Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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To cite this Article Sierakowski, Marek and Domański, Andrzej W.(1993) 'A novel liquid crystal light modulator', Liquid Crystals, 14: 2, 287 — 291

To link to this Article: DOI: 10.1080/02678299308027642

URL: http://dx.doi.org/10.1080/02678299308027642

LIQUID CRYSTALS, 1993, VOL. 14, NO. 2, 287–291

A novel liquid crystal light modulator

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We present a conception of two optical modulators. One of these, which we have called the scattering liquid crystal cell seems to be promising with a view to possible applications. We assumed that the modulator could be used in optical logic as a gate element, but other applications in optoelectronics would appear also to be possible. Some preliminary results of an experimental examination of the modulators are also presented.

1. Introduction

Optoelectronics now competes successfully with classical electronics in many technical applications, ranging from telecommunications, across medicine and metrology to computing techniques. Such accelerated progress in optoelectronics has been achieved thanks to versatility, convenience of use, reliability, and speed of operation. The structural basis of optical control systems involves optical connections combined with optical processing and sensing elements. To accomplish these last two functions a number of novel inventions have been realized. For these purposes in the past few years liquid-crystalline controllable elements have been introduced. The concept we would like to demonstrate is a novel use of a controllable birefringement element as an optical modulator. The modulator, initially designed for optical logic [1] as a gate element, is based on a typical liquid crystal cell of a sandwich type. The device which is demonstrated can potentially realize diverse optical functions, for example as a controllable polarizer or high band pass filter, or even as a sensor.

2. Device conception

We started with the following idea: a phase diffraction grating working in a birefringent medium with an externally controlled index of refraction n. A simple way to realize this is to set up a typical liquid crystal sandwich cell containing a *monocrystalline* liquid crystal layer between two plane electrodes. The inner surface of the first of the electrodes which contacts the liquid crystal has to be periodically cut to form a phase diffraction grating. As the orientation of the birefringent liquid crystal layer depends on external voltage, then the light passing through the cell will meet a diffractive texture followed by a medium with a variable refractive index, taking a value between n_o and n_e. Considering now the grating conditions for arbitrary incidence one obtains:

$$\sin r = (1/n_e)(m\lambda/p \pm \sin i), \qquad (1\,a)$$

or

$$\sin r = (1/n_o)(m\lambda/p \pm \sin i), \qquad (1\,b)$$

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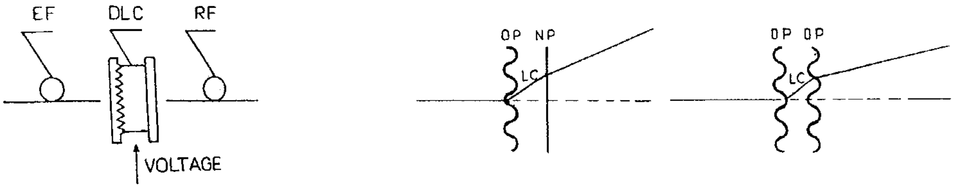
where i, r are incidence and diffraction angles, λ is the vacuum wavelength, p is a grating period and m is an integer. Birefringence of the liquid crystal material could be relatively high, and $\sin i = 1$. So if we now make the period p of the grating close to λ, although ensuring $\lambda/p < n_e$, we can expect a large-angle diffraction to appear. In addition, a zero order term could be suppressed for grating of a phase type. On the other hand, in the case of a sufficiently large liquid crystal birefringence one manages also to allow p to obey the relation $p/\lambda > n_o$. Thus, by planar alignment of the liquid crystal layer, diffraction is allowed, while by homeotropic alignment diffraction is not allowed and only a plane wave propagates. Now, let us combine the device with emitting and receiving fibres, as it is shown in the figure 1 (*a*). This results in the accomplishment of a time-amplitude function: the incoming light beam if not diffracted leaves the diffracting liquid crystal cell collimated and can then be launched into the receiving fibre. When diffraction occurs light is emitted angularly distributed and only a small part of it remains in the limits of the numerical aperture of the receiving fibre, therefore it cannot be introduced inside the receiving fibre. This is to emphasize that the modulating function is polarization-of-light sensitive and means that modulation only concerns this part of the beam, which can propagate with its light vector parallel to the liquid crystal optic axis in any state of the diffracting liquid crystal cell. In opposite, the beam component polarized orthogonally is affected permanently only by n_o, it is then never diffracted and can be introduced undisturbed into the receiving fibre.

However, any value of birefringence for practically attainable liquid crystal types will not exceed 15 per cent of n_o. This fact, as well as the acting principle of the diffracting liquid crystal cell result in a large diffraction angle, low efficiency and high light losses due to intrinsic reflections. To diminish this and make the performance of the device softer (i.e. its response to an applied voltage) one can replace an optically neutral electrode by a second grating, as shown in figure 1 (*b*). The period of the second grating can be arbitrarily chosen in order to obtain a symmetrical or asymmetrical structure of the diffracting liquid crystal cell. As already stated, our intent was to apply the modulator to optical logic. Unfortunately the device presented above limits the possibility of cascading a number of elements in one array because of its axially extended geometry which is required for its functioning. Therefore, we have changed our concept and modified our modulator. We have decided to propose another device which has a similar structure but works on a scattering principle. Namely, if one decreases the period p of grooves beyond wavelength λ, light scattering will appear and become more intense with decreasing p. Obviously, a pronounced optical interface with scattering centres has to exist. In our case, this means that the index of refraction of the glass plates containing the scattering texture and that of the liquid crystal layer must be



(*a*) (*b*)

Figure 1. (*a*) The diffracting liquid crystal cell optical modulator: EF is the emitting and RF the receiving fibres; (*b*) possible configurations of the diffracting liquid crystal cell : OP is the diffraction grating and NP a neutral glass plate.

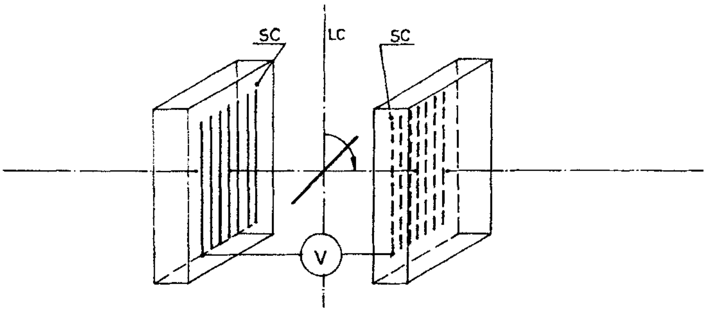


Figure 2. Construction of the scattering liquid crystal cell; SC, surface with scattering texture.

different. If they are close to each other, scattering no longer occurs because optically the glass–liquid crystal interface no longer exists and there are no scattering centres. A proposed device, a scattering liquid crystal cell is shown in figure 2. The scattering surfaces of the electrodes touch the ordered liquid crystal layer. The refractive indices n of the electrode plates and one of the two, n_0 or n_e, of the liquid crystal layer must be well tuned. The optimal geometry of the scattering centres form parallel scratches, the mean period of which should be maintained below the wavelength λ whilst still obeying the Mie scatter condition [2] (i.e. this should not be smaller than some critical value). This ensures a spatial anisotropy of scattering with the major part of the light directed forwards. The principle of operation of the proposed scattering liquid crystal cell resembles that of the well known Christiansen filter [3].

Other features and the performance of the scattering liquid crystal cell combined with fibre connections are the same as those already described for the diffracting liquid crystal cell: an applied voltage forces the liquid crystal layer to reorient and changes its effective index of refraction, thus switching the modulator between two states—scattering for $n_e \neq n$, and unscattering if $n_0 = n$ (or vice versa).

3. Experimental

3.1. *Examination of the diffracting liquid crystal cell*

In constructing a diffracting liquid crystal cell one must adjust carefully the grating period p, refractive indices of the liquid crystal (birefringence), and the wavelength of light λ. In our experiment we have used a liquid crystal material of biphenyl type (pentacyano-biphenyl-PCB-3, synthesized in our Institute) having $n_0 = 1{\cdot}522$ and $n_e = 1{\cdot}718$. Thus, for laser light $\lambda = 633$ nm the grating should consist of between 2400 and 2700 lines per mm. Such a dense grating pattern will require great technological precision and this is an obvious disadvantage of our construction. We have chosen one with 2500 lines mm^{-1} which give the first order of diffraction at 67°. The prepared cell was thick and we had many problems in adjusting the whole set up axially. Finally, on achieving this we obtained in the receiving fibre only a very weak output signal. Moreover, the beam passing the diffracting liquid crystal cell which was undiffracted and should have been well collimated, appeared to be slightly scattered. Therefore, we decided to continue the experiment only with the scattering liquid crystal cell.

3.2. *Examination of the scattering liquid crystal cell*

In making up the cell we used the same liquid crystal material, PCB-3, planarly oriented between two scattering surfaces. The scattering texture was made simply by

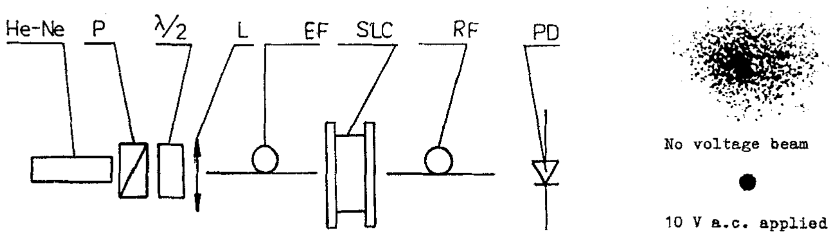


Figure 3. Experimental arrangement consisting of a He–Ne laser, polarizer P, halfwave plate $\lambda/2$, lens L, the scattering liquid crystal cell, EF the emitting fibre and RF the receiving fibre and photodetector PD; to the right the beam image behind the scattering liquid crystal cell.

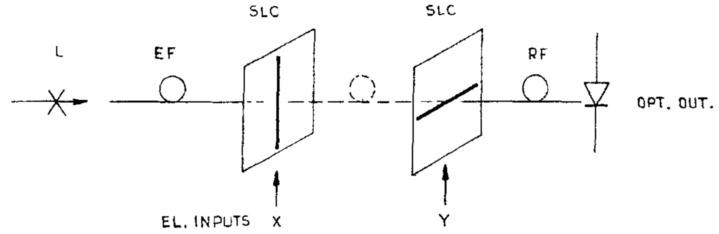


Figure 4. A logic gate arrangement based on two scattering liquid crystal modulators.

unidirectional polishing of thin substrate glasses with calibrated diamond powder (0·5 μm diameter). An optical glass (Crown K 523/596) with $n_d = 1{\cdot}5225$ was used. Next, the plates were covered with ITO electrodes and the usual rubbing procedure agreeing with polishing direction was applied without any surfactant. Finally, the cells were established by 15 μm spacers and filled with PCB-3. The experimental arrangement is presented in figure 3. The polarized light beam was injected into a Hi–Bi emitting fibre which maintained the initial polarization of light. The plane of polarization could have been controlled by a half-wave plate ($\lambda/2$). Light emitted from the emitting fibre travelled through the scattering liquid crystal cell and was then launched into an ordinary receiving fibre and led to a photodetector. Before measuring the output signal level we had visually checked the action of the device. Namely, we placed the scattering liquid crystal beyond the emitting fibre and so observed a pronounced scatter of light altering to a well collimated beam by application of a few volts AC on the electrodes. This effect is shown in figure 3. As expected, scattering was only noticed for light polarized along the optic axis of the cell. Turning the polarization plane to a perpendicular orientation eliminated all scattering for any voltages. Then the receiving fibre was positioned and we measured output signals by means of a lock-in nanovoltmeter. This enabled us to find the magnitude of modulation contrast C taken as maximal to minimal output signals for the both states of the modulator. In our experiment C usually exceeded 20.

The results encouraged us to arrange two scattering liquid crystal modulators positioned orthogonally to each other. Such a combination forms an optical gate structure, as shown in figure 4. Here the two electrical inputs X and Y, drive the optical carrying signal and control the optical output. The setup can realize an intensity-logic gate where an input high state (or logic value 1) is represented by the presence of a switching voltage (10 V) and low state (logic 0) by no voltage. An output high state signifies the presence of light. Regarding the principle of operation of the modulators, it is easy to deduce from figure 4, that this configuration implements an OR-gate, in the case of a positive dielectric anisotropy and planar initial alignment of the liquid crystal. In the opposite case, negative dielectric anisotropy and homeotropic alignment, this configuration gives a NAND-gate. Other modifications of the arrangement are also possible. The experiment is still in progress and detailed results will be reported elsewhere.

4. Conclusions

We proposed and examined two concepts of optical modulators. One of them, working on similar principles to the Christiansen filter, can be, we believe, of practical value after some possible improvements. The modulator enables arranging of electrooptical logic gates but, if a little imagination will here be justified, it can also accomplish some other optical functions. To support our suggestion we can, for example, indicate following possible applications:

an electrically controllable polarizer, since the modulator enables attenuation of one light component of selected polarization,

a high-band–pass filter working analogical to the Christiansen filter but electrically addressed,

a displacement sensor because light transmission conditions can be influenced by external deformations.

References

[1] Sierakowski, M., and Domański, A., 1991, *Laser in Engineering* (Springer-Verlag), pp. 670–674.

[2] See, for example Meyer-Arendt, U. R., 1972, *Introduction to Classical and Modern Optics* (Prentice Hall).

[3] Fabelinskii, I. L., 1968, *Molecular Scattering of Light* (Plenum Press).