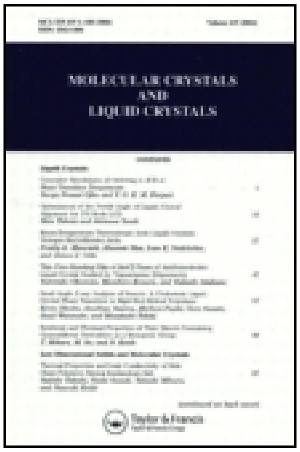

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Leakography: Visualization of Losses in Fibers and Fiber-Optics Systems Using Liquid Crystals

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Leakography: Visualization of Losses in Fibers and Fiber-Optics Systems Using Liquid Crystals

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It is experimentally demonstrated that liquid crystals can play the role of 'streak cameras' and visualize traces of leakage of optical radiation from microscopic areas of essential fiber-optics components such as tapers, couplers, switches, as well as from uncontrollable inhomogeneity regions and imperfections. By that, extended regions of fibers can be simultaneously monitored and distribution of strain and temperature in long fibers visualized.

Keywords: Nematics; liquid crystals scattering; fiber optics; tapers

Leakage of radiation is inevitable in all key elements of fiber optics communication and sensor systems. Particularly strong losses occur during coupling of radiation into the fiber and out of it, in switches, polarizers, tapers. Losses can be caused also by curvatures of fibers, by strains and temperature gradients, by presence of technical imperfections and defects occurring in the fiber manufacturing process. Usually, the power of radiation in fibers is rather small, and the detection of the light leakage requires special experimental arrangements and sensitive equipment. It is even a more complicated problem to test extended lengths of fibers. In a first part, we explain what the leakography is and in a second one we present some experimental examples of such an analysis.

PRINCIPLE OF LEAKOGRAPHY

Few years ago, it has been shown a very nice device that allows to control electronic chips [1]. In that device, the chip is covered with a NLC layer and a transparent and conductive plate. As some special wire is addressed, a potential exists in between that line and the upper plate which reorients locally the NLC: as a result, the addressed wire becomes visible providing that polarizers are properly installed. In case of any trouble in the circuitry, it is immediately visualized and this control can be done on a quite large scale. The main used property in this case is the well known Frederikcz transition.

What we present in this paper is, in the spirit, similar to that chip control. We will show that liquid crystals (LC), particularly nematic LC (NLC) provide unique possibilities for visualization and control of leakage of radiation in optical fibers and fiber optics systems. The properties of LC which are used for this purpose are the following:

1. Extraordinarily large cross-section of light scattering due to thermal fluctuations of the optical axis (the director) orientation of NLC even in perfect homogeneously oriented samples [2]. The typical magnitude of the extinction constant of NLC is of the order of $10\,\mathrm{cm}^{-1}$ which is 6 orders of magnitude larger than the characteristic one of isotropic liquids, including the isotropic phase of the NLC itself. This enormous value of light extinction due to scattering is the result of combination of the large optical anisotropy of the NLC and the large thermal fluctuations of the optical axis [2–4].
2. Negligibly small absorption of NLC throughout the visible and near infrared wavelengths. Typically, the absorption constant of NLC is of the order $10^{-2}\,\mathrm{cm}^{-1}$ [5]. Thus, the scattered light is visible during propagation in the NLC over considerable distances, and there are no unwanted consequences like absorption-induced heating. This makes also the technique suitable for controlling telecom fiber based devices.
3. The liquid nature of NLC. This allows objects of complex geometrical form to be embedded in the NLC. This allows also extended lengths of fibers and areas of waveguides to be covered with the NLC, and the field of losses to be visualized.

Combination of liquid and crystalline properties of cholesteric LC is widely used for visualization of thermal fields [6]. By analogy with LC-Thermography, we can name our control method 'Leakography'.

Schematically, the device that has to be controlled is sunk in a liquid crystal bath, the observation is made through a microscope and the possible leaking out of the device is visualized through the scattering of the leaking beam (Fig. 1).

Before illustrating some possibilities of leakography, let us outline here the main peculiarities of light scattering in NLC related to the polarization and angular dependence of the scattering cross-section. These features can be found in major books devoted to Liquid Crystals, the more specific situation of waveguides can be found in the references [7–10]. First of all, the scattering with changing of the polarization state between ordinary (o-wave) and extraordinary (e-wave) types is weaker compared to the forward scattering of an e-wave into e-waves. The polarization dependence of the scattering cross-section can be conveniently approximated by $(i_x s_z + i_z s_x)^2 + (i_y s_z + i_z s_y)^2$ where **i** and **s** are unit vectors determining the polarization state of the incident and scattered light, respectively, [2]. The z-axis of the Cartesian coordinate system is chosen along the optical axis of the NLC, (Fig. 2).

The extinction constant of the NLC for an incident o-wave, $\sigma^{(o)}$, only slightly depends on the angle α between the director and propagation direc-

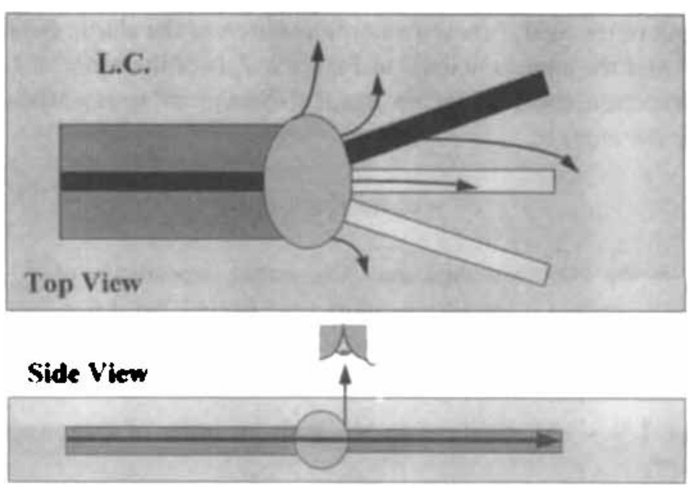

FIGURE 1 Principle of leakography: a schematic coupler device is sunk in a Liquid Crystal bath greyish), the beam travelling through this device (black) is leaking out (black curved lines; these secondary beams are scattered in the LC and thus are visible.

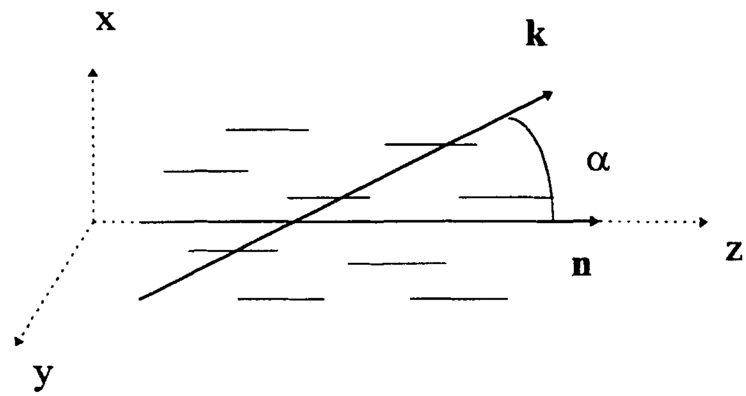

FIGURE 2 Light scattering in NLC: the unit vector **n** shows the orientation of the optical axis of the NLC; **k** coincides with the propagation direction of the incident light in the NLC.

tion of the incident beam and, with good accuracy, can be estimated as

$$\sigma^{(o)}(\alpha) = \frac{\pi k_B T \varepsilon_a^2}{\lambda^2 K n_o n_e} f_o(\alpha) \equiv \sigma_o f_o(\alpha) \tag{1}$$

where $k_B = 4 \times 10^{-14}$ erg/K is the Boltzmann's constant; T is the absolute temperature; K is the elastic constant of the NLC; $\varepsilon_a = n_e^2 - n_o^2$ is the anisotropy of the dielectric constant of the NLC at the light frequency; λ is the wavelength of the light, $f_o(\alpha)$ is a smooth function of the elastic constants of the NLC and the angle α defined in Figure 2; f_o is of the order of 1, [9].

The extinction constant for an incident e-wave $\sigma^{(e)}$ is essentially determined by the angle α:

$$\sigma^{(e)} = \sigma_0 \sin^2(2\alpha) \ln(L/\lambda) \tag{2}$$

where L is the NLC-cell thickness. The actual dependence of $\sigma^{(e)}$ on the incidence the angle α is remarkably more complicated, but it does not change neither the character of the dependence (2) nor its order of magnitude [9].

Let us stress out three important features of e-wave scattering.

1) In case $L/\lambda \sim 100$, $\sigma^{(e)}$ turns to be about an order of magnitude larger than $\sigma^{(o)}$;
2) Even if $\sigma^{(e)}$, depends on the LC layer thickness, it is an extremely weak dependence and can be neglected in actually all situations;
3) $\sigma^{(e)}$ is maximum at $\alpha \sim 45°$.

Equation (2) describes only the strongest part in the scattering cross-section which is due to an incident e-wave scattering into an e-wave and the corresponding scattering does not vanish at $\alpha = 0$ or $\alpha = 90°$. The case $\alpha = 0$ is identical with the case of o-wave scattering: for propagation along the optical axis of the medium, the difference between the o- and e-waves disappears, and $\sigma^{(e)} = \sigma^{(o)}$. The last relationship holds with good accuracy also for the case $\alpha = 90°$. Equations (1) and (2) allows us to evaluate how the scattering is modified by all the physical parameters that influence on it. Namely, the variations in the temperature, the strains and deformations are reflected in the changes of the refractive indices of the material of the fiber and the LC, as well as influence on the orientation of the latter and these correlations are the keys to properly decypher a 'Leakograph'. As it can be seen on the Figure 1, what is observed through leakography is mainly the light scattered at right angle: a more specific study of such a scattering geometry will be presented in a forthcoming paper.

EXPERIMENTAL

Let us first illustrate our purpose by looking at some photographs of scattered light (shortened as 'leakograph' in the following). On the first one (Photo 1) is shown most of the interesting features of what we call leakography. The system is a fiber roughly tapered (see below for some technical characteristics), embedded in a nematic liquid crystal which is itself contained in a capillary. The beam leaking out of the fiber is clearly visible and can be traced out. Also, the different bright spots reveal the imperfections and the impurities of the tapered region: a quite large area can be checked in one shot. On the second leakograph (Photo 2), it can be seen a strongly bent fiber: the beam can be easily traced out first in the core of the fiber and second its leaking out of it. On the third leakograph (Photo 3) the coupling in between two bend tapers is clearly visible, only few bright spots reveal some impurities. On these two last photographs, the fibers have been exaggeratedly bent for the leakography demonstration.

Let us now focus on the taper characterization using leakography. A taper is a narrowed part of a fiber obtained by simultaneously pulling and heating it locally. The guiding properties of a taper depend on its geometry: new radii of the core and cladding, length and shape of the narrowing. In such a tapered region, it is in fact hard to define the core and cladding parts of the fiber. The guided wave is no longer confined in the thin central part of the fiber and penetrates deep into the cladding. Its transverse size

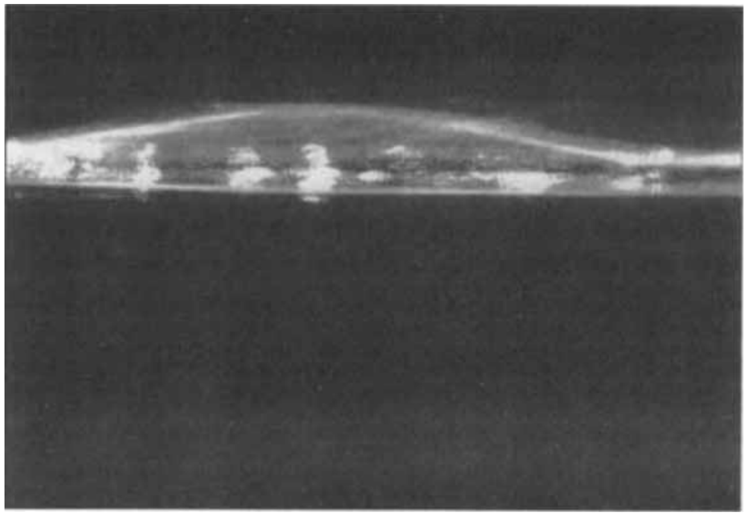

PHOTO 1 Experimental observation of the tapered region corresponding to Figure 3 with no heating (nematic phase present only). Bright spots reveals impurities.

increases during propagation in the taper and, eventually, splits into a number of modes some of which becoming leaky [11–12]. In a previous paper [11], it has been shown how the waist of the propagating beam in the taper can be derived from the angle of emergence of the beam, measuring it from a leakograph of a cleaved taper sunk in a LC matrix. Besides the waist and radii which determine the propagation property after the taper, another characteristic is the angle of emergence of the leakage out of the taper which is an important parameter in coupling applications: an image processing can give quite readily this angle (see for instance Photo 3). To illustrate this, we present some experiments we have undertaken to study the tapers, after having noticed that all the collected informations depend on the value of the indices and especially on that of the external material. If one puts a birefringent material, it will be possible to extract more informations on the polarization of the leakage and thus on the modes. Therefore in leakography, besides the strong scattering, the birefringent nature of the liquid crystal can play an interesting role.

What we present in this paper is the way the leakography has been used to study the tapers: the results by themselves (calibration and standardization of our tapering machine) are beyond the scope of the paper. In the experiments, the taper under study is arranged in a capillary embedded by a NLC. The fibers are tapered with the aid of a splicer (Erickson FSU 925).

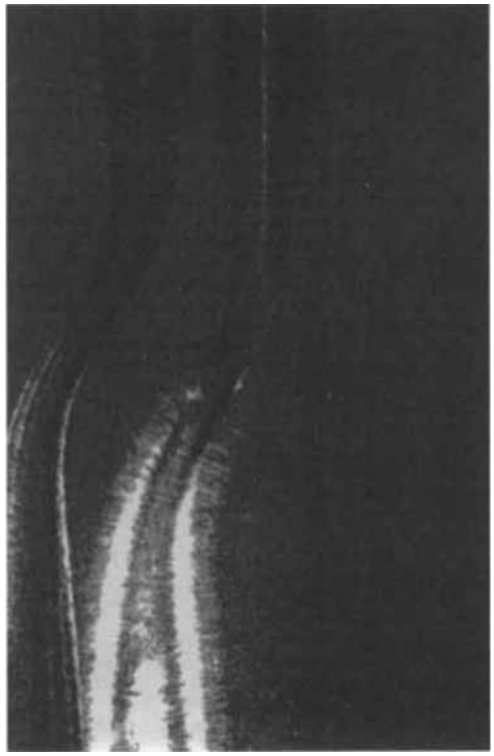

PHOTO 2 Leakograph of a bend taper.

The NLC is a special mixture of OS 33 and OS 53 (Merck) chosen for small values of its refractive indices comparable with the refractive index of silicon at room temperature: $n_e = 1.496$, $n_o = 1.458$ for the red wavelength $\lambda = 630$ nm [13, 14]. Let us mention also the importance of using low refractive index NLC to prevent violation of waveguiding conditions and excess leakage [15–17].

The internal diameter of the glass capillary is 250 μm. The walls of the capillary have been treated with lecithin to ensure radially symmetric homeotropic orientation at the capillary walls. The following arrangement allowed us to demonstrate clearly the principle and the power of LC-Leakography. Namely, a heating coil has been placed over the one side of the capillary to induce a temperature gradient along the fiber, Figure 3. Thus, the NLC was heated up to the isotropic state closer to the coil region, and the nematic phase was maintained further from the coil, due to the temperature gradient. The transition point from the isotropic to the nematic

PHOTO 3 Visualization of coupling between fibers through tapered regions.

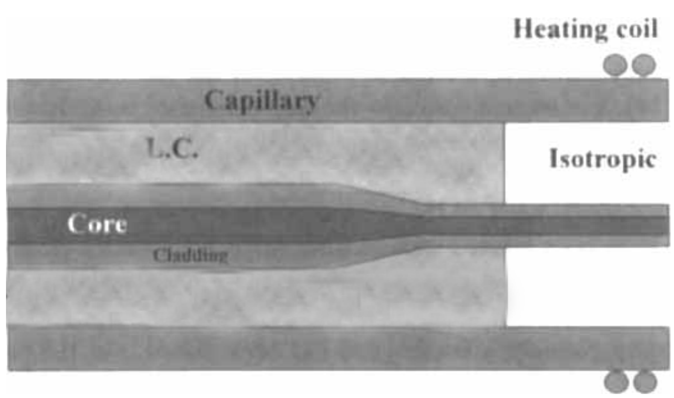

FIGURE 3 The experimental set-up used to study the taper: a capillary is filled with a LC and the fiber is insered in it; an heating coil can be placed to heat the LC and get the isotropic phase in some place.

phase was arranged to be close to the center of the tapered region, actually, it can be positioned wherever we want by adjusting the electrical intensity. A microscope positioned on top of the tapered region allows to view it.

The radiation of He–Ne laser ($\lambda = 633$ nm) was coupled into the fiber by focusing it upon one of its cleaved ends. The coupling efficiency was about 33%, and 3 mW of laser power was measured at the output of the fiber.

The observed picture presented in Photo 4 looks highly unusual: light wave is leaking out of the taper, propagates in the nematic medium, undergoing reflections on the internal surface of the capillary and on the interface nematic – isotropic and disappear. Actually, since the scattering of light is negligibly small in this region, the wave still propagates in the isotropic region and is visible only when travelling through the region of the nematic phase. This is presented schematically in Figure 4.

It is worth noticing that in most of the leakographs, the path of the beam is well defined and provided the precise knowledge of physical properties of NLC and its orientation, it will allow analysis of the optical properties of tapered and other kinds of complex regions in fibers and around them. On the contrary, such an opportunity of tracing the beams in the birefringent material can help in determination of the structure of this material: a forthcoming paper will be devoted to this special topic.

Due to longer wavelengths, infrared radiation is weaker scattered by the fluctuations of the NLC director, but the scattering it is still orders of

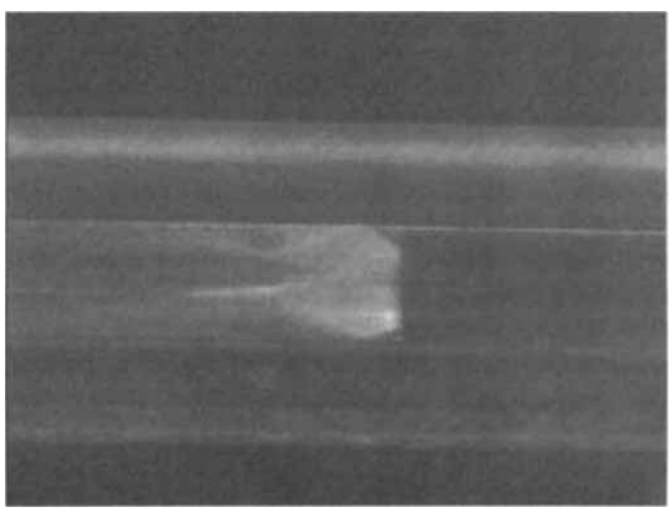

PHOTO 4 This leakograph of a tapered fiber in a glass capillary tube demonstrates the path of the leaking beam and reveals heterogeneity in the tapered region.

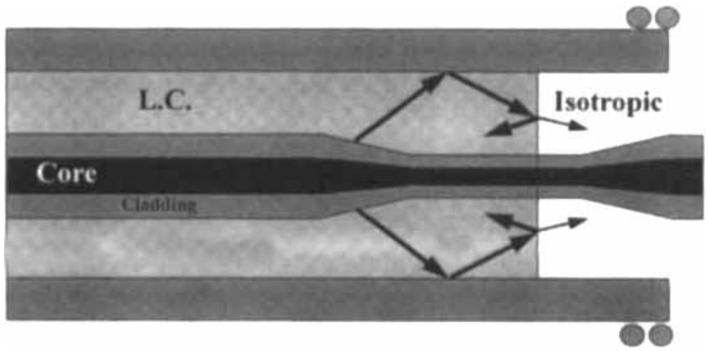

FIGURE 4 Schematic view of the photo 4. The ordinary index of the used nematic is lower than the cladding one: there is only the 'extraordinary' beam that is leaking out of the taper.

magnitudes stronger compared to other materials. Obviously, an infrared camera will be required for the extension of the method to the infrared region of wavelengths.

CONCLUSION

Thus, the phenomenon conventionally regarded as the main obstacle for the use of LC in fiber optics [7, 8], can find unexpected and important application: a thin layer of NLC which can be easily 'dropped' on any surface due to its small viscosity plays a role of a 'streak camera' for the light leaking from the microscopic regions of fiber optics systems of arbitrary geometrical shape.

Such a visualization of light leakage can be applied, particularly, for control of fiber alignment, automatization of coupling of radiation into and out of the fibers, for the detection of undesirable inhomogeneities, stresses and impurities in fibers and substrates, and for the detection of leakage from curved regions of fibers. By that the method allows coverage and check of extended fiber regions with varying geometrical shape which is hardly possible to carry out by other methods.

Technical realization of the opportunity we have found out requires additional studies for each particular situation. Certainly, whole regions of fibers can be covered by LC in special test baths like hollow core tubes we have used. It is important to note that such procedures would mostly be required only for the test, alignment and the study of the system, and the fibers and fiber network components shall not necessarily operate in an LC environment. However, even if constant monitoring is required for special applications, LC-based complex polymeric coatings can be designed for such purposes.

Additionally to the application discussed above, high sensitivity of the LC-orientation to the physical properties of surfaces can be utilized for visualization of surface anisotropy, inhomogeneities, stresses and charges [17], and can be developed to become an important method for the control of processes and technologies of fiber and waveguide manufacturing.

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