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Progress in liquid crystal optical fiber waveguides and devices for pressure sensing

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Progress in realizations of liquid crystalline optical fiber waveguides and devices for pressure monitoring is presented. This includes a compact fiber-optic low-pressure sensor based on nematic liquid crystal cells and a novel idea of high-pressure monitoring based on anisotropic liquid crystalline-core optical fiber waveguides. Both approaches combine unique optical advantages of anisotropic liquid crystals and high quality of all-fiber technology creating new possibilities in hydrostatic pressure sensing.

1. Introduction

Over the last thirty years many parameters modulating light propagation in liquid crystals (LCs) have been intensively studied in view of potential applications to various types of sensors employing also fiber-optic sensing techniques. Recently [1]–[6], it has been reported that liquid crystals could be successfully applied in fiber-optic sensing of hydrostatic pressure. Practical arrangements were based on the Bragg reflection as well as on strong rotatory power of chiral nematic LCs and created a background for new methods of low and high hydrostatic pressure monitoring.

In the low pressure region (up to 4 MPa), [2], [3], the proposed method employs pressure induced deformations occurring in nematic LC cells and makes use of the strong rotary power of chiral nematic LCs. This effect manifests itself in a rotation of linear polarization (Mauguin limit) of the light coming through the LC cell.

However, in the higher pressure regions (up to 100 MPa), the intensity-based method takes advantage of the effect of pressure-induced changes in the wavelength of selective Bragg light reflection observed in chiral nematic LCs [5], [6]. In this case, the following condition must be satisfied $\langle n\rangle P_0 = \lambda$, where $\langle n\rangle$ is the mean refractive coefficient of the chiral nematic LC, λ is the operating wavelength and P_0 – the undisturbed helicoidal pitch.

Since any prospective liquid crystal pressure-sensing device should be coupled to optical fibers that deliver optical signals to an elevated-pressure region, a new direction in fiber-optic liquid crystal sensing has been started [7]–[9]. The liquid crystal has been put inside capillaries (or hollow-core fibers) with few-micrometer diameters creating a novel fiber-optic structure, *i.e.*, an anisotropic liquid crystalline-core fiber. This case is also especially important from the point of view of integrated optics, since liquid crystalline waveguides could be used in polarizers, modulators, couplers and switches.

2. Liquid crystal sensor of low pressure

A monochromatic wave propagating through a twisted nematic (TN) cell can be described as a superposition of two normal modes. In a rotational coordinate system the normal modes are in general elliptically polarized, and the axes of their polarization ellipses rotate at the same rate as the light propagates through the chiral LC medium. However, if the total birefringence $\Delta\beta$ of the LC medium is much larger than initial twist (rotatory power) $q = 2\pi/P$, the light remains approximately linearly polarized [10]. Since $\Delta\beta = k\Delta n = (2\pi/\lambda)\Delta n$, this leads to the adiabatic approximation or the Mauguin limit $\lambda \ll \Delta n P$ [11]. When a linearly polarized light traverses the TN cell, the plane of polarization follows the twist of the LC directors if the Mauguin condition is satisfied, $\Delta n d \gg \lambda/4$.

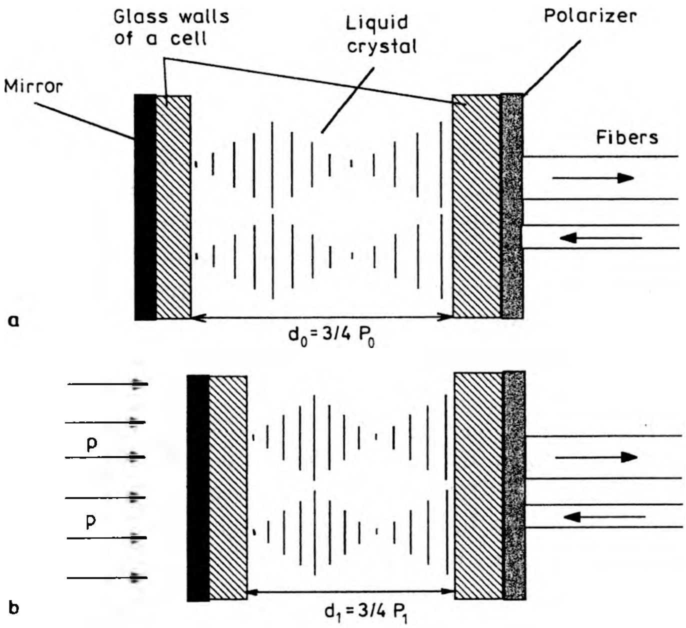

Fig. 1. Operation principle of the pressure sensor in the reflective configuration under atmospheric pressure (**a**) and under hydrostatic pressure (**b**).

Figure 1 presents the principle of operation of the pressure sensor in the reflective configuration. The measuring head of the low-pressure LC pressure sensor was composed of a standard and commercially available TN glass cell characterized by a thickness $d = 5$ μm. The polarizer was glued at 45° to the rubbing direction of the cell's cover plate. At the output, a multimode 200 mm-core receiving fibers was chosen that ensured independence of the output signal from pure mechanical disadjustments of the sensor head and a high level of the transmitted optical power.

Alternatively, LC cells configured in a homogeneous Frederiks geometry were also used. The sensor is composed of a round LC cell placed inside a specially designed pressure chamber in such a way that the pressure head does not have any contact with the measured liquid. The change of the colours of the anisotropic liquid placed between the crossed polarizers is a consequence of mechanical change of cell thickness.

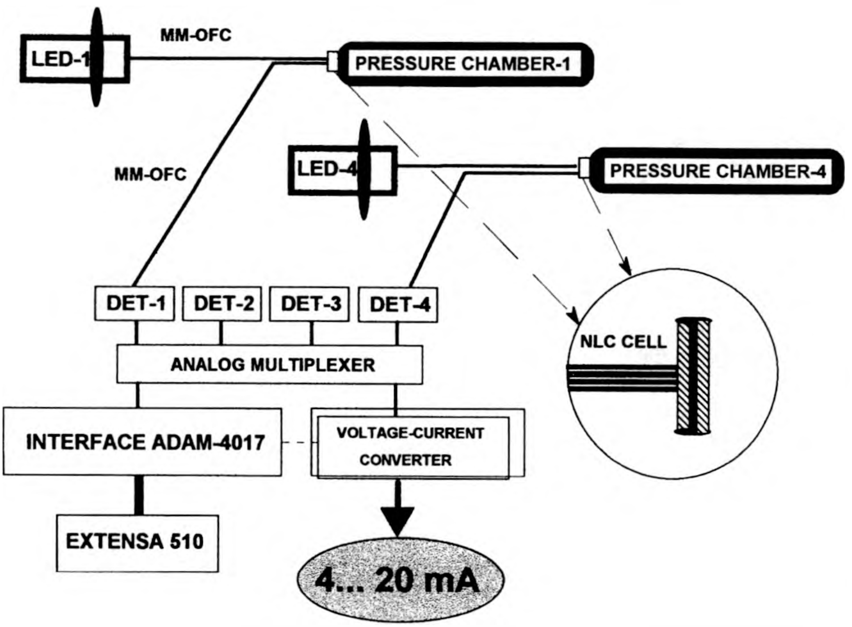

Fig. 2. Multiplexed fiber-optic sensor for continuous pressure monitoring based on nematic cells with an interface ADAM-4017 connected with a portable computer Extensa-510 and voltage current converter (MM-OFC — multimode fiber cable, LED-1(4) — light emitting diodes).

The experimental set-up of the prototype fiber-optic sensor for pressure monitoring in the reflective configuration is shown in Fig. 2. The fiber-optic sensor head was placed inside a specially designed and thermally stabilized prototype pressure chamber. As a light source we used a typical diode operating at red wavelength and modulated using standard techniques. The pressure transducer was connected to a computer with a specially designed interface built on the basis of advanced ADAM modules. The set-up included a synchronous detection multiplexed system composed of silicon photodetectors and analog multiplexer, and a portable personal computer Extensa-510 (Texas Instrument) as well as lead-in and lead-out multimode fiber bundles.

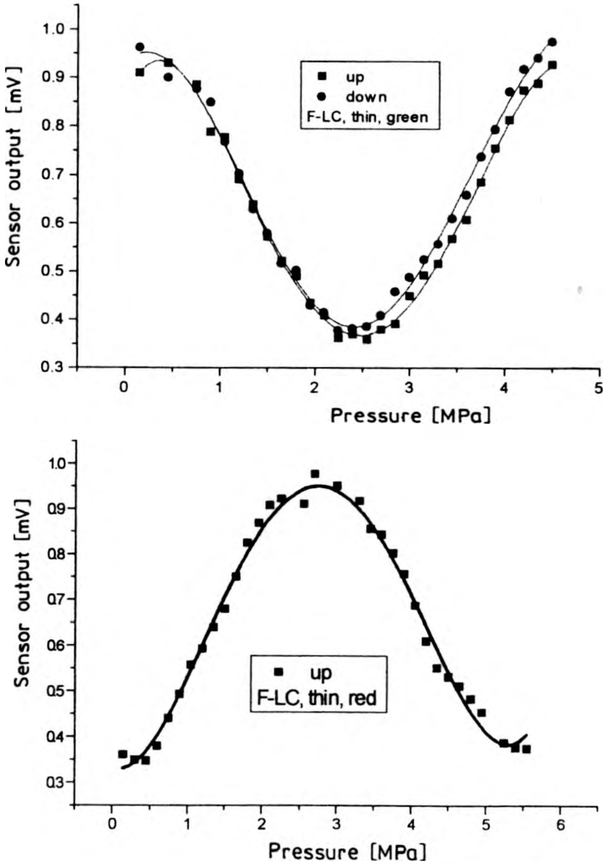

Fig. 3. Calibration of the liquid crystal pressure sensor in Frederiks configuration (F-LC) for red (crossed polarizers) and green (parallel polarizers) cells.

Typical characteristics of LC cells are presented in Fig. 3. It was found that the precision of the pressure measurement was better than 5%, in the temperature range from 0° to 50°. Also a good repeatability of the results with the possibility of shifting the starting point of the characteristic was achieved.

The prototype fiber optic pressure sensor exhibits very good pressure sensitivity and repeatability as demonstrated in Fig. 4. A negligible hysteresis bahaviour has been observed in the Frederiks configuration.

3. Liquid crystal-core fibers for high-pressure sensing

In the functional fiber optics there is a general tendency to replace optical bulk elements by their all-fiber equivalents. Consequently, in the past years much research effort has been devoted to exploring combined use of optical fibers and liquid crystals. In the studies, liquid crystals were used as cladding as well as core of the fiber [7], [8].

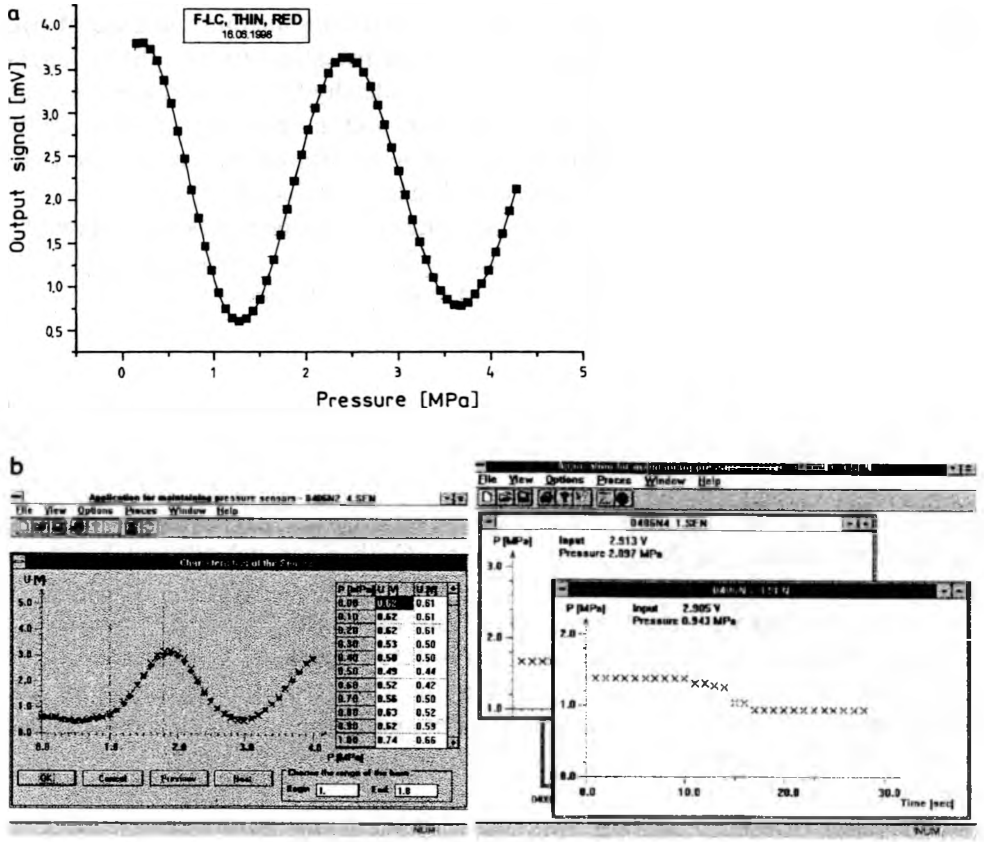

Fig. 4. Pressure characteristics of the sensor in the Frederiks configuration (**a**) and measurement of time-dependent pressure variations by using the field LC sensor (**b**).

Hereby, a totally new idea of pressure monitoring using fibers with control birefringence due to the presence of liquid crystal is proposed. Specially drawn hollow-core fibers were filled with chiral or nematic liquid crystalline mixtures. Three types of LC ordering inside the cores are possible: planar, radial and axial structures (Fig. 5).

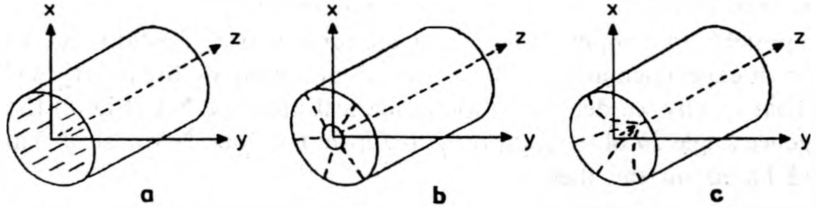

Fig. 5. Types of alignment of the LC director inside the fiber: **a** — planar structure, **b** — radial structure, **c** — axial structure.

The anisotropic liquid crystal fiber is a very interesting medium because of two aspects. First, it creates the possibility of theoretical investigation of light propagation under external parameters and in particular under hydrostatic stresses. Second, this kind of fiber can be applied for measuring and monitoring of pressure in pipelines and in any place difficult to access where traditional measuring methods cannot be used because of low accuracy and safety problems.

Liquid crystalline molecular ordering inside the core can be reversely modified by linear (or nonlinear) external perturbations. In this way, we obtain an externally controlled fiber with tunable birefringence governed by the dielectric tensor of the LC core

$$\bar{\varepsilon} = \begin{bmatrix} \varepsilon_\perp + \Delta\varepsilon \sin^2\theta & 0 & \Delta\varepsilon \sin\theta\cos\theta \\ 0 & \varepsilon_\perp & 0 \\ \Delta\varepsilon \sin\theta\cos\theta & 0 & \varepsilon_\perp + \Delta\varepsilon\cos^2\theta \end{bmatrix}, \tag{1}$$

where $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_\perp$ and θ is the angle between direction of the molecules and the symmetry axis. Hence the birefringence of the LC fiber can achieve much greater values in comparison with "classical" silica-glass highly birefringent fibers.

In theory, we start with the Maxwell equations and Frank free energy density for a LC core, which assumes that the orientation order of molecules is constant without changing the environment parameters. Then the characteristic equations for the following modes: TE_{01}, TM_{01} and HE_{11} are derived [9]. These formulas are called Hondros–Debay equations and due to them the propagation constant β for each of the modes can be found.

In the case of LC-core fiber waveguides, both leaky modes represented by imaginary part β_i and guided modes represented by real part β_r are considered. Hence a general formula describing the complex propagation constant is as follows: $\beta = \beta_r + i\beta_i$. Then the effective refractive index n_{eff} and the loss coefficient α, which depend on components of the propagation constant, can be defined

$$n_{\mathrm{eff}} = \frac{\beta_r}{k} \quad \text{and} \quad \alpha = -2\beta_i. \tag{2}$$

Note that the TE and TM modes exhibit different behaviour. The TE_{01} mode is a guided mode and its propagation constant has zero imaginary component, so the loss coefficient disappears. On the contrary, TM modes are leaky modes, so their propagation constants consist of both imaginary and real part.

However, it is possible to compute numerically the propagation constant, but it is difficult to measure it experimentally and hence we cannot compare the theory with the experiment. That is why we determine the numerical aperture NA (Fig. 6) that defines the divergence angle 2θ of the light outgoing from the fiber: $\mathrm{NA} = \sin\theta$. This can be calculated based on the theory

$$\mathrm{NA}^{\mathrm{th}} = \frac{\sqrt{k^2 - \beta^2}}{k_0} = \sqrt{n_{\mathrm{LC}}^2 - n_{\mathrm{eff}}^2} \tag{3}$$

and it can be compared with the data obtained from measurements

$$\mathrm{NA}^{\mathrm{ex}} = \frac{L}{\sqrt{d^2+L^2}} \tag{4}$$

where k is the wave vector inside the fiber, k_0 is the wave vector outside the fiber (in vacuum), d is the distance from fiber to the light spot, and L is the radius of the light spot [9]. The data obtained from the experiment have been used in calculations: $\lambda = 0.6328$ µm, $r = 2$ µm, $n_{\mathrm{cl}} = 1.4585$ and $n_{\mathrm{co}} = 1.4845$ for the planar structure, and $n_{\mathrm{co}} = 1.544$ for the radial structure. In the radial structure due to higher value of the refractive index ($n_{\mathrm{co}} = 1.544$) the modal structure of the guided field disappears.

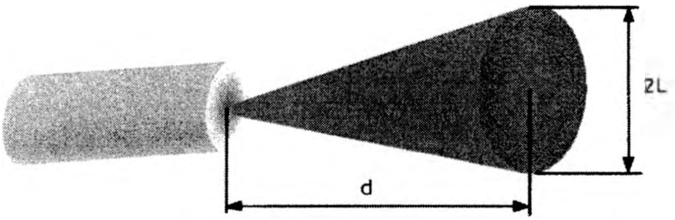

Fig. 6. Geometrical illustration for numerical aperture (d — distance from fiber to the light spot, L — radius of the light spot).

The changes of the numerical aperture influence the coupling between the LC fiber and lead-in or lead-out fibers and they give the intensity changes in the transmitted light. We assumed that different external parameters (electric or magnetic field, temperature, hydrostatic pressure, *etc.*) modify the numerical aperture of the LCF.

The initial experiments have been performed with circular-core liquid crystal fibers. The aim of this work was to investigate the liquid crystal fiber sensor in all-optical configuration, in which light does not leave the waveguide path (Fig. 7). Configurations of sensor with a single-mode fiber as a lead-in and a multimode fiber as a lead-out were considered which take advantage of the intensity-modulation effects. Specially drawn hollow-core fibers (capillary tubes of radii between 5 and 130 microns) were filled with a liquid crystal mixture. Another advantage of using all-fiber system is that it can stand very high pressure and can be used for measuring over 100 MPa range. It needs to be emphasized that the new method of coupling lead-in and lead-out fibers with the sensing waveguide filled up with liquid crystal was proposed in [3]. Such a configuration was suggested to avoid direct splicing of the liquid crystal waveguide that exhibits high thermal sensitivity.

High-pressure characteristics (Figs. 8 and 9) have been obtained for the radial and the planar configurations of the waveguide filled up with the nematic liquid crystal. Sufficient dynamic range and the valuable repeatability of the measurements the LC-in-fiber sensor are very important from the point of view of commercial applications. Figure 8 compares two sensors with different radii and shows better

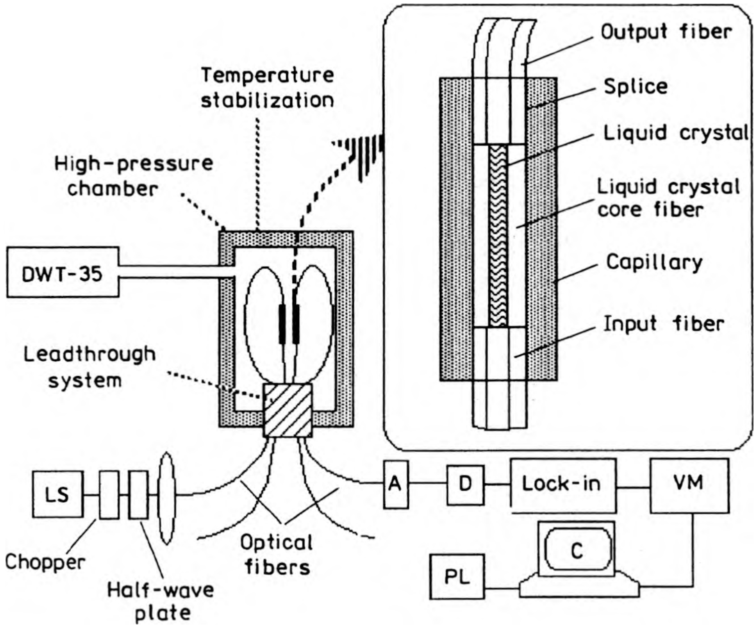

Fig. 7. Experimental setup of the fiber-optic liquid crystal pressure sensor in all-optical configuration. D — detector, VM-DC — voltmeter, C — computer, PL — plotter.

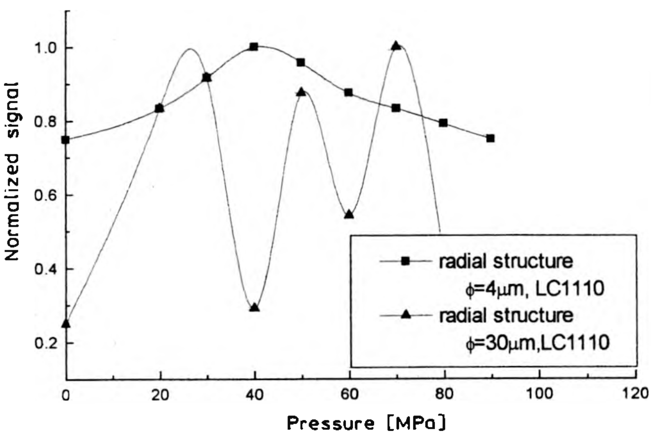

Fig. 8. Pressure characteristics of the radially oriented liquid crystal fiber with single mode lead-in fiber and a multimode lead-out fiber up to 100 MPa; 30-μm and 4-μm capillary filled up with nematics ($\lambda = 633$ nm).

dynamics for the larger radius. Also, Figure 9 compares two sensors with different kinds and structure of LC and shows different starting point of the pressure characteristics.

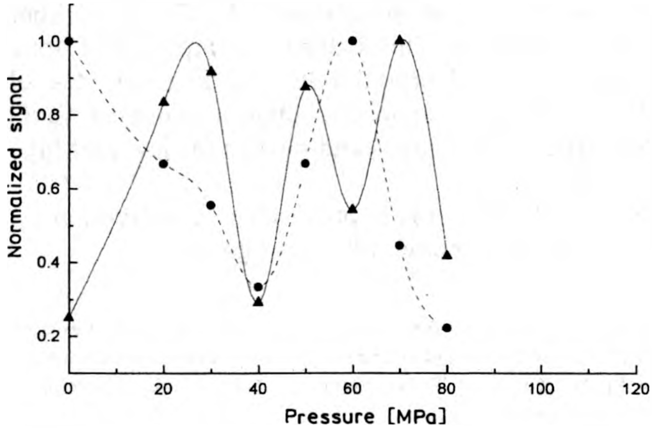

Fig. 9. Pressure characteristics of a radially and planar oriented liquid crystal fiber with a single-mode lead-in fiber and a multimode lead-out fiber up to 80 MPa. 30-μm capillary filled up with two different nematics ($\lambda = 633$ nm). ▲ – radial structure, $\varphi = 30$ μm, LC1110, ● – planar structure, $\varphi = 30$ μm, LC1115.

4. Conclusions

A significant progress in liquid crystalline fiber-optic systems for hydrostatic pressure monitoring has been achieved over the last years. It resulted in successful construction of the compact prototype fiber-optic liquid crystal sensor for low pressure monitoring. The prototype exhibits very good pressure sensitivity as well as repeatability with considerably reduced hysteresis, and is specially dedicated to pipelines and process-control applications. Another significant achievement was a construction of the fiber-optic liquid crystal pressure sensor in all-optical configuration.

Table. LC fibers and devices for low and high hydrostatic pressure sensing

Low-pressure devices: TN, F-LC cells

Pressure range (replaceable LC head):	0–5 MPa
Operating in temperature range:	−10 °C +70 °C
High pressure sensitivity:	$\alpha_p = (I/I)dI/dp \sim 5$ MPa^{-1} (in linear range)
Mean temperature stability	$\alpha_T = (I/I)dI/dT \sim 3\cdot10^{-3}$ deg^{-1}

High-pressure sensing: LC fibers

Pressure range	0–100 MPa
Anchoring conditions	planar or radial (homeotropic)
Core symmetry	circular or elliptical
Core size	5–30 μm

Summing up, the paper presents progress in realizations of LC optical fiber waveguides and devices for pressure monitoring. This includes a compact fiber optic low-pressure sensor based on nematic liquid crystal cells and a novel idea of high-pressure monitoring based on anisotropic liquid crystalline-core optical waveguides. The Table presents a comparison of LC fibers and devices for low and high hydrostatic pressure sensing.

Further optimization procedures leading to a prospective construction of a compact and miniature all-fiber LC sensor are still in progress.

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