

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 09-10-2009		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 25 September 2008 - 08-Jun-10	
4. TITLE AND SUBTITLE Optical signal processing with discrete waveguide arrays in nematic liquid crystals				5a. CONTRACT NUMBER FA8655-08-1-3045	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Professor Gaetano Assanto				5d. PROJECT NUMBER	
				5d. TASK NUMBER	
				5e. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NooEL, University Roma Tre Via della Vasca Navale 84 Rome 00146 Italy				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD Unit 4515 BOX 14 APO AE 09421				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) Grant 08-3045	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report results from a contract tasking NooEL, University Roma Tre as follows: INTRODUCTION and TECHNICAL PROPOSAL State of the art The development of integrated guided-wave microsystems requires a novel paradigm for an advanced technology aimed at the realization of coupled waveguide arrays with tight tolerances and tailored channel-to-channel coupling, both of which need be electrically tuned through the application of an external voltage. Such innovation is at hand by the use of nematic liquid crystals, offering precise control of geometric and material parameters to the required extent. Such material has shown great potentials for the fabrication of voltage-tunable waveguide arrays with bias-controlled confinement and transverse (evanescent tail) coupling, exhibiting discrete light propagation and discrete light localization in the form of discrete spatial solitons.[1-3] In addition, these discrete systems encompass the possibility of all-optically angle steering of the light beam and the information it carries,[4] paving the way to a number of promising applications in optical signal processing, from spatial demultiplexing to network readdressing and reconfiguring, especially in the presence of defects [5]. In addition, the inclusion of active dye molecules in liquid crystalline materials has been proven to permit light amplification by external optical pumping. Such opportunity, readily available in the same material system, could allow for the first demonstration of discrete light propagation and localization in dissipative systems with gain, never reported before and of the utmost interest for applications such as communications, where insertion losses are an issue and device cascadability an important requirement.					
15. SUBJECT TERMS EOARD, Lasers, Optically addressed spatial light modulators					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON A. GAVRIELIDES
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (include area code) +44 (0)1895 616205

AQ F11-05-0640

Grant # 083045

NATO-EOARD Project on

“Optical signal processing with discrete waveguide arrays in nematic liquid crystals”

Fourth and Final Periodic Report

Prof. Gaetano Assanto

Nonlinear Optics and Optoelectronics Lab

Department of Electronic Engineering, University “Roma Tre”
Via della Vasca Navale 84, 00146 Rome - ITALY

Table of Contents

- Summary
- 1. Introduction
- 2. Methods, Assumptions, and Procedures
 - 2.1 Discrete structures in chiral nematic liquid crystals
 - 2.2 Distributed Feedback Reflector in Nematic Liquid Crystal Waveguides
- 3. Results and discussion
 - 3.1 Discrete structures in chiral nematic liquid crystals
 - 3.2 One-dimensional photonic crystal in Nematic Liquid Crystals
- 4. Conclusions
- 5. List of Figures
- List of Symbols, Abbreviations and Acronyms
- Appendix: confirmation of expenditures

Summary

In the fourth trimester of the Project, we tried to complete the numerical study of Bragg reflectors with coplanar electrode geometries, in collaboration with the University of Rome “Sapienza”, Department of Electronic Engineering (Italy); we also undertook an investigation on the use of chiral/twisted nematic liquid crystal planar samples for discrete light propagation, in collaboration with the Technical University of Warsaw.

1 Introduction

The Project aim consists in demonstrating the feasibility of periodic and/or discrete dielectric structures for light propagation using liquid crystalline structures for optical and all-optical signal processing, using various technological routes. In this Project we explored electro-optical planar waveguide lattices, polymer/liquid-crystal/polymer structures (POLICRYPS), planar Bragg reflectors with electrodes across the liquid crystal thickness, distributed waveguide reflectors with coplanar electrodes, chiral/twisted nematic liquid crystal systems. In the first periodic Report on the Project we summarized the state of the art and the main advantages of the undertaken approaches. In the second report we illustrated the first results on preparation and characterization on POLICRYPS and the design/analysis of Bragg reflector waveguide channels defined by electro-optically modulating a liquid crystalline thin layer and operating with Transverse Magnetic eigenmodes. In the third report we summarized the results experimentally obtained in POLICRYPS, as well as the results of a numerical investigation of an alternative (easier to realize) distributed Bragg reflector in a channel

waveguide. In this fourth and final report we summarize the results obtained with chiral/twisted nematic liquid crystals and in the analysis of guided-wave Bragg reflectors.

2 Methods, Assumptions, and Procedures

2.1 Discrete structures in chiral nematic liquid crystals

In the analyzed configurations as shown in Fig.1, a light beam propagates along z with wave vector parallel to the confining glass plates. The cell is filled with 6CHBT (4-trans-4'-n-hexyl-cyclohexyl-isothiocyanatobenzene) with a chiral dopant (Fig. 1(b)). The light is polarized along y , so that the beam propagates in the layer close to the plane where the ChNLCs major molecular axes are parallel to y .

Light beam propagation in films of ChNLC was investigated experimentally using the setup schematically drawn in Fig. 1b, employing a femtosecond Ti:Sapphire ($\lambda = 793 \text{ nm}$) laser. ChNLC scatters light due to fluctuations in director orientation; hence, the beam traveling in the cell could be observed using a 16x microscope objective and a CCD camera mounted in a (x,y,z) stage.

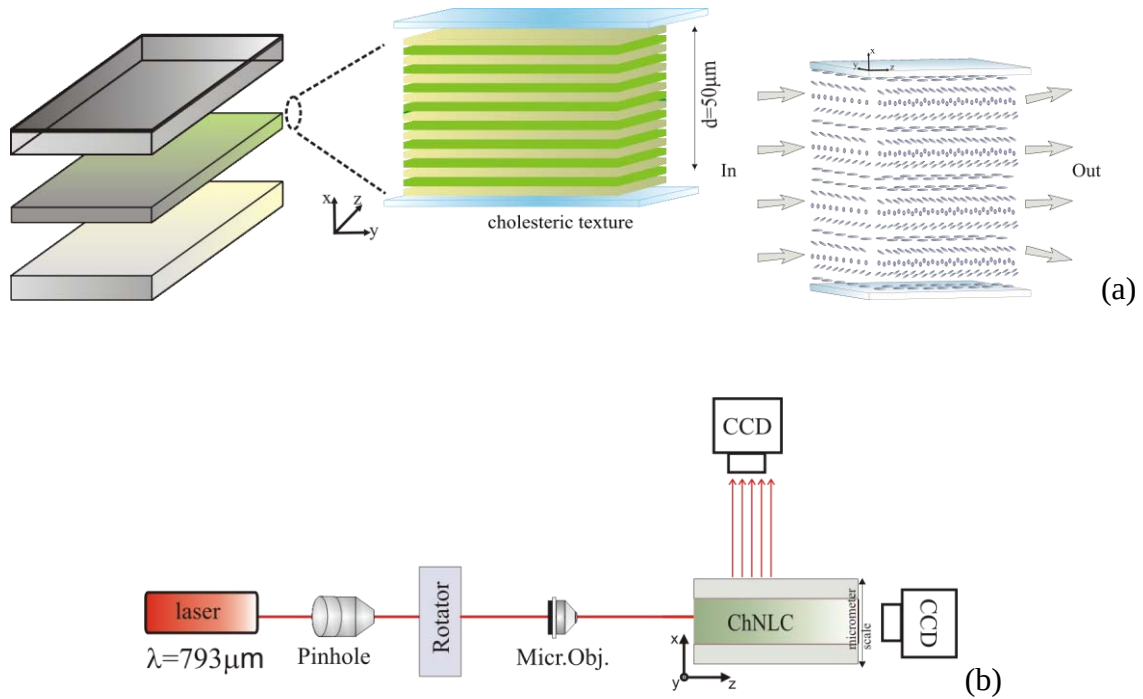


Fig.1. Configuration of nematic liquid crystal cells and experimental setup. (a) Chiral nematic liquid crystal system and sample; (b) sketch of the setup.

For the numerical simulations we used 1550 ChNLC –(see Fig. 2 for the refractive indices) at two temperatures: room temperature at which the birefringence is high and at $T\sim 78^\circ\text{C}$ at which the birefringence is the lowest. By changing the chirality pitch p , the range of discrete diffraction was also modified. Another important parameter was the beam waist w_0 . In the simulations we solved a $(1+1)$ dimensional scalar problem in the isotropic dielectric corresponding to the refractive index for a linearly extraordinarily polarized beam.

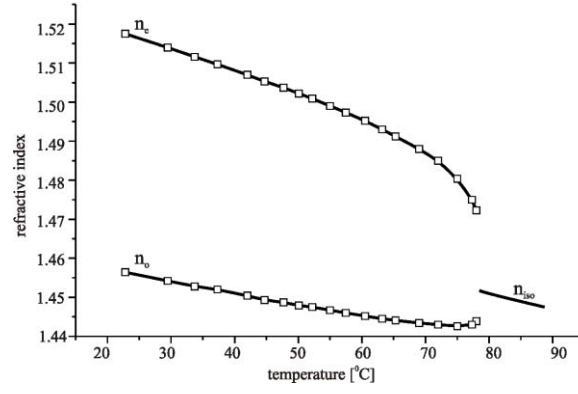


Fig. 2. Refractive indices for uniaxial 1550 ChNLC.

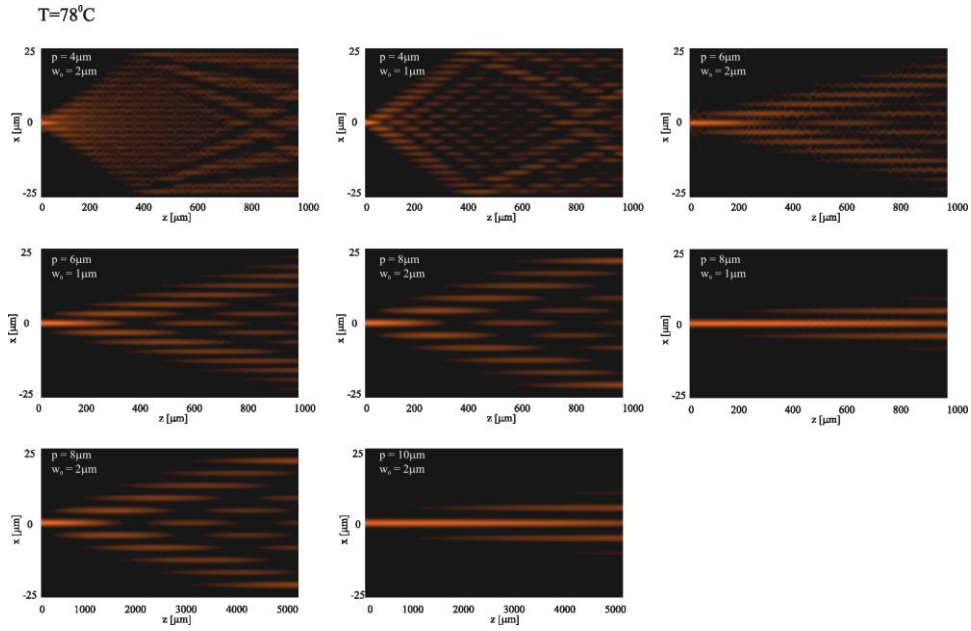


Fig. 3. Simulations of light propagation at 78°C versus medium birefringence, chirality pitch and beam waist.

$T \sim 22^\circ\text{C}$

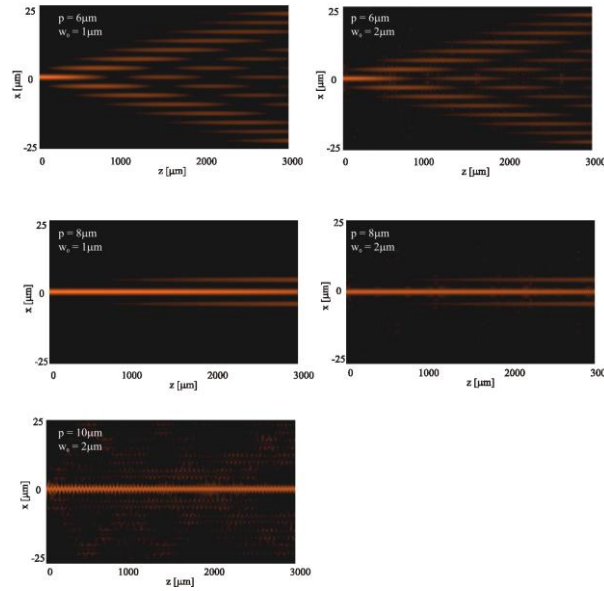


Fig. 4. Simulations of light propagation at room temperature.

2.2 Distributed Feedback Reflector in Nematic Liquid Crystal Waveguides

Having illustrated the basic concept and design of a novel electro-optic distributed feedback waveguide (DFBW) in nematic liquid crystals, in collaboration with University of Rome “Sapienza”, we numerically analyzed the operation of the planar waveguide with coplanar electrodes, reproduced in Fig. 5.

The design parameters, aiming at a single mode waveguide, low applied voltage and full reflectivity near 1550 nm were: standard nematic liquid crystal E7 (supplied by Merck) and $K_{11} = 12$ pN, $K_{22} = 7.3$ pN, $K_{33} = 17$ pN, $\epsilon_{\perp} = 7$, $\epsilon_{\parallel} = 20$, $n_{\perp} = 1.50$, $n_{\parallel} = 1.689$; planar anchoring by rubbing of a thin Nylon6 spin-coated film on the two interfaces, pre-twist of $\approx 4^\circ$ substantially to eliminate the Fréedericks threshold; cladding and substrate in borosilicate BK7 glass, with refractive index ≈ 1.5 at $\lambda = 1550$ nm; transparent electrodes in 100 nm thick Indium Tin Oxide, with real refractive index equal to 1.3 and imaginary refractive index close to 0.1; thickness $h = 1$ μm ; electrodes of size $a = b = 500$ μm , $c = 250$ nm, $t = 250$ μm and $T = 500$ μm .

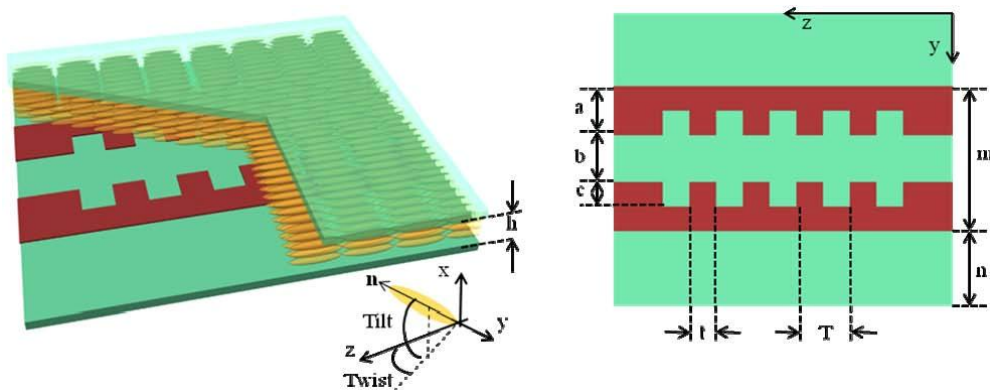


Fig. 5. 3D sketch and parameters of the novel DFBW geometry with coplanar electrodes at the bottom interface of the planar cell. The inset shows the coordinate system and parameters related to the director orientation.

3. Results and Discussion

3.1 Discrete structures in chiral nematic liquid crystals

Some of the obtained results are displayed in Figure 6. For high enough input excitations, at powers $P \sim 8.64 \text{ mW}$ a spatial soliton is generated. The solitary beam has an invariant transverse intensity distribution over a propagation distance of about 2mm (i.e. in excess of 80 times the linear Rayleigh length). The initial beam waist at 793 nm was estimated in about $2 \mu\text{m}$. We also considered the impact of the initial waist on soliton generation (see Figure 6(d)). Due to the finite thickness of each layer in the chiral structure, only at certain input waists self focusing can exactly balance diffraction and result in a self-trapped wavepacket. Changing the launch location of the beam across the nematic layer, direction and number of the excited solitons could be controlled.

In the used setup we were able to control the vertical position of the liquid crystal cell with respect to the excitation beam, observing soliton creation in various layers across x . A synopsis of the experimental results is shown in Figures 6 through 9.

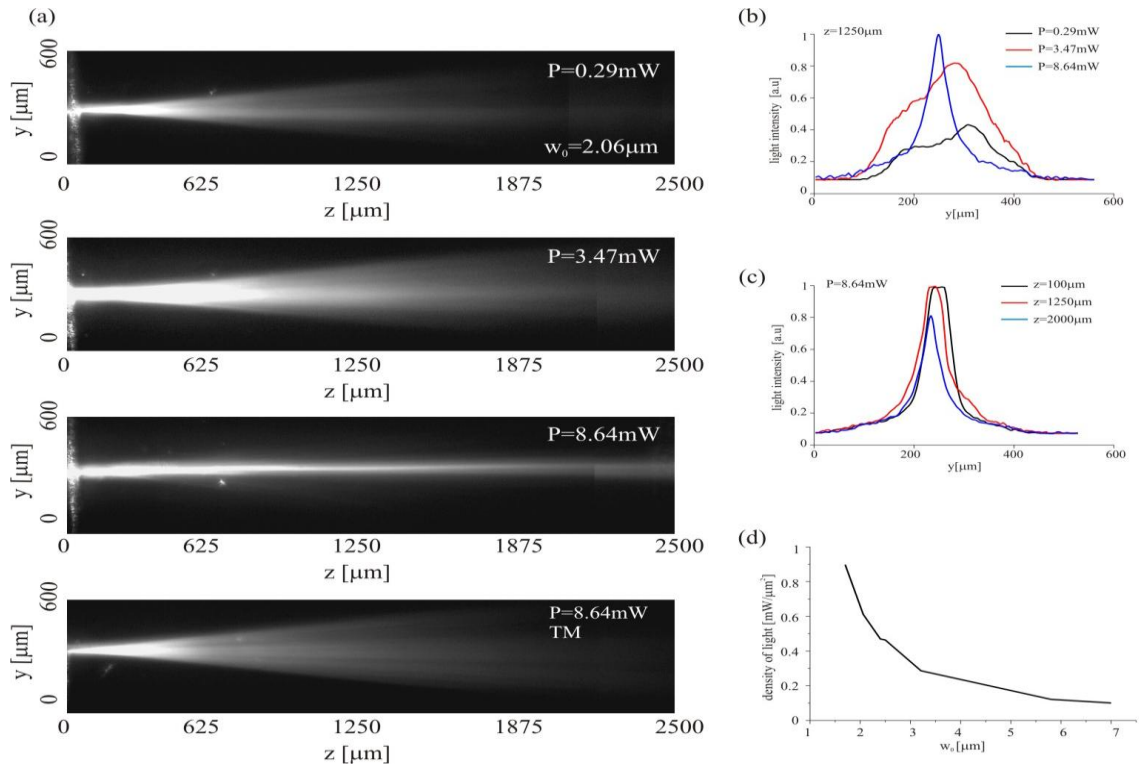


Fig. 6. Experimental results on the creation of spatial optical solitons in ChNLC. (a) Beam propagation for various TM excitations (marked on the photos) after launching it in the midplane of the cell. (b)-(c) Intensity profiles at low and high power, respectively, and various propagation distances; (d) input beam width vs. power density [$\text{mW}/\mu\text{m}^2$].

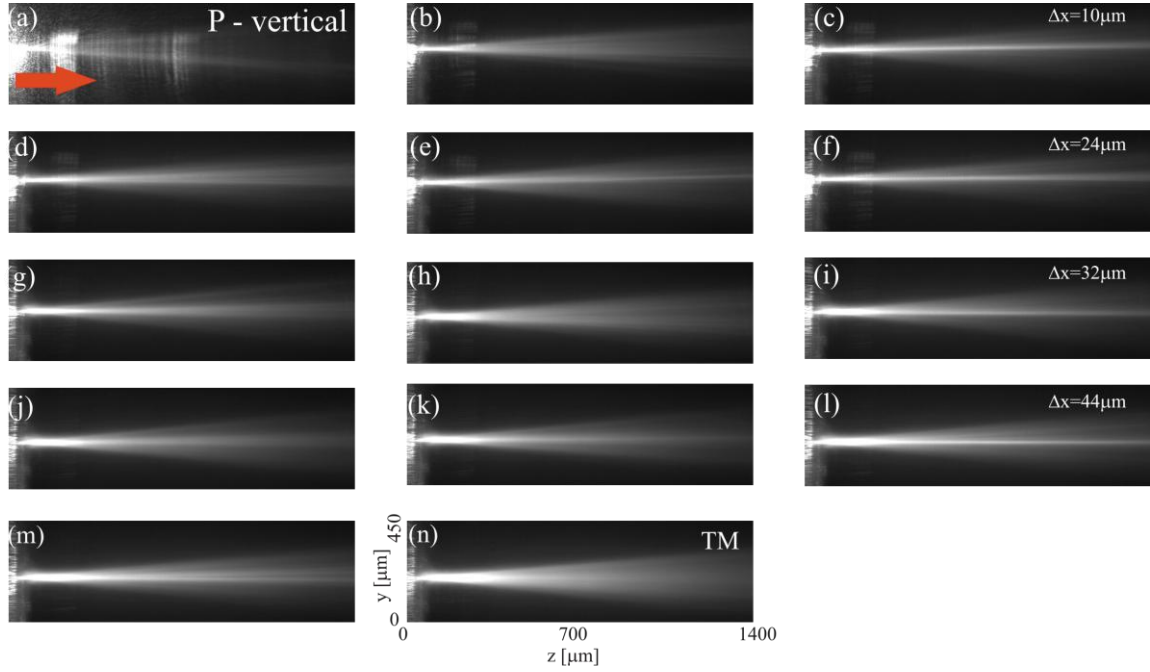


Fig. 7. Acquired results for various laser beam inputs versus x . Panels (c)-(f)-(i)-(l) show solitons propagating in four different layers.

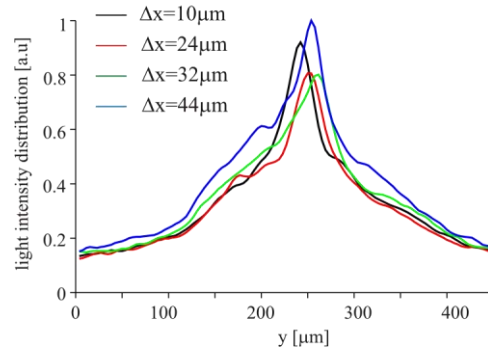


Fig. 8. Cross-sections of the beam intensity taken from the photographs in figure 3 at the approximate distance of 1mm.

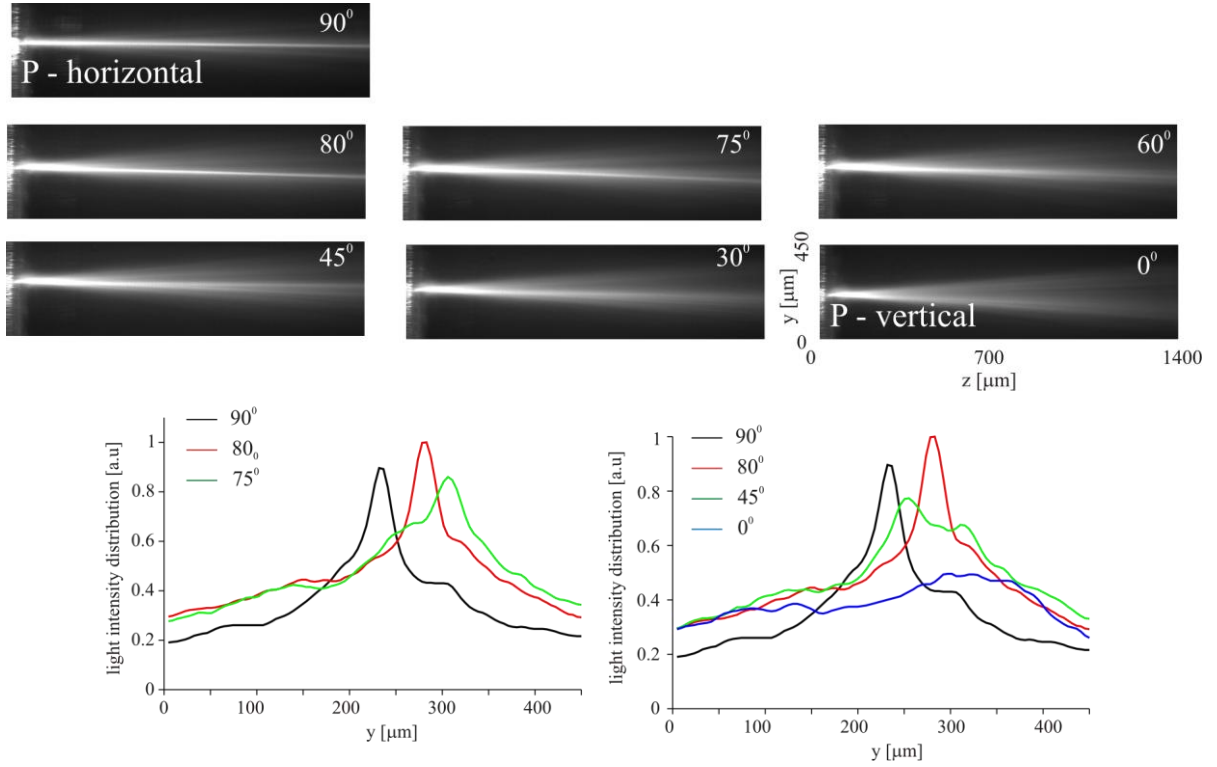


Fig. 9. (Top) Results on light propagation depending on input polarization and (bottom) cross-sections after 1000 μm .

3.2 One-dimensional photonic crystal in Nematic Liquid Crystals

Using the finite element method to calculate the director distortion and the corresponding index modulation, we computed the maximum index contrast versus applied voltage, as summarized below in Fig. 10 for a period 0.5 μm and duty cycle of 50%.

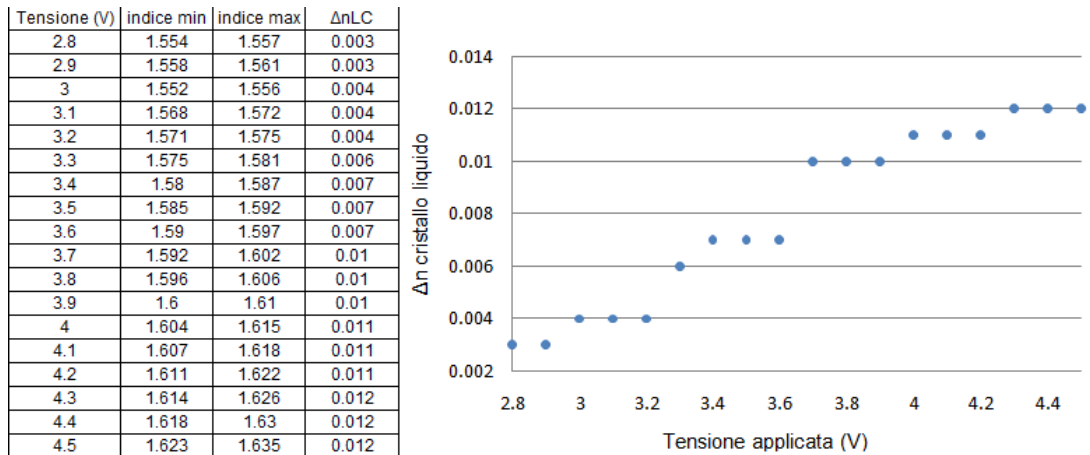


Fig. 10. Calculated extraordinary index or various applied voltages, from 2.8 to 4.5V with 0.1 V increments.

A summary of the results is provided in Table I, demonstrating the broad tenability of this device for moderate applied voltages.

Applied Bias (V)	DFBW length (mm)	Reflectivity peak (μm)	Resonance FWHM (nm)
2.8	6.0	1.50739	0.21
3.2	3.0	1.5152	0.39
3.8	1.5	1.52979	1.08
4.2	1.2	1.53958	1.32
4.5	1.0	1.54786	1.54

Table 1. Calculated voltage-tuning of the Bragg resonance and its FWHM.

4. Conclusions

In our investigation of various approaches to periodic/discrete structures for light propagation and control in nematic liquid crystals we have assessed some interesting features and requisites of *electro-optic undoped nematic liquid crystals* and *Polymer Liquid Crystal Polymer Slices*, conducting some preliminary morphologic and optical tests on the samples. We numerically investigated and designed *guided-wave distributed feedback reflectors* exhibiting broad wavelength tunability versus applied voltage. In the framework of a collaboration with Sapienza University we analyzed two geometries with distinct electrode arrangements in order to define guided-wave channels and modulated index gratings with the correct (Bragg) periodicity for use at and around the communication wavelength of 1550nm. A novel route to discrete light *propagation in arrays of waveguides was undertaken in twisted/chiral nematic liquid crystal layers*, defining parallel one-dimensional guiding films for TE or TM light. We presented some preliminary experimental results in chiral systems through collaboration with Warsaw Technical University. Some new and interesting physics was demonstrated in these structures.

5. List of figures

Fig.1. Configuration of nematic liquid crystal cells and experimental setup. (a) Chiral nematic liquid crystal system and sample; (b) sketch of the setup.

Fig. 2. Refractive indices for uniaxial 1550 ChNLC.

Fig. 3. Simulations for light propagation at 78°C versus medium birefringence, chirality pitch and beam waist.

Fig. 4. Simulations of light propagation at room temperature.

Fig. 5. 3D sketch and parameters of the novel DFBW geometry with coplanar electrodes at the bottom interface of the planar cell. The inset shows the coordinate system and parameters related to the director orientation.

Fig. 6. Experimental results on the creation of spatial optical solitons in ChNLC. (a) Beam propagation for various TM excitations (marked on the photos) after launching it in the midplane of the cell. (b)-(c) Intensity profiles at low and high power, respectively, and various propagation distances; (d) input beam width vs. power density [$\text{mW}/\mu\text{m}^2$].

Fig. 7. Acquired results for various laser beam inputs versus x. Panels (c)-(f)-(i)-(l) show solitons propagating in four different layers.

Fig. 8. Cross-sections of the beam intensity taken from the photographs in figure 3 at the approximate distance of 1mm.

Fig. 9. (Top) Results on light propagation depending on input polarization and (bottom) cross-sections after 1000 μ m.

Fig. 10. Calculated extraordinary index for various applied voltages, from 2.8 to 4.5V with 0.1 V increments.

Table 1. Calculated voltage-tuning of the Bragg resonance and its FWHM.

List of Symbols, Abbreviations and Acronyms

ITO: Indium Tin Oxide

TM: Transverse Magnetic

TE: Transverse Electric

DFBW: Distributed FeedBack Waveguide

CCD: Charge Coupled Device

POLICRYPS: Polymer Liquid Crystal Polymer Slices

FWHM: Full width at half maximum

Appendix: confirmation of expenditures

I confirm that expenditures in excess of \$13,820.00 were incurred for during the final three months of the Project started last October 15, 2008, including overhead, consumables, equipment, travel and payment of external personnel.

Sincerely,

Prof. Gaetano Assanto

