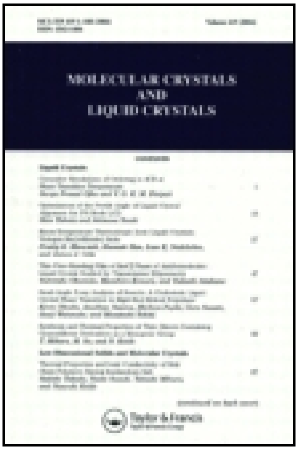



Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

# Integrated Electro-Optic Switch Based on a Ferroelectric Liquid Crystal Waveguide

Giusy Scalia [a] [b], David Sparre Hermann [a], Giancarlo Abbate [b] [c], Lachezar Komitov [a], Pasquale Mormile [d], Gian Carlo Righini [e] & Luigi Sirleto [e]

[a] Department of Microelectronics and Nanoscience, Chalmers University of Technology, S-412 96, Göteborg, SWEDEN

[b] Dipartimento di Scienze Fisiche, Università di Napoli, Via Cintia Monte S. Angelo, I-80126, Napoli, ITALY

[c] INFM, Via Cintia Monte S. Angelo, I-80126, Napoli, ITALY

[d] Istituto di Cibernetica CNR, Via Toiano 6, I-80072, Arco Felice, Napoli, ITALY

[e] Istituto di Ricerca sulle Onde Elettromagnetiche, IROE CNR, Via Panciatichi 64, I-50127, Firenze, ITALY

Version of record first published: 24 Sep 2006

Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 320:1, 321-335

To link to this article: http://dx.doi.org/10.1080/10587259808024404

*Mol. Cryst. Liq. Cryst.*, Vol. 320, pp. 321–335
Reprints available directly from the publisher
Photocopying permitted by license only





# INTEGRATED ELECTRO-OPTIC SWITCH BASED ON A FERROELECTRIC LIQUID CRYSTAL WAVEGUIDE

GIUSY SCALIA[a, b], DAVID SPARRE HERMANN[a],
GIANCARLO ABBATE[b], LACHEZAR KOMITOV[a],
PASQUALE MORMILE[c], GIAN CARLO RIGHINI[d], and LUIGI SIRLETO[d]
[a] Department of Microelectronics and Nanoscience, Chalmers University of Technology, S-412 96 Göteborg, SWEDEN; [b]Dipartimento di Scienze Fisiche, Università di Napoli, and INFM, Via Cintia Monte S.Angelo, I-80126 Napoli, ITALY; [c]Istituto di Cibernetica CNR, Via Toiano 6, I-80072 Arco Felice, Napoli, ITALY; [d] Istituto di Ricerca sulle Onde Elettromagnetiche, IROE CNR, Via Panciatichi 64, I-50127 Firenze, ITALY

An electro-optic switch based on a planar, ferroelectric liquid crystal waveguide oriented in the bookshelf geometry has been realized and tested. The waveguide device consists of three stages: two glass waveguides and an FLC waveguide in between, permitting coupling and decoupling of the light into and out of the glass waveguides with prisms. The refractive indices of the FLC used were determined with a total internal reflection method. The time characteristics of the ON-OFF switch and the OFF-ON switch have been studied. Our main aim was the experimental demonstration of previous theoretical studies and no attempt was made up to now to optimize the device performance.

Keywords: integrated optics; electro-optic device; waveguide; guided mode, ferroelectric liquid crystal

## INTRODUCTION

Research on materials for integrated optics is continuously in progress to achieve better efficiency both for nonlinear optical and for electro-optic (e-o) effects, in order to reduce the driving field intensities. Among these materials, Liquid Crystals (LC) have a special place because of their particular advantages and disadvantages. Early attempts in the 70's[1-4] to use LC in e-o integrated devices were not successful mainly due to extremely large scattering losses, of the order of 20 dB/cm. Furthermore, very fast devices are based on electronic effects and hence LC materials are generally not considered, at least in their mesophase, because the optical and electro-optic effects in these materials are based on a relatively slow collective molecular reorientation. For these reasons, LC based integrated devices have not been considered for a long time. This situation is rapidly changing in the 90's as reviewed in a recent paper by Walker and coworkers[5]. The first reason for this renewed interest resides in the possibility to have much reduced scattering losses, less than 2 dB/cm, in strongly confined systems[6,7]. Moreover, the collective molecular motion, which limits the response time to the range of milli- and microseconds, is on the other hand responsible of a large enhancement of the nonlinear and/or the e-o response coefficients, which can be orders of magnitude larger than in their solid state counterparts. In the cited paper, Walker et al. point out that Surface Stabilized Ferroelectric Liquid Crystals (SSFLC) promise to be a very convenient candidate for the realization of integrated e-o devices. In fact, their mesophase, SmC$^*$, is much more ordered than the nematic phase and the alignment of the molecules is bound along the surface, hence scattering losses are significantly reduced[8]. SSFLC's exhibit a bistable electro-optic behavior[9], the switching between the two stable states can be driven by an applied voltage of the order of 10 V and can be as fast as a few microseconds with recently developed mixtures. A large number of studies and applications of SSFLC have been proposed in the last 15 years[10]. However, in contrast to the situation for nematic liquid crystal waveguides[1-4, 6-7, 11-16], only few studies have been reported on waveguides based on ferroelectric smectic C* liquid crystals[5, 17-19].

Starting from previous studies on integrated optical devices with a nematic LC waveguide[20-21] and following the theoretical study of Walker et al., the aim of the present work was to realize an integrated electro-optic switch based on a ferroelectric liquid crystal waveguide, and to examine the material and device parameters significant for its operation.



## EXPERIMENTAL

### The FLC material

The FLC used, SCE10 (BDH), has the phase sequence iso → 109°C → N* → 61°C → SmC*. As a first step it is important to know the parameters involved in the operation of this device, that is, the refractive indices of the FLC which we have measured with a total internal reflection (TIR) method[22]. While being a standard type measurement for ordinary liquids and nematic LC's, these measurements nevertheless pose some technical problems with FLC, in particular to achieve a good molecular alignment. An FLC film is sandwiched between two prisms of refractive index $n_p$ = 1.76 at the Argon laser wavelength ($\lambda$ = 514.5 nm) which is used in the experiment. The boundaries are coated with polyimide and rubbed in the x direction in order to promote planar alignment of the director along this direction. Properly choosing the polarization of the laser beam with respect to the molecular alignment both ordinary and extraordinary refractive indices can be measured. We get the following values: for the ordinary index $n_o$ =1.50 and for the extraordinary index $n_e$ =1.67. These values are in agreement with the birefringence value provided by the company, $\Delta n$=0.17 at the same wavelength, and with an independent measurement of $n_o$ made on a homeotropically aligned sample.

The tilt angle value $\theta$=30° and the molecular director switching time $\tau_m$=380 μs were provided by the company and were experimentally checked.

## The waveguide device

We have designed and realized the planar guiding structure as schematically represented in figure 1.

Such a structure was obtained by using a sol-gel deposition on an Indium Tin Oxide (ITO)- covered glass substrate. The resulting planar waveguide is a step-index bi-modal waveguide whose thickness is 0.8 μm with refractive index $n_g$ =1.601 at the wavelength $\lambda$ = 514.5 nm. The substrate refractive index is $n_s$ =1.516. A basin to be filled with the FLC, whose length along the propagation direction is 500 μm and with the same thickness of the glass waveguide core, was obtained in two steps: a microlithography process followed by an etching process. As a cover we deposited a thin layer of ITO on a glass substrate with refractive index $n_c$=1.55, chosen to be intermediate between the two principal values of the FLC refractive index. The final structure consisted of a three stage planar waveguide, having the basin as the middle stage and the two glass waveguides as the other stages. We also checked that usual ITO films of 200 nm thickness drastically changed the guiding properties while thinner films of 20 nm have almost negligible effects on the modal structure. Only the latter coatings were thus used for the realization of our electro-optical devices.

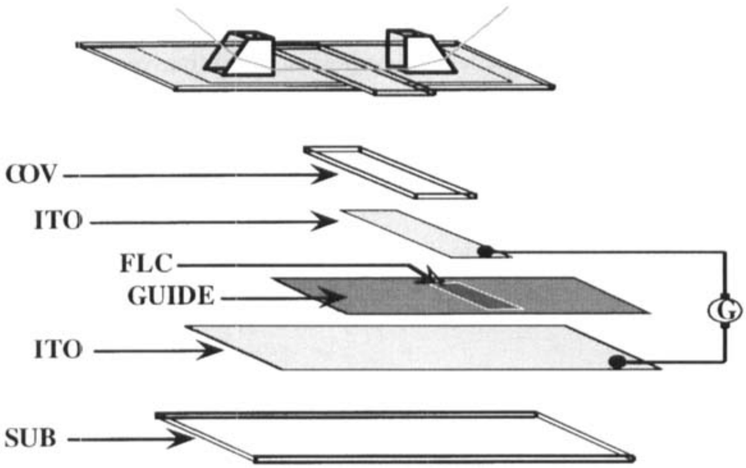



FIGURE 1 Schematic representation of the realized planar waveguide. COV: cover; SUB: substrate; ITO: indium tin oxide; FLC: ferroelectric liquid crystal; G: voltage generator.

## The integrated electro-optic switch

An integrated electro-optic switch based on an FLC waveguide has been realized by filling the basin dug out in the glass waveguide with the FLC material. The described three-stage asymmetric device was used to solve the non trivial problem of coupling light into the FLC waveguide. The light beam was coupled by a high index prism via the evanescent field in the air gap between the prism and the guiding glass film. The prism and film refractive indices and the thickness of the air gap are the parameters which determine a good coupling efficiency. The guided wave then travels through the FLC waveguide and finally into the last glass waveguide. A prism mounted on the last stage permits a decoupling of the guided wave. This set up is shown in Figure 2. An Argon laser beam, at $\lambda$=514.5 nm, is TE polarized by a system of polarizers. A lens with the focal length f= 100 mm is used to focus the beam into the coupling prism. The focal point was chosen in the first glass stage of the device but very close to the prism edge to maximize the coupling efficiency and minimize the lateral beam waist in the transversal direction. A second lens is used to focus the output beam onto a photodiode. A beam splitter permits to monitor the input power which was kept sufficiently low, no more than 90 mW, to avoid a temperature increase in the air gap which would change its thickness and thus possibly cause a decrease of the coupling efficiency.



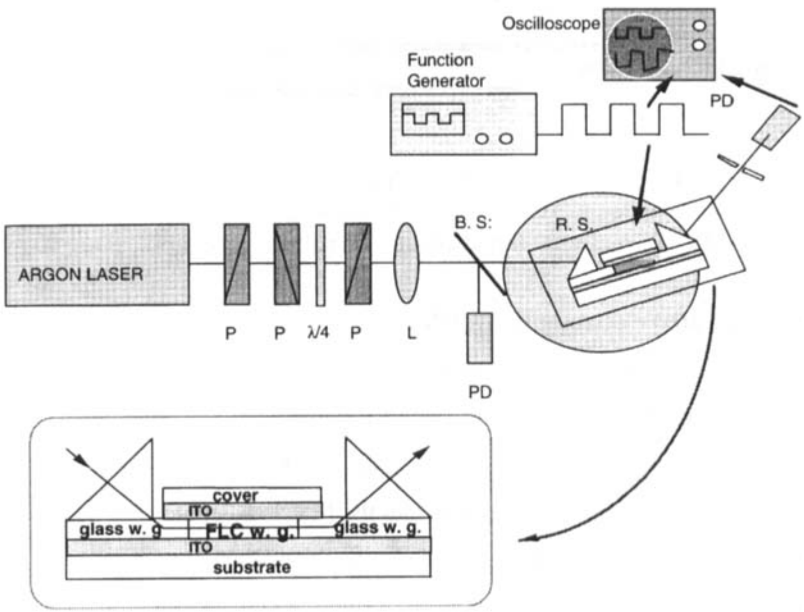



FIGURE 2 Experimental set-up and the three stage device.

Two different three-stage samples having the same characteristics were used in the experiment. In one of them the alignment of the FLC was obtained by evaporating $SiO_x$ at oblique incidence onto the cover and the substrate. The other waveguide only had the cover treated. The director was aligned in the N*-phase along the y-direction. Then, the sample was cooled slowly into the SmC*-phase under application of an electric field, so that a monodomain was obtained with the smectic layer normal inclined with respect to the alignment direction by an angle equal to the tilt angle of the liquid crystal (30°), see Figure 3.

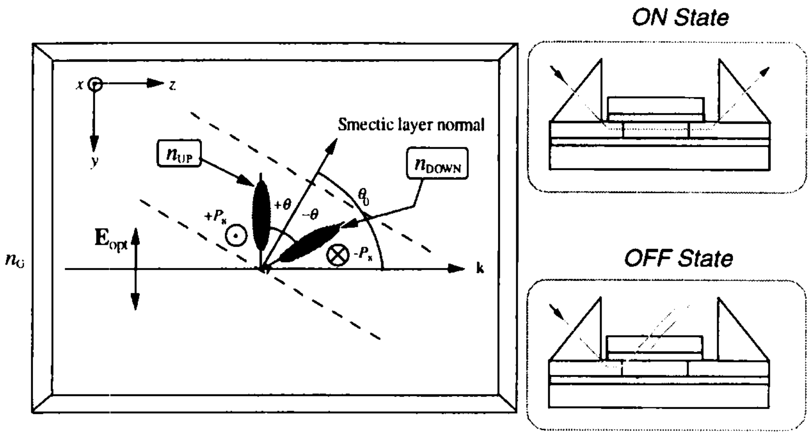



FIGURE 3 A schematic description of the switching process with regard to the light polarization and the change of the refractive indices.



## The optical switching mechanism

The realized alignment means that when switching the FLC between the UP-state and the DOWN-state a TE-polarized light beam traveling in the z-direction sees two different refractive indices. In the UP-state the refractive index is purely extraordinary and a guided mode is obtained ($n_e$ = 1.67 > $n_c$ and $n_s$). In the DOWN-state the director is tilted 2θ = 60° with respect to the polarization direction of the light, giving an effective refractive index of 1.54 < $n_c$. At this point the guiding condition breaks down, the light leaks out through the cover and the light power detected after decoupling suddenly drops. When the light travels through the whole device as a guided beam the state of the device is ON. The OFF state is obtained when the director is tilted with respect to the polarization direction of the light and there is no guided mode in the FLC stage, which thus acts as a shutter between the two glass stages. A schematic of this process is shown in figure 3.

## RESULTS AND DISCUSSION

We have realized such an ON-OFF device and the modulation of the output light for the first mode and the second mode is observed while driving the device by a square wave applied voltage. A fast rise and decay time in the optical response has been observed in the first waveguide, using a voltage of Vpp= 45 V at frequency $\nu$=500 Hz. The 10%-90% rise and fall time has been estimated to be ~120 μs (Figure 4). The extinction ratio between the ON state and the OFF state is 5:1. The very low transmission of the device, a few per cent, and the consequent low extinction ratio are due to two main reasons. The most important is the large mismatch of the refractive indices between the film of the glass waveguide and the FLC at the two interfaces, $\Delta n \approx 0.07$, which causes a large fraction of the input energy to be reflected at the interfaces. The second is the thickness of the FLC waveguide, which actually is larger than designed, i.e. larger than the glass waveguide core and this causes the mode profiles in the two adjacent stages not to overlap properly, yielding a reduced energy transfer.

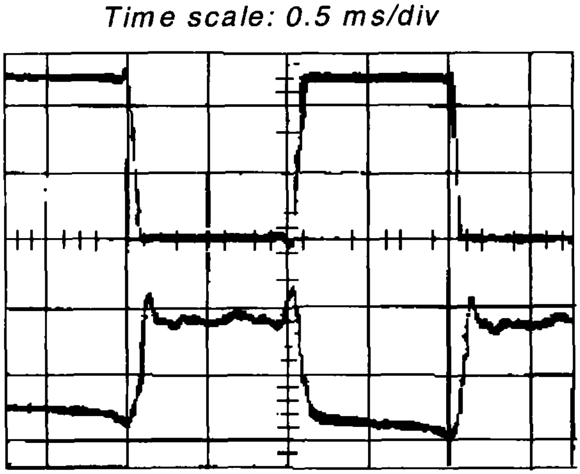



FIGURE 4. Oscilloscope traces of the driving voltage (upper) and of the optical signal (lower) for the first three-stage device.

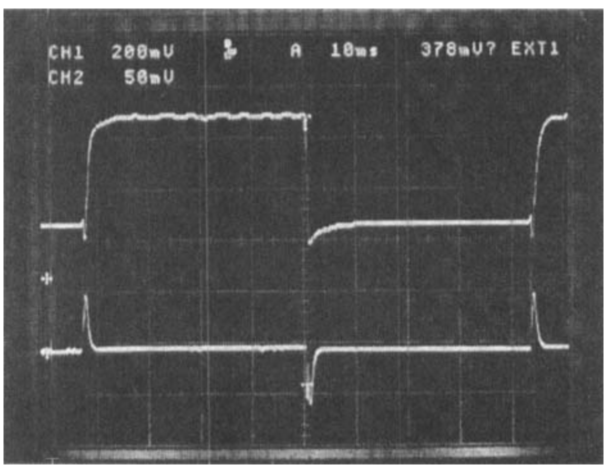



FIGURE 5. Optical response of the second three-stage device (upper trace) and electric response (lower trace).

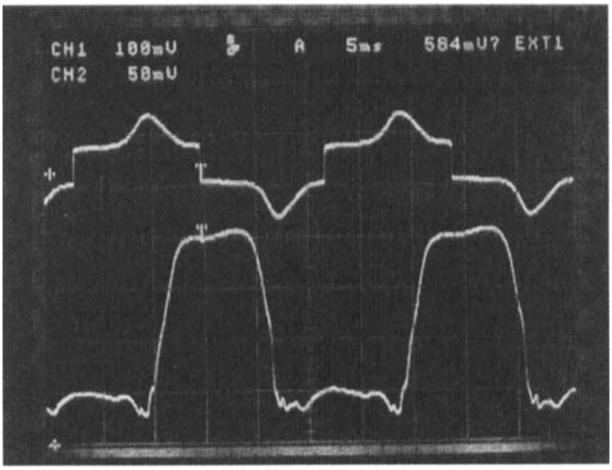
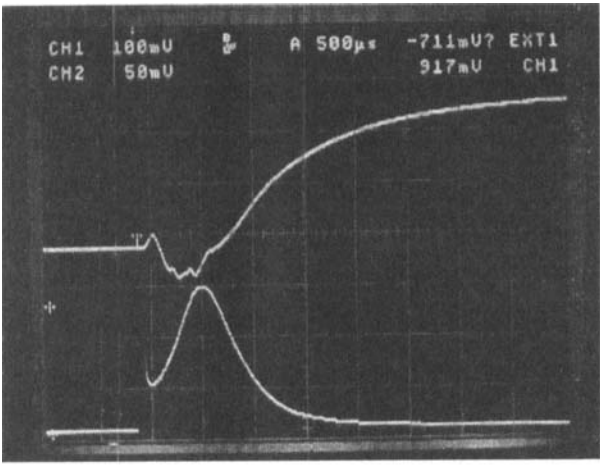



FIGURE 6. Electrical (upper trace) and optical (lower trace) response to a triangular wave

Electro-optic switching was observed also in the second waveguide as shown in Figures 5 and 6, where the electric response is reported as well. It is thus possible to obtain a sufficiently good alignment with only the cover plate treated with $SiO_x$. The change of the optical response corresponds to the polarization reversal current response (Figure 5). The extinction ratio was slightly lower in this case (4:1). As driving voltage we also used a triangular wave as shown in Figure 6.

a)




b)

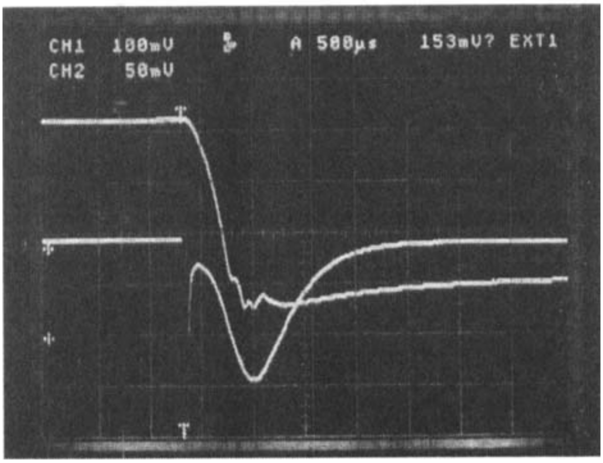



FIGURE 7. a) reversal current peak (lower trace)and rise of the optical response (upper trace); b) reversal current peak (lower trace) and fall of the optical response (upper trace).

A closer look at the time behavior reveals that, when passing from the OFF to the ON state, the optical response begins to increase in the middle of the cone switch, at the time of the maximum of the polarization reversal current peak. See Figure 7a. When passing from the ON to the OFF state, however, the decrease appears before the maximum of the polarization reversal current peak, during the first half of the switch. See Figure 7b. Recalling that the current behavior is a monitor of the molecular switching process, what we observe is a delay time in the optical response for the OFF-ON switch, whereas there is no delay time for the ON-OFF switch. Moreover, in both cases the optical switching is at least twice as fast as the molecular switching. We can give a physical explanation for this unusual behavior: in contrast to the free propagation of a light wave, the propagation of guided light strongly depends on even very small changes of the refractive index of the core, and this is particularly true when the value of the refractive index is close to the cut off condition for the guided mode. In the present waveguide geometry one of the two stable states corresponds to a high refractive index of the core which thus can sustain a guided mode, while the other state corresponds to a core index lower than the index of the cover and hence to a non-guided mode. When switching from OFF to ON, we can presume that the effective index value is continuously changing during the cone switch of the molecular director and the proper high index value ensuring the transmission state of the device is reached only during the latter part. When switching from ON to OFF, however, the high index value starts to decrease during the first part of the cone switch. Therefore there is no delay time for the ON-OFF switch and, since the needed optical change of the guided modes occurs well before the polarization reversal is complete, the optical switching time is much shorter than the liquid-crystal switching time.

## CONCLUSION

In this work we have experimentally demonstrated the feasibility of an integrated electro-optic device based on a FLC waveguide which was first proposed in a theoretical study by other authors[5]. Apart from this result, a number of clear indications emerge from this experiment about the way to reach a device optimization, which may lead to practical applications. It has to be stressed, however, that the optimization of the device design was absolutely not our aim in this first experiment. In particular, we made the choice of the material just because of the availability, ease of treatment and ease of work in this demonstration experiment and the glass waveguide samples were originally designed for a different experiment[20-21]. As a consequence, we get a significant mismatch among the indices of the different stages, which should be avoided in an optimized device to achieve significantly improved transitivity and extinction ratio. The response time can be lowered more than one order of magnitude simply by choosing a faster FLC material.

We have also demonstrated that the tilt angle does not necessarily have to be large, since the optical change occurred in our experiment before the FLC molecular switch was completed. If the refractive indices of the waveguide and the alignment and the choice of the FLC are fine-tuned, a material with a relatively low tilt angle could be used. This could mean a further improvement in the response time.

Another important result is that the alignment can be achieved only by treating the cover glass plate. This means that the initial director orientation, hence the refractive index in the ON state, can be changed by simply rotating the cover plate. This is a very important simplification in the sample preparation procedure, allowing one to determine the smectic layer orientation with respect to the polarization vector of the TE-polarized light for optimization purposes, as well as allowing sample reuse in different experiments.

Finally, we would mention the possibility to exploit other electro-optic effects in LC's, such as the electroclinic effect in the SmA* phase or the flexoelectrooptic effect in short-pitch cholesteric liquid crystals[23], which may prove useful for a further improvement of the device performance. Further work in these directions is currently underway.

**Acknowledgements**

Dr. Dag Hanstorp and M. Sc. Jonas Enger at the Atomic Physics Group of Chalmers University of Technology are gratefully acknowledged for providing generous access to the Ar-ion laser lab. M. Sc. Pontus Jägemalm is gratefully acknowledged for technical assistance. Financial support from the EU Thematic Network "LC-PHOTONET" for Giusy Scalia is gratefully acknowledged.



**References**

[1.] D. J. Channin, *Appl. Phys. Lett.* **22**, 365 (1973).
[2.] T. G. Giallorenzi and J. P. Sheridan, *J. Appl. Phys.* **46**, 1271 (1975)
[3.] C. Hu, J. R. Whinnery, *J. Opt. Soc.Am.* **64**, 1424 (1974)
[4.] J. R. Whinnery, C. Hu and Y. S. Kwon, *IEEE J. Quantum Electron.* **QE-13**, 262 (1977)
[5.] D. B. Walker, E. N. Glytsis and T. K. Gaylord, *Appl. Opt.* **35**, 3016 (1996)
[6.] M. Green, S.J. Madden, *Appl. Opt.*, **28**, 5202 (1989)
[7.] G. Abbate, L. De Stefano, P. Mormile, G. Pierattini, E. Santamato, M. Villiargio, *Opt. Comm.*, **109**, 253 (1994)
[8.] N.F. Hartman, T.K. Gaylord, T.J. Drabik, M. A. Handschy, *Appl. Opt.*, **32**, 3729 (1993)
[9.] N. A. Clark, S.T. Lagerwall, *Appl. Phys. Lett.* **36**, 899 (1980)
[10.] See for example the reviews by S.J. Elston, *Liquid Crystals*, **9**, 769 (1991); and S.J. Elston, *J. of Mod. Opt.*, **42**, 19 (1995)
[11.] M. Kobayashi, M. Kawachi, and J. Noda, *IEEE J. Quantum Electron.*. **QE-18**, 1603 (1982)
[12.] Y. Okamura, K. Kitatani, and S. Yamamoto, *J. Lightwave Technol.* **LT-4**, 360 (1986)
[13.] H. Lin, P. Palffy-Muhoray, *Opt. Lett.* **17**, 722 (1992)
[14.] I.C.Khoo, H.Li, App. Phys. **B**, **59**, 573 (1994)
[15.] G. Abbate, L. De Stefano, E. Santamato, J. Opt. Soc. Am. **B**, **13**, 1536 (1996)

[16.] G. Abbate, F. Castaldo, L. De Stefano, *Mol. Cryst. Liq. Cryst.* **282,** 269 (1996)

[17.] N. A. Clark and M. A. Handschy, *Appl. Phys. Lett.* **57**, 1852 (1990)

[18.] M. Ozaki, Y. Sadohara, T. Hatai, and K. Yoshino, *Jpn. J. Appl. Phys.* **29**, L843 (1990)

[19.] W. Y. Lee, J. S. Lin, K. Y. Lee, W. C. Chuang, *J. Lightwave Technol.* **LT- 13**, 2236 (1995)

[20.] G.Abbate, F.Castaldo, L. DeStefano, E.Santamato, P.Mormile, *J. of Phys.* **B 30**, 5587 (1997)

[21.] L.Sirleto, G.C.Righini, A.Verciani, G.Abbate, E.Santamato, P.Mormile, G.Pierattini, *Photonics*, Ed.J.P.Raina and P.R. Vaya, Tata Mc Graw Hill, **1**, 629 (1996).

[22.] See for example Y. Levy, D. Riviere, C. Imbert and M. Boix, *Optics Commun.* **26**, 225 (1978) or L. Komitov and A. G. Petrov, *Phys. Stat. Sol.* **A76**, 137 (1983).

[23.] J. Patel and R. B. Meyer, *Phys. Rev. Lett.* **58**, 1538 (1987); P. Rudquist, L. Komitov, and S. T. Lagerwall, *Phys. Rev. E*, **50**, 4735 (1994)