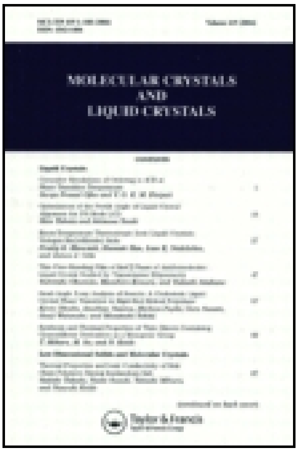

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Liquid Crystalline Cells for Fiber Optic Sensing of Low Hydrostatic Pressure

Tomasz R. Woliński [a], Roman Dabrowski [b], Andrzej Bogumił [a] & Zofia Stolarz [b]

[a] Institute of Physics, Warsaw University of Technology Koszykowa, 75, 00-662, Warszawa, Poland

[b] Military Technical Academy, Kaliskiego, 1, 00-908, Warszawa, Poland

Version of record first published: 23 Sep 2006.

To cite this article: Tomasz R. Woliński , Roman Dabrowski , Andrzej Bogumił & Zofia Stolarz (1995): Liquid Crystalline Cells for Fiber Optic Sensing of Low Hydrostatic Pressure, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 263:1, 389-397

To link to this article: http://dx.doi.org/10.1080/10587259508033599

Mol. Cryst. Liq. Cryst. 1995, Vol. 263, pp. 389–397
Reprints available directly from the publisher
Photocopying permitted by license only

LIQUID CRYSTALLINE CELLS FOR FIBER OPTIC SENSING OF LOW HYDROSTATIC PRESSURE

TOMASZ R. WOLIŃSKI, ROMAN DĄBROWSKI*, ANDRZEJ BOGUMIŁ, AND ZOFIA STOLARZ*

Institute of Physics, Warsaw University of Technology
Koszykowa 75, 00-662 Warszawa, Poland
**Military Technical Academy, Kaliskiego 1, 00-908 Warszawa, Poland*

Abstract The paper presents a new approach to a low-pressure fiber-optic sensing employing pressure-induced deformation effects occurring in twisted nematic LC cells. This method is particularly suitable for measurement of pressures up to 2 MPa and utilizes strong rotatory power occurring in chiral nematic liquid crystals. The effect manifests itself in rotation of linear polarization of light coming through a LC cell and resides in detecting changes in helicoidal pitch of a chiral nematics under the pressure-induced deformation of the cell. Results indicate that this method of hydrostatic pressure measurement offers high response to pressure with reduced temperature sensitivity and, depending on the on the specific LC materials and on geometry of the LC cell used, can be pre-set for a required range of pressure.

INTRODUCTION

Pressure effect in liquid crystals (LCs) have been intensively studied over the past years since they can give new insides into the nature of molecular interactions responsible for liquid crystalline ordering and also they hold great potential for applications in pressure metrology. Among liquid crystalline phases, chiral nematic (cholesteric) LCs posses unique optical properties associated with a helical arrangement of two dimensional nematic layers. Most characteristic properties of cholesteric LCs are associated with selective (Bragg) reflection and non-common in other materials a very high rotatory power. Since optical parameters (helicoidal pitch, P and birefringence $\Delta n = n_e - n_o$) of a cholesteric phase strongly depend on external factors such as temperature and pressure, liquid crystals can be applied to temperature and pressure sensing. The influence of hydrostatic pressure on cholesteric LCs was initially described by Pollmann [1] who determined the wavelength of Bragg reflection of light, λ_R of cholesteric mesophases for pressures up to 500 MPa. His results showed that sensitivity of the wavelength λ_R to pressure can be extremely large, with a red shift of λ_R, providing a new method of pressure measurement [2].

Hydrostatic pressure metrology using fiber optic sensing techniques holds great potential for application in the modern economy. Recently, we have introduced [2], implemented [3] and patented [4] a novel and cost-effective method for measurement of high hydrostatic pressure (up to 100 MPa) applied to a sensing element comprising a chiral nematic liquid crystal coupled to multimode optical fibers and based on the pressure-induced shift of λ_R.

Another approach of pressure sensing utilizing unusual optical properties of LCs - specially dedicated to low pressures (in order of 1MPa) is based on polarization properties of twisted nematic (TN) cells. In a twisted nematic cell composed of a chiral nematic LC with a higher value of pitch (P above 10μm) in comparison with cell thickness, the magnitude of the pitch can be in a certain range modified by changing the cell thickness. In general, an incident linearly polarized light becomes elliptically polarized, and the polarization ellipse rotates as the wave propagates through the twisted nematic cell modifying its ellipticity ε and azimuth θ due to twisting. The magnitude of twist and ellipticity strongly depend on the cell thickness. Locating at the back wall of the cell an analyzer we can obtain a simple pressure sensor that, in fact will detect changes in thickness of the TN cell.

The paper presents a further development of a fiber-optic low hydrostatic pressure measurement based on pressure-induced deformations occurring in a twisted geometry of a LC cell [5]. In comparison to the recently developed fiber-optic liquid-crystal pressure sensor [2-4] based on the effect of selective Bragg refection (measuring range 20-200 MPa), the device proposed in this paper operates in a low pressure range (up to 2 MPa) and employees mechanical deformations in the twisted nematic cell. The effects manifests itself in rotation of linear polarization of light coming through a liquid crystalline cell and resides in detecting changes in helicoidal pitch of a chiral nematics under the pressure-induced deformation of the cell. Sensitivity of such a pressure sensor depends on P and on birefringence, but also on elasticity of the glass cell. Additional advantage of liquid crystals with large pitch is a very good temperature stability (clearing point can be above 100° C). Hence, in the range 20-40° C the sensor can operate with negligible thermal drift. In the theoretical part we present calculations of transmission characteristics of TN and STN cells filled with chiral nematics. By using the Jones N matrix method we briefly discuss the influence of pitch size and azimuth the input light on sensor characteristics. Theoretical results are fully confirmed in the experimental part of the paper.

TRANSMISSION OF TWISTED NEMATICS UNDER PRESSURE

The polarization state of light which propagates in an anisotropic medium is described by the Jones vector ε. The anisotropic medium can be characterized by its differential propagation N matrix introduced initially by Jones [6,7]. Following this approach we can immediately derive differential equation for the Jones vector results from the definition of the N matrix:

$$\frac{d\varepsilon}{dz} = N\varepsilon \qquad (1)$$

Expanding (1) gives:

$$\frac{d\varepsilon_1}{dz} = n_{11}\varepsilon_1 + n_{12}\varepsilon_2$$
$$\frac{d\varepsilon_2}{dz} = n_{21}\varepsilon_1 + n_{22}\varepsilon_2 \qquad (2)$$

where n_{ij} are elements of the N matrix. For generality ε_1 and ε_2 represent projections of the Jones vector ε along any pair of basis polarization states.

The system of equations (2) can be easily brought to one by substituting a complex variable:

$$\chi = \frac{\varepsilon_2}{\varepsilon_1} \qquad (3)$$

By taking first derivatives of both sides of (3) and eliminating ε_1 and ε_2 in Eq. (2) we obtain:

$$\frac{d\chi}{dz} = -n_{12}\chi^2 + (n_{22} - n_{11})\chi + n_{21} \qquad (4)$$

Consider propagation of a totally polarized light through a twisted nematic cell along its helical axis (parallel to z-axis of the XYZ Cartesian system). Since a twisted nematic LC may be regarded as a medium that is composed from infinite stack of birefringent planes, the N matrix takes a form:

$$N = g_o \begin{bmatrix} 0 & -ie^{-i2\alpha z} \\ -ie^{i2\alpha z} & 0 \end{bmatrix} \quad (5)$$

where $\alpha=2\pi/P$, $g_o= 1/2(k_x-k_y)$, and k_x, k_y are the principal propagation constants. The N matrix in Eq. (5) describes the simplest case that occurs in real situations under the Maugin limit. In the Maugin limit, the eigenwaves that are propagating in a twisted nematics can be regarded as linearly polarized. Such situations occur when pitch $P>>10\lambda$. Substituting Eq. (5) into Eq. (4) we obtain a general solution:

$$\chi(z,\chi_0) = \left[\frac{(\beta - i\alpha \tan\beta z)\chi_0 + (-ig_0 \tan\beta z)}{(-ig_0 \tan\beta z)\chi_0 + (\beta + i\alpha \tan\beta z)}\right] e^{i2\alpha z} \quad (6)$$

where χ_0 -is an initial polarization.

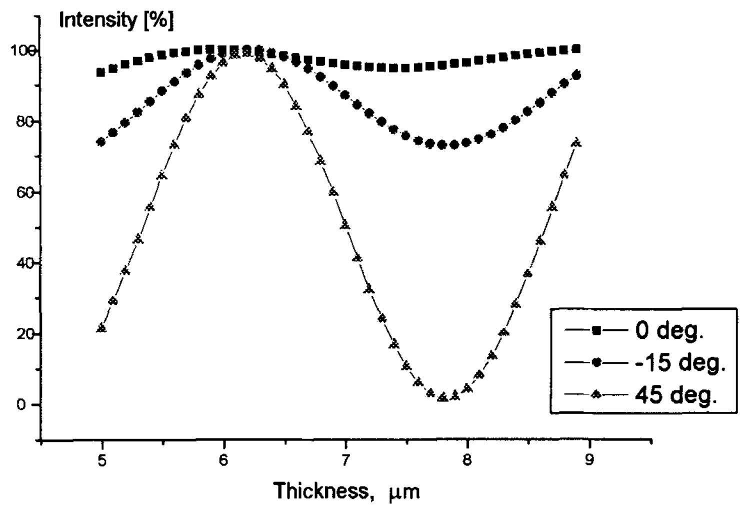

FIGURE 1 Theoretical curves for the $1/2\pi$ cell plotted for selected values of the incident light polarization azimuths

Consider complex function $\chi(z,\chi_0)$. If we know χ we can easily compute polarization ellipse parameters: azimuth and ellipticity. However, the relationship that links azimuth and ellipticity to the complex plane variable depends on the basis polarization states that are used for the definition of χ in Eq. 3. If the basis states are two orthogonal right and left circular polarized states then azimuth θ and ellipticity ε are expressed as follows:

$$\theta = \frac{1}{2} Arg(\chi)$$
$$e = \frac{|\chi| - 1}{|\chi| + 1} \tag{7}$$

We calculated intensity of the light passed through a twisted nematic cell. The initial thickness of a twisted nematic cell was 9μm and under pressure-induced deformations the cell thickness diminished. We established initial values of the pitch for two 9μm-thick cell: P=12μm and P=36μm (n_o=1.517, n_e=1.732). In such a way director made angle: 3/2π and 1/2π, respectively. The incident light was linearly polarized with a non-zero azimuth (see Fig. 1) and the analyzer was set on maximum transmittance (the longer axis of ellipse of the output light was parallel to the polarizer axis).

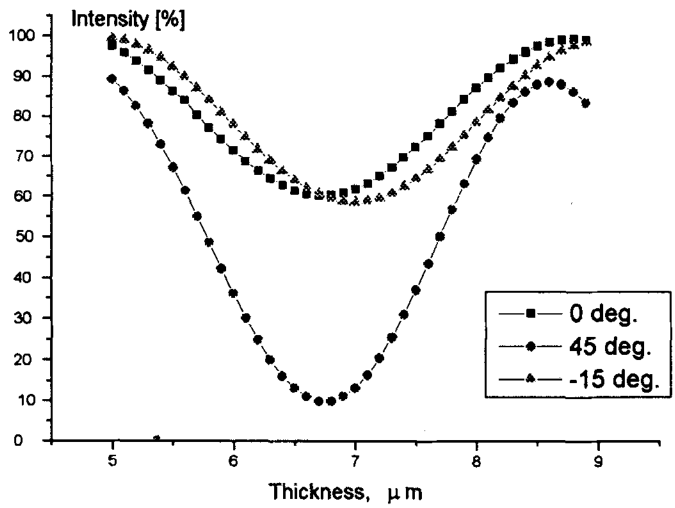

FIGURE 2 Theoretical curves for the 3/2π cell plotted for selected values of the incident light polarization azimuths

As we can see from characteristics presented in Fig. 1 and 2, sensitivity and dynamics of the pressure sensor strongly depends on the incident light azimuth but also on the helicoidal pitch P of a twisted nematic liquid crystal. The best sensitivity was achieved for the azimuth θ = 45 deg. and for the pitch P = 36μm.

EXPERIMENTAL

The experimental setup is also presented in Fig. 3. The fiber optic head was glued to the input/output optical fibers which were used to transport optical signals in and out of the pressure region. As the input, a highly birefringent (HB) single-mode bow-tie fiber was used. The HB fiber can maintain a linear polarization when injected along one of its principal birefringence axes. At the output of the head we attached a polarizer which without external pressure ensured the conditions of maximum light transmission. The polarizer was directly coupled to an output multimode fiber with a high core diameter (200μm). As a light source a 10 mW He-Ne laser at 633 nm wavelength modulated using standard techniques was used. A typical computer-controlled synchronous detection system including a detector, a lock-in amplifier, and a digital DC voltmeter was used to recover measurement information from pressure modulated light transmitted through the LC film.

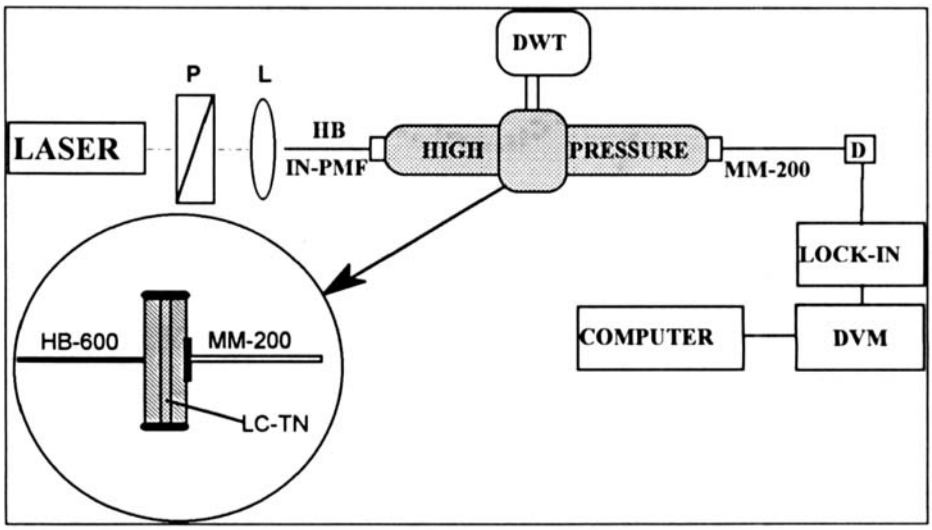

FIGURE 3 The experimental set-up: P - polarizer, L - lens, D - detector, DWT - deadweight tester, LOCK-IN - lock-in amplifier, DVM - digital multivoltmeter, HB-600 - highly birefringent polarization-maintaining leading fiber, MM-200 - multimode (200μm-core) receiving fiber, LC-TN - liquid crystalline twisted nematic cell

Two different sensor configurations have been constructed: first one utilized multimode fibers and in the second a HB fiber served as an input. The sensor head was composed of a standard and commercially available glass cell characterized by a thickness d = 9μm. As the cell undergoes squeezing we glue it with 20% air inside. In the configuration with all multimode fibers two sheet polarizers were attached to the cell. The input polarizer was glued at 45 degrees in respect to the rubbing director of cell's cover plate whereas the analyzer was glued in the orientation corresponding the maximum transmittance of the cell.

In the configuration with the HB fiber, only polarizer glued at 45 degrees to the output glass rubbing direction was required due to the polarization maintaining capabilities of the fiber. Birefringence axes of the HB fibers were oriented at 45 degrees to the input rubbing direction and consequently no polarizer was required. At the output, we chose multimode 200μm-core receiving fibers which ensured independence of the output signal from pure mechanical disadjustments of the sensor head and a high level of the transmitted optical power.

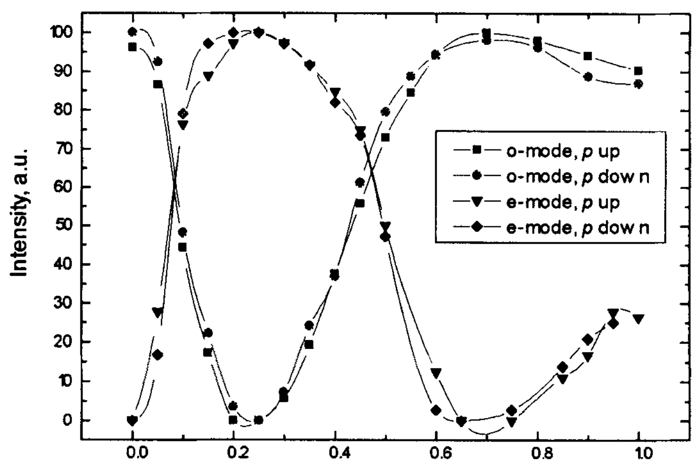

FIGURE 4 Pressure characteristics for the TN cell (1/2π twist)

In the experiment, we used twisted and supertwisted nematics cells characterized by helicoidal pitches: P = 12μm and P = 36μm, respectively. The liquid crystalline material used was a mixture of nematic LCs (catalogue number 770, supplied by *AVAT Comp., Poland* [5]) characterized by refractive indices n_o=1.517, n_e=1.732 which was doped with a left-handed optically active chiral compound (helical twisting power β=19.4 μm/mol). Under hydrostatic pressure, the cell was elastically compressed due to appropriate bonding procedure and large surfaces (20 mm x 20 mm). The sensor assembly was placed inside a standard thermally stabilized pressure chamber designed to sustain pressures up to 4 MPa. As a light source a He-Ne laser operated at 633 nm wavelength was used, modulated using standard techniques The experimental details were described elsewhere [5].

RESULTS AND CONCLUSIONS

The low hydrostatic pressure sensor based on deformations induced in a twisted liquid crystal cell was characterized for a temperature range up to 40^0 C. The output signal (I) mean temperature stability expressed as $\alpha_T=(1/I)\ dI/dT$ was in the order of 3 10^{-3}deg.$^{-1}$.

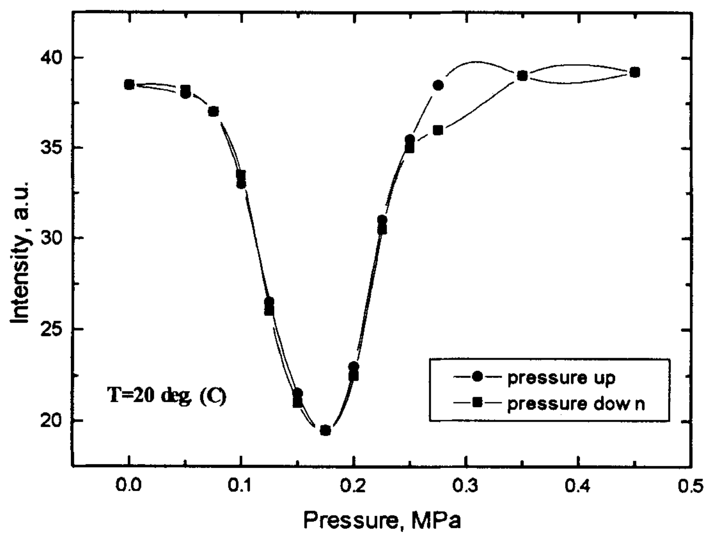

FIGURE 5 Pressure characteristics for the STN cell (3/2π twist)

The pressure characteristics were obtained for two types of twisted-nematic cells : with 1/2π twist (Fig. 4, TN-cell) and with 3/2π twist (Fig. 5, STN cell). In both cases, we observed a residual pressure hysteresis that was rather attributed to elastic properties of

9μm-thick spacing elements of the glass cell than to thermodynamic properties of the TN (STN) liquid crystal material.

The output signal (I) mean pressure-sensitivity expressed as $\alpha_p = (1/I)\ dI/dp$ was found to be about 1.5 MPa^{-1} for the 1/2π twist and about 4.5 MPa^{-1} for the 3/2π twist, both calculated in the linear region of pressure characteristics. The results indicate that this method of hydrostatic pressure measurement offers high response to pressure with reduced temperature sensitivity and, depending on the liquid crystalline cell used, can be pre-set for a required range of pressure. Potential areas of applications include pipe-lines and mining instrumentation, process-control technologies and environmental protection. In comparison with the previous results [2-4] for a liquid crystal pressure sensor utilizing the selective reflection phenomenon, the low-pressure fiber optic liquid crystalline sensing device demonstrates significantly reduced thermal sensitivity over a broad range of temperature, and consequently no reference schema was required.

ACKNOWLEDGEMENTS

The work was supported by the Polish State Committee for Scientific Research (KBN) under the grant no. 8/S505/004/04.

REFERENCES

1. P. Pollmann, *J. Phys. E Sci. Instrum.* 7, 490, (1974)
2. T. R. Woliński, and W. J. Bock, *Mol. Cryst. Liq. Cryst.*, **199**, 7, (1991).
3. T. R. Woliński, W. J. Bock, and R. Dąbrowski, *Mol. Cryst. Liq. Crys.* (1994), in press.
4. W. J. Bock and T. R. Woliński, *US Patent,* No. 5,128,535, (1992).
5. T. R. Woliński, R. Dąbrowski, W. J. Bock, A. Bogumił, S. Kłosowicz, *Thin Solid Films,* (1994), in press.
6. R. M. A. Azzam, and N. M. Bashara, *J. Opt. Soc. Am.*, **62**, 1252, (1972).
7. J. Nehring, *J. Chem. Phys.*, **75**, 4326-4337, (1981).