beams reflected by the layer; d is the liquid crystal layer thickness; $k = \frac{2\pi}{\lambda}$ is the wave number in vacuum; λ - radiation wavelength; θ_R - angle of refraction at the glass-LC interface which is given by Snell's law:

$$n_{glass} \cdot \sin(\theta) = n_{LC} \cdot \sin(\theta_R),$$

where θ is the angle of incidence;

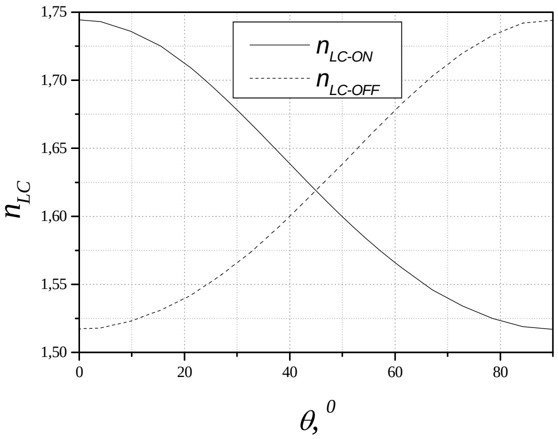

Figure 3. Calculated dependencies of refracting indices on the angle of incidence for OFF and ON modes.

$$M = \frac{4R}{1 - R^2},$$

and $R = \frac{I_r}{I_o}$ - intensity of the reflected light I_r at the glass-liquid crystal interface related to the incident intensity I_0, which is given by:

$$R_\perp = \frac{\sin^2(\theta_R - \theta)}{\sin^2(\theta_R + \theta)} \qquad (7a)$$

for the light with its **E** component perpendicular to the plane of incidence and

$$R_\parallel = \frac{\tan^2(\theta - \theta_R)}{\tan^2(\theta + \theta_R)}, \qquad (7b)$$

for the case when vector **E** is parallel to the plane of incidence.

Fig.4 shows simulated dependence of the switch transmittance on the LC refractive index and the incident angle. Liquid crystal layer totally reflects the light when the material's refractive indices and the angle of incidence satisfy the condition of total internal reflection:

$$n_{LC} \le n_{glass} \cdot \sin(\theta). \qquad (8)$$

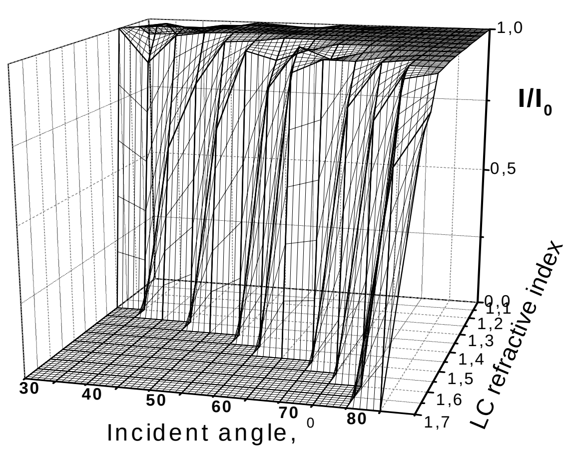

Figure 4. Simulated dependence of the total reflection switch transmittance on liquid crystal refractive index and the incident angle of incoming beam (n_{glass} = 1.67).

The figure shows that the total reflection switch design and operating modes are defined by the correlation between the glass prisms material, nematic liquid crystal refractive indices and the angle of incoming beam incidence. Thus to achieve a maximum switching transmittance change it is necessary to make an optimization of these parameters. In such a way it is possible to choose an optimum incident angle for the fixed nematic – glass combination. It should be noted, that the choice of an appropriate incident angle defines the glass prisms shape, which should be simple and suitable for incorporating the switching element into a matrix.

The thickness of liquid crystal layer does not significantly influence on the switch performance unless it is close to the radiation wavelength value. In this case an evanescent field may reduce the intensity of the reflected beam. This parameter is more important from the driving voltage point of view as long as increasing of the layer thickness leads to the control voltage growth.

In our experiment the switch parameters are justified to operate at λ = 633nm and to provide the angle of reflection of 45^0. The glass prisms are rectangular shaped to simplify a matrix design.

Experimental results

The total reflection switch performance was investigated in the sample on the base of two glass prisms (n_g = 1.6744) with transparent electrodes. The prisms were coated in a centrifuge with PVA, both substrates were rubbed and then aligned antiparallel to each other. The liquid crystal material (Merck E63, n_e = 1.7444, n_o = 1.5172, Δn = 0.2272 at λ = 589.3 nm) was introduced into the cell by capillary action. The thickness of the nematic liquid crystal layer was 25 μm.

The experimental set-up is shown in Figure 5. The LC cell (total reflection switch) is designed to operate at 633 nm wavelength of He-Ne laser. For rectangular prisms used in measurements the incident angle value is 75^0 and the incident light polarization is parallel to the direction of the rubbing of the aligning layer.

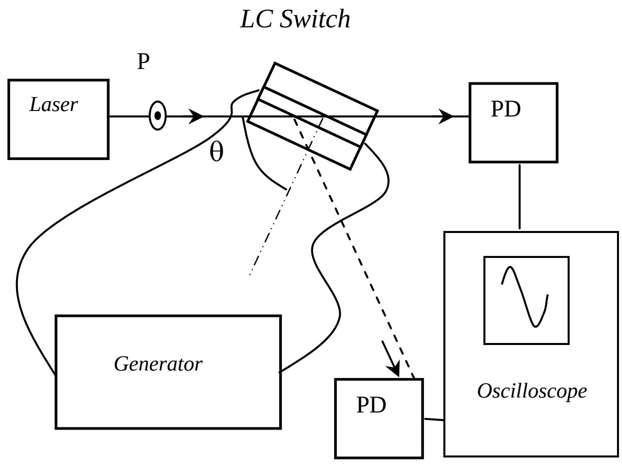

Figure 5. Total reflection switch experimental set-up: P – polarizer, PD – photo-diode.

The total reflection element is driven with a bipolar square wave signal with an amplitude from 0 V to 35 $V_{p\text{-}p}$. The frequency of the driving signal equals to 1 kHz.

A typical electro-optic response for the total reflection switch is shown in the Figure 6. The measurements to evaluate the switch performance show the follow results - switching contrast: 42dB for transmitting mode and 20.5dB for reflecting mode, insertion loss level: 2.8dB and switching time: 0,34ms.

The glass parts of both switches did not have an anti-reflection coating on their surfaces. The insertion loss can be reduced by use of a 100% polarizer, based on cholesteric mirrors. Such a component could have a high transmission, limited only by the optical precision and material orientation defects.

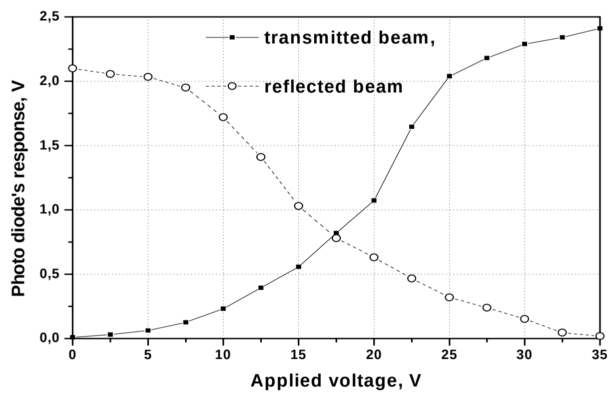

Figure 6.Typical electro-optic response for the total reflection switch.

Conclusion

In conclusion, we have described a switching device using the total reflection phenomena on the base of glass prisms and a nematic liquid crystal layer. Prototype of single switch has been designed and its parameters have been investigated. The first experimental results for a visible radiation indicate that a high switching contrast (40dB) and a satisfactory low (3dB) insertion loss level can be achieved for the given type of switch. The advantages of the proposed design are simple and compact structure, electric control, low power consumption and good scalability. Work in progress includes minimizing the insertion loss and cross talk for incorporation into a switch matrix.

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