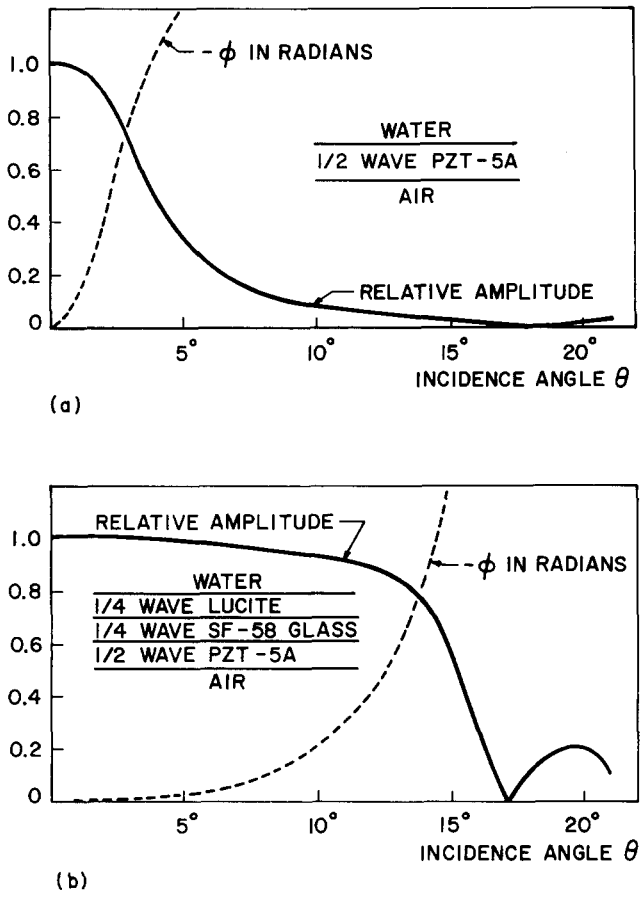

FIG. 2. Angular response of (a) unmatched, and (b) matched PZT transducers. Stiffened velocities and impedances are used.

angle $\theta = 0$ and the angular response at constant frequency ω. For the air-backed unmatched transducer of Fig. 1(a), the frequency response is very narrow band and one would expect a very narrow angular response. In the case of a transducer matched with multiple quarter-wave transformers, broad-band frequency response has been experimentally demonstrated.[7,8] Such structures should, then, also have a broad angular response.

For incidence angles appreciably different from zero, the effect of shear waves can no longer be ignored; and the transducer performance can be determined only from the computer solution. However, the conclusion that broad-band frequency response leads to broad angular response is still correct. Figure 2 compares the angular responses of an air-backed transducer with and without matching transformers. In the second case, up to $\theta = 15°$, the amplitude response is essentially uniform and the phase response $\phi(\theta)$ deviates from the ideal cosine law,

$$\phi = b(1 - \cos\theta),$$

by less than the 0.7 rad required for distortionless imaging.[6] This corresponds to a resolution of $(2\sin\theta)^{-1} = 1.93$ wavelengths in the water, which is sufficient for most imaging applications.

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Alignment of nematics and smectics on evaporated films*

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We discuss the alignment of nematics and smectics on substrates where an obliquely evaporated thin film has been previously deposited. In the planar samples, the surface anchoring energy is substantially larger than with the traditional rubbing technique. We can also uniformly align the liquid crystals obliquely, in particular by coating the evaporated film by a surfactant.

Janning[1] has indicated that a uniform alignment of nematic liquid crystals (N) contained between two parallel glass slides could be obtained if the plates were initially coated with a thin film evaporated under oblique incidence. Shortly after it was shown[2] that different alignments could be obtained depending on the value of the angle θ between the evaporation beam and the normal to the plates [Fig. 1(a)]. In this letter we give a sys-

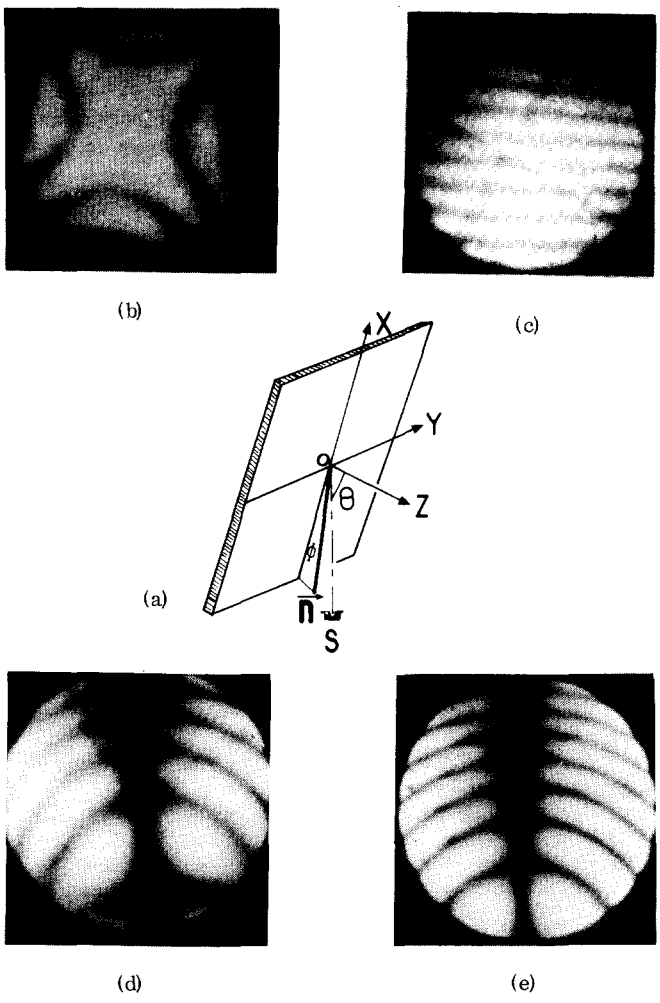

FIG. 1. (a) Geometry: θ is the angle between the direction of evaporation, S is the evaporation source. **n** is the director (case $\theta > 75°$). Conoscopic figures of uniaxial mesophases of BBOA obtained on evaporated plates. (b) $\theta \sim 60°$ planar orientation. (c) $\theta \sim 77°$ tilted smectic phase. (d) Plates coated with CTAB solution; nematic phase. (e) Plates coated with CTAB solution; smectic phase.

tematic report of this effect and extend it to the study of smectics (S).

The alignment is determined by the homogeneity of the microscopic image in polarized light and from the conoscopic image in converging light which is *needed* for an unambiguous determination of the alignment angle. The preparations reported are very reproducible and do not depend crucially on vacuum conditions (conventional diffusion oil system is used) or film thickness (average thickness $\bar{d}$ ranged from 50 to 1000 Å). Evaporated Au and SiO films were used with very similar results. Gold films are preferred if conducting electrodes are needed, whereas SiO gives more transparent layers.

The results of Ref. 2 obtained on MBBA have been extended to many different nematics and are summarized below.[3]

Where $40° < \theta < 75°$, the nematics align with the director **n** perpendicular to the plane of incidence of the beam and in the plane of the plate [direction Y of Fig. 1(a)].

The anchoring energy W erg/cm^2, which is a measure of torque required to turn the molecules in the plane of the plate from their preferred direction, can be estimated from a measurement of the width of disinclination lines attached to the plates.[4] Surprisingly it does not vary much with θ, and the unpinning of molecules from the preferred direction for low θ is obtained by losing the alignment over larger and large domains rather than by a progressive decrease of W. A typical value of $W = 0.6$ erg/cm^2 is larger by a factor of 10–100 than the value obtained with surfaces[4] treated by the Zocher-Chatelain[5] polishing technique. An estimate of W can be made using an elastic calculation by Berreman[6] who gives $W \sim 2\pi^3 \bar{K}(\delta d)^2/e^3$. The evaporated film thickness inhomogeneity δd was determined from grazing incidence x-ray scattering measurements.[7] For $\theta = 60°$ and a thickness $\bar{d} = 200$ Å, $\delta d \sim 100$ Å. The period e of the grooves in the film, statistically parallel to Y due to self-shadowing of grains,[8] is typically 200–400 Å.[9] Using an average elastic constant $\bar{K} \sim 5 \times 10^{-7}$ erg/cm, we get $W \sim 1$ erg/cm^2. This value, in agreement with our measurements, is larger by a factor 10 than that obtained by Berreman,[6] essentially because the period of the grooves, e, is much smaller than the value with rubbed plates. In addition to the simplicity and the reproducibility of the technique, the large value of the surface energy is an essential characteristic of this method. In particular, one is able to align nematics (tolanes) which could not be aligned in the planar state by the conventional rubbing method.

For angle values smaller than 40°, the liquid crystal (LC) does not align uniformly. However, the director remains in the XY plane (planar degenerate). This can be checked by measuring the capacitance of such a liquid crystal film as a function of a magnetic field parallel to Z. No distortion was obtained when the field was below the critical Freedericksz threshold. This demonstrates that the molecules were initially everywhere perpendicular to Z.

For grazing incidence of the evaporation beam, $\theta > 75°$, the liquid crystal aligns with its director in the plane of the beam but out of the plane of the plate and directed towards the evaporation beam. The angle of **n** with X, $\phi \sim 20$ to 30°, is relatively independent of the evaporation conditions as has been justified from an elastic model.[2]

The reliability and ageing properties of the evaporated plates were studied before and after filling with the LC. Systematic thermal cycling (~100 times) from room temperature to 250 °C did not affect the aligning properties of the plates when performed before the cell was filled, nor the alignment of the LC if the cell was filled before the cycling. Samples aged over one year did not show any appreciable decrease in the quality of the alignment. A given cell can be used several times after cleaning with toluene.

The study was extended to smectic phases where a uniform alignment with molecules in the plane of the plates (planar orientation) is difficult to obtain, even when it is obtained in the nematic phase of the same material. (The homeotropic alignment with molecules perpendicular to the plates is easier to get if surfactant agents are used.) In the case of a planar orientation,

the structural defects of the substrates have a dramatic effect owing to the very anisotropic elastic properties.[10] We found in fact that we could not align smectics except with fused or float glass plates which do not have small-scale defects. We also used optically polished copper blocks successfully.

The alignment was tested on three compounds: TBBA[3] which has S_A, S_C, and S_B phases, DOBCP which has S_C and N phases, BBOA which has N, S_A, and S_B phases. The S_C phases and the TBBA S_B are biaxial.

For evaporation angles $50° < \theta < 75°$, uniform planar alignment of the uniaxial phases, as determined from uniform extinction between crossed polarizers and from the typical hyperbolas of the conoscopic image [Fig. 1(b)], was obtained systematically in the various uniaxial mesophases. The anchoring is strong enough to accommodate a small relative twist to the limiting glass plates without losing the surface alignment. This result is of interest for the study of bulk defects introduced in smectics due to bend or twist.[11] In the S_A phase, the microscopic observations show some poorly contrasted traces of focal conics with very elongated ellipses parallel to Y. They do not seem to affect the orientation very much. The S_B phase shows less textures than the S_A and is better ordered.

When $\theta > 75°$, the conoscopic observation shows that $\mathbf{n}$ is out of the plane of the plates, as with nematics. There is no observable change in the conoscopic figure across the N-S_A transition. We have also checked independently that the birefringence does not vary strongly around the transition. Hence the angle is of the same order in both phases [Fig. 1(c)]. The conoscopic figure remains the same in the S_A and S_B phases.

With the same evaporation angle, we are relatively successful in getting a uniform alignment of the smectic C phase. By carefully cooling TBBA from the aligned oblique S_A phase, we get a uniform alignment in S_C over the whole sample (1 cm^2) with molecules out of the plane of the plates. Cooling very slowly the DOBCP nematic phase, the S_C appears with focal domains of area ~1 mm^2 at 45° from the direction of extinction in the nematic phase.

Finally we studied the influence of coating the evaporated surface by a surfactant agent: CTAB (cetyltrimethylammonium bromide). The coating is done by slowly pulling vertically the plates from the surfactant solution. If the concentration of the solution of CTAB is large enough,[12,13] a monomolecular layer deposited on untreated glass plates or evaporated plates with $\theta < 40°$ give an homeotropic alignment.

For intermediate evaporation angles ($\theta \sim 65°$), the orientation of BBOA mesophases is nearly homeotropic, apart for a very small distortion along the Y direction, independently of the direction of pulling of the plates. This indicates that the chemical mechanism is "stronger" than the elastic one. On $\theta > 75°$ evaporated plates, the LC optical axis is distorted in an appreciable way from homeotropic in the X direction [conoscopic images are shown in Figs. 1(d) and 1(e)]. In the nematic state, the distortion angle Φ is of the order of 70° when the plates are pulled from the solution along the Y direction, 85° when pulled along the X direction. (In both cases the angle in the smectic phase appears to be smaller by several degrees.)

Such a result can be of importance in increasing the sensitivity of devices which use the progressive distortion of homeotropic samples under electric or acoustic fields directed perpendicular to the plates. No threshold should be obtained if Φ is different from $\frac{1}{2}\pi$.

In order to understand and better control the mechanism of alignment, we are doing independent studies of the evaporated film properties: (a) scanning electron measurements in agreement with already reported results[8,14]; (b) grazing x-ray diffraction and diffusion measurements[6] which give access to the rugosity of the film; (c) surface area measurements from an anodic oxydation technique.[15] These results will be presented in a future report.

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