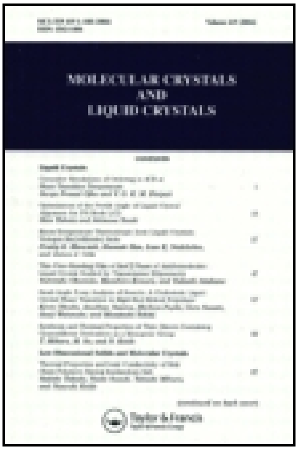

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Smectic Liquid Crystal Waveguides with Cylindrical Geometry

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Smectic Liquid Crystal Waveguides with Cylindrical Geometry

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We have shown that the homeotropic alignment of smectic-A liquid crystals inside a ~150 μm diameter glass capillary satisfies the classic Frank solution. Optical loss as low as 1.7 dB/cm, including interface losses, has been obtained from these waveguides. Very interesting multimode propagation characteristics have been observed and are compared to similar waveguides filled with nematic liquid crystals.

I. INTRODUCTION

It has been suggested[1,2] that homeotropically aligned smectic-A liquid crystals in a cylindrical configuration would prefer the Frank solution[3] with an isotropic core, instead of the nonsingular transition found in the nematics.[4–6] For the latter, the molecular directors rotate through 90° from perpendicular to the wall to parallel to the axis over a broad region. Homeotropic alignment of the smectic-A in a cylindrical structure has never been reported. The alignment of the liquid crystals in a waveguide is critical in determining the index profile of the guide since liquid crystals are highly birefringent. Modulation of liquid crystal alignment through electrical or optical fields results in modulation of the index profiles and hence the light propagation properties in the waveguides. Many electro-optical and opto-optical devices are conceivable depending on the sensitivity of the modulation to the external fields.[7]

We have recently made liquid crystal cylindrical waveguides with low optical loss, which allow us to systematically study the physical, electro-optical and opto-optical properties of these structures. Unique behaviors under heat treatment and interesting light propagation characteristics in the smectic and nematic liquid crystal cylindrical waveguides have been observed. In our study of the smectic-A, 8 CB (4-cyano-4′-octylbiphenyl), cylindrical waveguide, we have shown that the homeotropic alignment satisfies the classic Frank solution. The molecular directors of the 8 CB liquid crystals are confined to the radial plane, and at the center of the waveguide, the free energy diverges and the liquid crystals form an isotropic core. This result is rather surprising considering the large radius (75 μm) of the waveguide. The corresponding radial index profile of the waveguide has a lower index core and a constant index annular profile, thus providing a unique type of waveguide geometry for optical study. In this paper, we will focus on the supporting evidence that shows the smectic liquid crystals oriented homeotropically inside the cylindrical structure indeed satisfy the Frank solution.

II. WAVEGUIDE STRUCTURE

The single-channel guided structure was made of quartz capillary with an index of 1.4585 and an inner diameter of ~150 μm, typically 50 mm in length. These were filled with the smectic 8 CB or several nematic liquid crystals and aligned homeotropically with respect to the inner wall of the capillaries. Our study was conducted at room temperature (23°C), at which 8 CB is in the smectic-A phase. After filling the capillaries with the liquid crystals, optical glass fibers of smaller diameter were inserted into each end. The optical fibers, with the plastic buffer stripped off, were in optical contact with the liquid crystals to maximize coupling of light into and out of the waveguide. We found that the optical fibers were essential for isolating the optical effects contributed by the liquid crystal core. The glass fibers were cemented to the capillary with an epoxy, sealing the liquid crystals inside the capillary. The assembly was mounted onto a glass plate for ease of handling. A schematic of the waveguide structure is shown in Figure 1. The alignment of the liquid crystals and light propagation through the waveguide was observed under a high-power polarizing microscope with the capillary immersed in an index-matching fluid sandwiched between glass plates.

III. ALIGNMENT STUDY

We were able to obtain good alignment in the capillaries using the cleaning procedure outlined in Reference [8], followed by coating the inner walls of the capillary with alignment agents such as cetyl trimethyl ammonium bromide (CTAB) or trimethoxysilyl propyldimethyl octadecyl ammonium chloride (silane, Dow Corning X1-6136). In contrast to the intense Rayleigh scattering patterns reported elsewhere,[4-6] which we also observed in the capillaries filled with nematic liquid crystals, the alignment result in the smectic-A 8 CB was dramatically different. There was a complete absence of the Rayleigh scattering pattern and the presence of a tightly defined core region (see Figure 2).

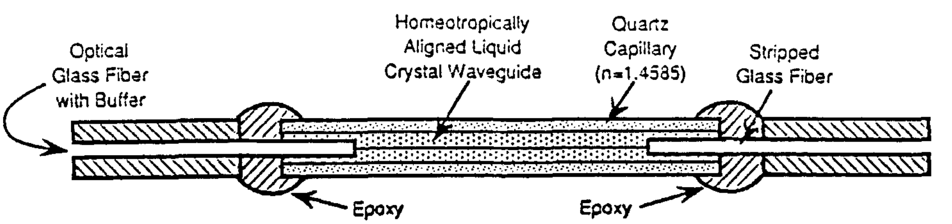

FIGURE 1 A schematic of the cylindrical liquid crystal waveguide structure.

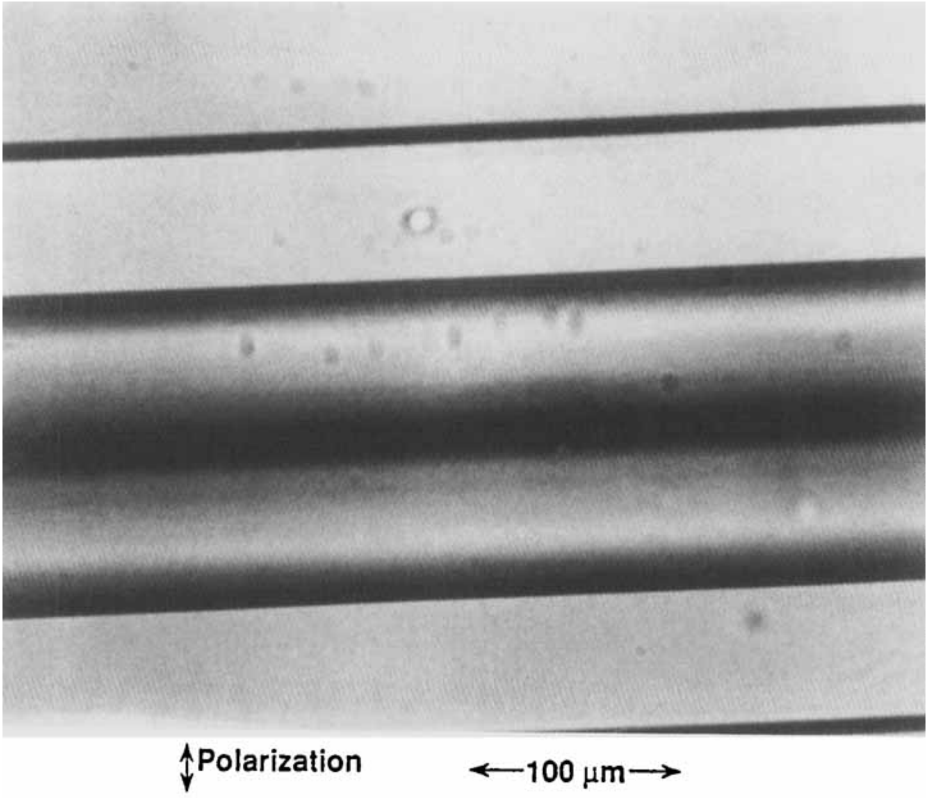

FIGURE 2 Light transmission through smectic liquid crystal waveguide with cylindrical geometry focused slightly above the diametrical plane. Polarization of incident light is perpendicular to the cylindrical axis.

The incident light in Figure 2 was polarized perpendicular to the axis of the waveguide. The bright and dark areas in the waveguide represent concentration and bending of light into and away from those regions respectively. The bright areas on both sides of the waveguide indicate concentration of light due to the higher refractive index in those regions compared to the lower refractive index of the capillary and that of the core region. Because of the cylindrical structure, the index contrast results in a positive lensing effect near the glass/liquid crystal boundaries. The liquid crystals were homeotropically aligned in the region between the core and the wall so that light polarized perpendicular to the axis is parallel to the molecular director in the diametrical plane and sees an effective index, $n_e = 1.6971$. On the other hand, polarized light passing through the small section containing the core region is perpendicular to the liquid crystals in the homeotropic region and sees an effective index, $n_0 = 1.5142$.

Based on Figure 2 alone, it was not possible to determine if the core was isotropic or nematic in alignment since in both cases the light would see a lower index than n_e. However, as the polarization of the incoming light was rotated to become parallel to the axis, as shown in Figure 3, the core region almost disappeared and the dark bands in the homeotropic region also diminished significantly. With this

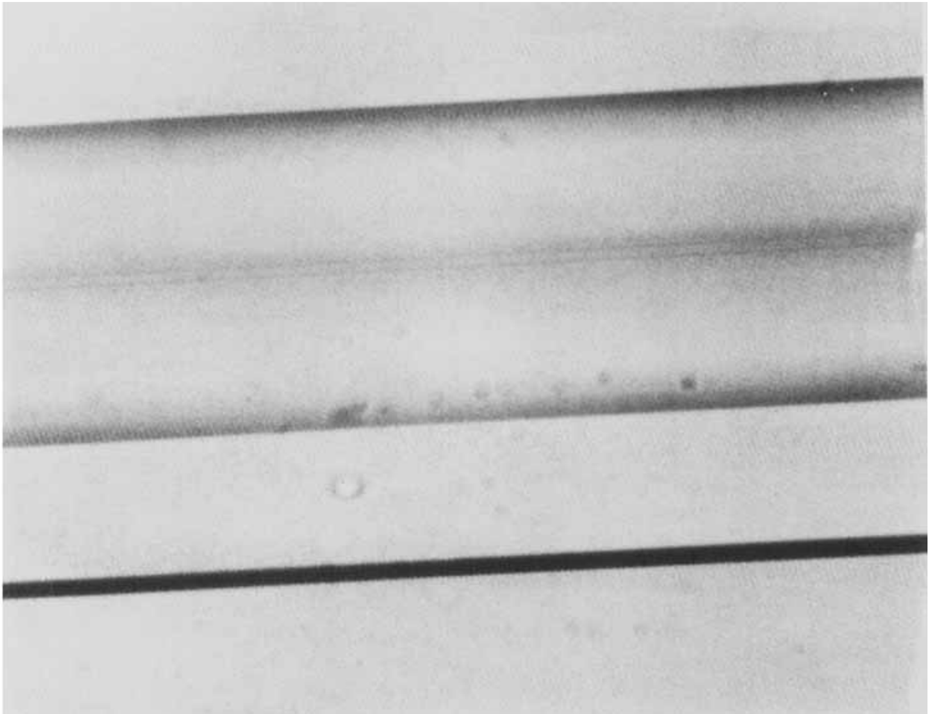

FIGURE 3 Same as Figure 2 except the polarization of light is parallel to the cylindrical axis.

polarization, the incident light is always perpendicular to the directors in the homeotropic region and hence experiences a lower index, n_0. If the core region were nematic, this polarized light would be parallel to the director and would see a higher index n_e, which would show up in the micrograph as a brighter region and dark bands showing bending of light toward the higher index region. According to the micrograph there was almost no distinction between the core region and the homeotropic region, showing that the index contrast between the homeotropic region and the core was very small. This could only be the case if the core were isotropic. Therefore, we conclude from the polarizing micrographs that the smectic-A waveguide has an isotropic core.

It has been postulated that a smectic-filled cylindrical structure could have an isotropic core even for relatively large physical dimensions. However, no prediction of the size of the cylinder nor the isotropic core radius was given since the actual magnitude of the bend-elastic constant, K_{33}, was unknown. On the other hand, knowing the core radius, the bend-elastic constant can be determined by considering that the core thermal energy should be offset by the elastic energy at the core boundary. For example, it can be shown[4] that $r_p = \sqrt{(K/2E)}$ where K is the elastic constant and $E = NK_B\Delta T_c$ is the thermal energy per unit volume; N is the number of molecules per unit volume, K_B is the Boltzmann constant; ΔT_c is the temperature difference between the clearing point and temperature of observation. In a nematic liquid crystal the elastic constant, K, is approximately 10^{-6} cgs, the derived core radius, r_p, is of the order of 55Å. In the smectic liquid crystal the elastic core energy per unit length, E_1, is given by[6]:

$$E_1 = (\pi/2)K_{33}\ln R/r_p \tag{1}$$

Dividing this by the area of the core $= \pi r_p^2$ yields the elastic energy per unit volume, which should equal the thermal energy per unit volume (neglecting latent heats). From this, the core radius can be expressed as:

$$r_p^2/\ln(R/r_p) = K_{33}/(2NK_B\Delta T_c) \tag{2}$$

Based on our observation of a core radius of ~1 μm and $R = 75$ μm, we estimate from Equation 2 the magnitude of K_{33} in the smectic phase to be $\sim 10^{-2}$ cgs. This is about 10^4 times larger than the splay elastic constant, K_{11}. This is in stark contrast to nematic liquid crystals where the ratio of K_{33}/K_{11} is of the order of unity.

IV. HEAT TREATMENT

As stated above, the local alignment of the cylindrical waveguide was excellent. The alignment along the entire 8 CB waveguide was dramatically improved when heat treatment was applied. As the temperature increased, the higher energy core region expanded toward the inner wall of the waveguide even though heat was conducted from the wall toward the center of the guide. As the core region expanded, we were able to observe more clearly the mesophases of the core region. As far as we could resolve, the core region appeared to be homogeneous and to lack the characteristic flickering of a nematic phase. This is further evidence that the smectic cylindrical waveguide has an isotropic core.

Overall misalignment in the waveguide disappeared as the 8 CB went through the smectic-isotropic transition. After heat was removed, as the capillary slowly cooled to room temperature, the wall regions went through the isotropic-nematic-smectic transition and the phase boundary slowly advanced toward the center of the cylindrical structure. Flickering of the nematic phase was clearly observed near the wall, but was soon replaced by the nonflickering, highly transmissive smectic-A phase. In some regions near the axis, a helical twist, perhaps of a bend-twist type ordering, was observed that finally stabilized to the tight isotropic core region shown in Figures 2 and 3. At the interface with the optical fiber, a singularity was created due to the tendency of the 8 CB to align perpendicular to the tip of the fiber as well as to the wall, which resulted in misalignment at the interface. The misalignment at the fiber/liquid crystal interface was the largest contributor to scattering losses measured in the 8 CB waveguide.

V. WAVEGUIDING PROPERTIES

Observations of the guiding modes in the smectic 8 CB filled capillary further substantiate the alignment properties of the smectic cylindrical waveguide. Comparison of multimode propagation characteristics of the nematic and smectic cylindrical waveguides shows that the ray trajectories, node spacing, mode coupling and linear losses are different from each other. The differences largely arise from the alignment of the liquid crystals and the resulting index profiles.

It was necessary to use a 20 mW cw HeNe laser to observe light scattered from the smectic waveguiding modes. After coupling into the liquid crystal waveguide, the laser yields an optical field intensity of approximately 40 to 80 W/cm^2, taking into account coupling loss at the input glass fiber. At this intensity, we should still be in the linear optical region in the waveguide since a typical nonlinear threshold for the giant nonlinearity[9] in liquid crystals is ~200 W/cm^2 using a cw laser.

Figure 4 shows the propagation of the light from the HeNe laser in the 8 CB cylindrical waveguide coupled through a glass fiber in a configuration described in Section II above. The ray trajectories are linear in the smectic 8 CB waveguide, showing a constant index profile in the homeotropically aligned region. This constant index profile is only possible if the directors of the 8 CB in the homeotropic

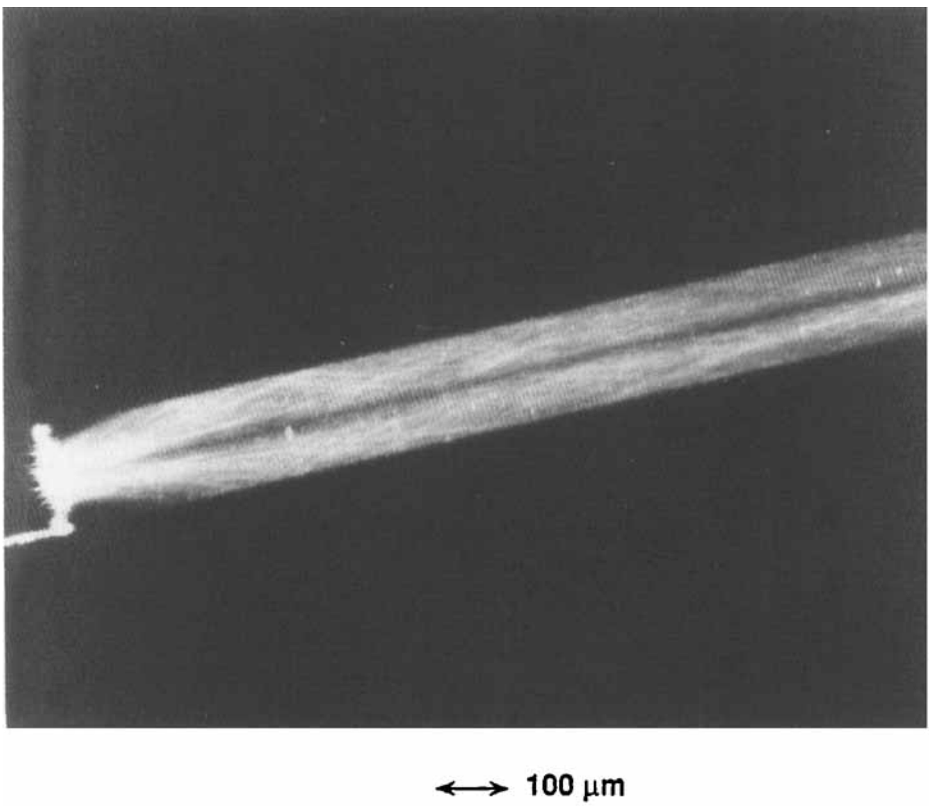

FIGURE 4 Propagation modes in smectic liquid-crystal waveguide near the optical fiber input.

region lie strictly in the plane perpendicular to the axis of the waveguide. Otherwise, the effective radial index profile would be strongly dependent on the radial position in the waveguide as in the nematic liquid crystal waveguide case. An index gradient in the homeotropic region would diffract the beam toward the higher index region, which is observed consistently in the nematic cylindrical waveguide. An example of the light propagation in the nematic waveguide is given in Figure 5 for the nematic liquid crystals E7 (a derivative of cyanobiphenyls). Clearly, the ray trajectories in the E7 cylindrical waveguide are highly nonlinear, with a definite curvature toward the waveguiding wall. Because of the alignment agent, the effective index of refraction near the capillary wall for linearly polarized light would be the highest and equal to n_e.

Furthermore, there is a well-defined core region in the 8 CB waveguide (Figure 4) in which all of the propagating modes are excluded, in contrast to the soft core region in the nematic waveguide (Figure 5). In fact, all of the ray trajectories or guiding modes in the 8 CB waveguide experience a clear internal reflection at the core/homeotropic boundary, showing the core region has a well-defined core radius with a lower refractive index than the annulus homeotropic region. Comparison of Figures 4 and 5 also shows that the node spacing in the nematic waveguide is smaller than that observed for the smectic. This implies that the propagation con-

FIGURE 5 Propagation modes in nematic (E7) liquid-crystal cylindrical waveguide near the optical fiber input.

stant in the smectic waveguide was approximately three to four times smaller than that in the nematic waveguides. The difference is related to the "step" index profile in the smectic versus a gradient index profile in the nematic waveguides.[10] This is in agreement with the alignment profile predicted by the Frank solution.

VI. LINEAR LOSSES

The intensity of scattered light from the smectic waveguide was much lower than that of the nematic. In the case of the nematic waveguide, we had to greatly attenuate the input laser relative to that of smectic waveguides in order to photograph the details of the propagation modes at the same exposure. There was also much less coupling between propagating modes in the 8 CB waveguides compared to the nematic waveguides. Reduced scattering losses in the smectic waveguide are thought to be due to the restriction of thermal fluctuations of the directors to splay distortion over large distances.[11] Mode conversion was identified to be the major intrinsic scattering loss mechanism in the smectic planer waveguide.[12] In the 150 μm cylindrical guide, we estimate that over 800 modes could be activated. Over a distance of several millimeters the propagation modes in the smectic waveguide were still distinct from each other showing little coupling among different modes. Most of the scattering losses were observed at the fiber/liquid crystal interface where the liquid crystals deviate from radial alignment.

The linear losses in these waveguides were measured against a similar waveguide filled with a high-index isotropic fluid. A synchronously chopped 1 mW HeNe laser was used as source and a silicon photodiode was placed at the output end of the glass fiber. The signal from the detector was fed into a lock-in amplifier. We obtained 7.5% absolute transmittance in a 3 cm long smectic 8 CB waveguide compared to 25% absolute transmittance in the isotropic fluid. Therefore, the loss calculated over the smectic waveguide length of 3 cm, including interface losses, was ~1.7 dB/cm, which was comparable to the loss reported in the planar waveguide configuration.[12] As mentioned, much of the loss in the smectic waveguide was due to the misalignment at the input and output of the glass fiber and liquid crystal interface. Since the losses in the nematic waveguide were much higher, measurement was not as reliable. We estimate that the signal obtained was about 40 dB weaker than that from the smectic waveguide, and thus the loss in the nematic liquid crytsal waveguide was about 14 dB/cm. This value is again smaller than that reported in the planar waveguide.[13] It is expected that the loss in the nematic waveguide could be dramatically improved with an applied AC field perpendicular to the waveguide direction at frequencies above the realignment threshold. With an applied AC field, much reduced thermal fluctuation was observed, which implies that Rayleigh scattering losses would be suppressed. The results of the effects of applied fields will be reported in a future communication.[14]

VII. CONCLUSION

A novel smectic liquid crystal cylindrical waveguide was fabricated. We determined that the alignment of the smectic liquid crystal in the guide satisfies the Frank solution with an isotropic core based on the analysis of the polarized optical micrographs, heat treatment study and observations of the waveguiding properties. Given the low linear losses in these waveguides, nonlinear optical properties can be systematically studied. We believe that given the large nonlinearities in the liquid crystals and the low scattering losses, promising optical devices such as power or intensity limiters, frequency tuning of distributed feedback lasers, etc.,[7] may become realizable.

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