

EXPERIMENTAL STUDIES ON PHASE TRANSITIONS IN LIQUID CRYSTALS

by

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DECLARATION

I hereby declare that the entire work embodied in this thesis is the result of the investigations carried out by me independently in the Liquid Crystal Laboratory, **Raman** Research Institute, Bangalore, and that no part of it has been submitted for the award of any Degree, Diploma, Associateship or any other similar title.



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Certificate

I certify that this thesis has been composed by **Mr.D.S.** Shankar Rao based on the investigations carried out by him at the Liquid Crystal Laboratory, **Raman** Research Institute, Bangalore, under my supervision. The subject matter of this thesis has not previously formed the basis of the award of any Degree, Diploma, **Associateship**, Fellowship or **other** similar title.



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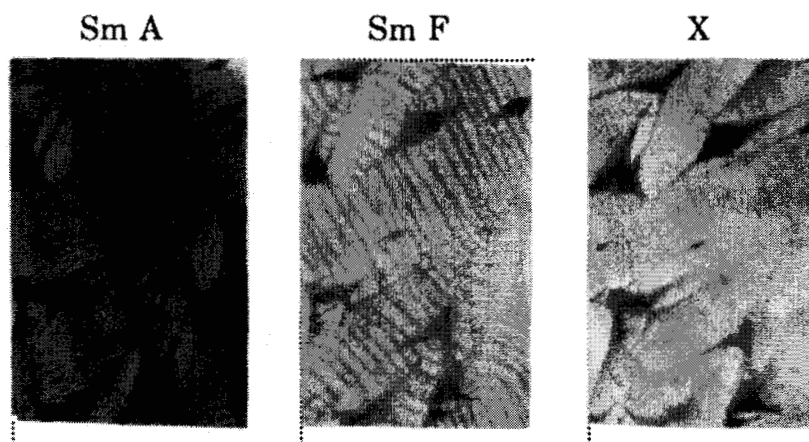
I thank all my friends at RRI who have helped in many ways and made my stay here most enjoyable.

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Cover photo: Optical textures for a compound with a novel phase sequence of Sm A - Sm F - X phases observed at high pressure (For details see chapter 7).

Chapter 1

Introduction

Liquid crystals represent states of matter in which the degree of molecular order is intermediate between the crystalline solid and the amorphous liquid.^{1,2} These states are strongly anisotropic in some of their properties like a crystal, and at the same time exhibit some fluid properties as well. Transition to these states can be brought about either by the effect of temperature or by the influence of solvents. The former is referred to as thermotropic mesomorphism and the latter lyotropic mesomorphism. In general, molecules exhibiting liquid crystalline phases are rod-like, but disc-shaped molecules³ are also found to show liquid crystallinity. This thesis deals only with thermotropic liquid crystals composed of rod-like molecules.

1.1 Classification of thermotropic liquid crystals

Thermotropic mesophases are broadly classified into three types: nematic, cholesteric and smectic.

1.1.1 Nematic

The nematic (N) phase has a high degree of long-range orientational order but no long range translational order (see figure 1.1a). The molecules are spontaneously oriented with their long axes parallel to some preferred direction referred to as the director, denoted by a unit vector \hat{n} . The preferred direction usually varies from point to point in the medium, but a uniformly aligned specimen is optically uniaxial, positive and strongly birefringent (Biaxial nematic phases have been discovered only very recently.⁴) The director \hat{n} is apolar, i.e., $+\hat{n}$ and $-\hat{n}$

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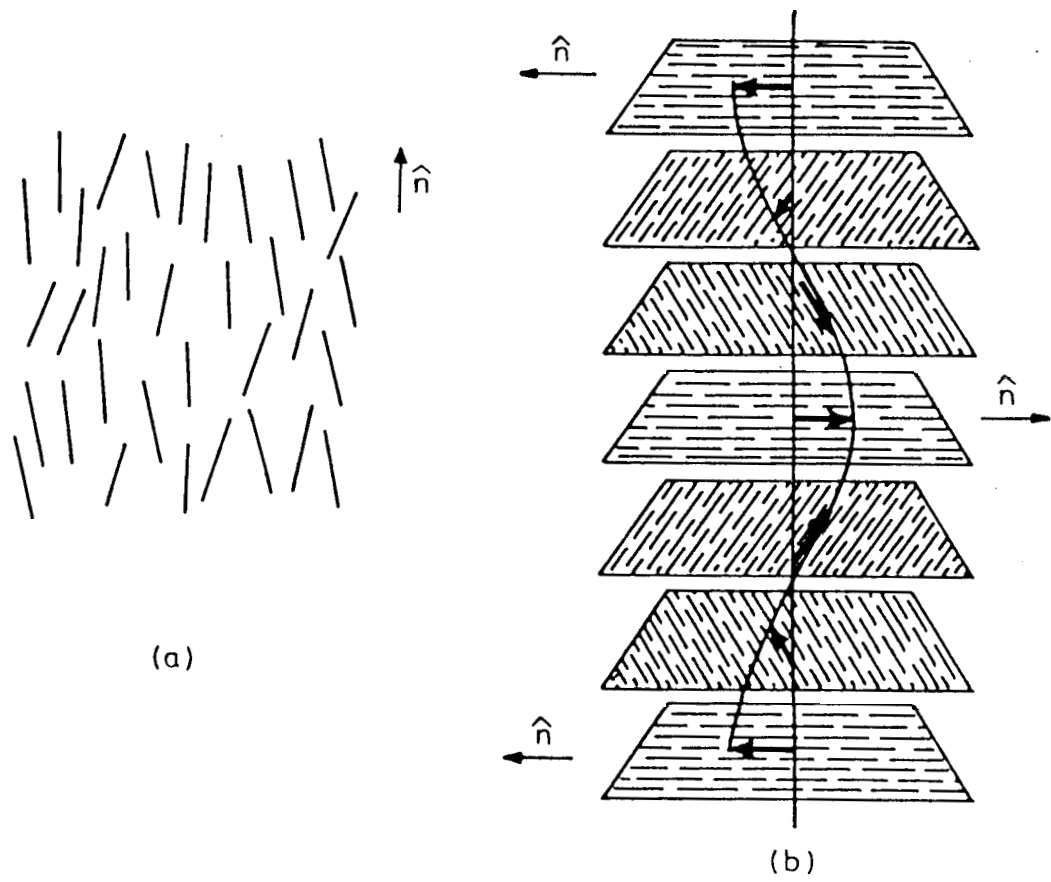


Figure 1.1: Schematic representation of the molecular arrangement in (a) nematic & (b) cholesteric phase. \hat{n} denotes the director.

are equivalent.

1.1.2 Cholesteric

The cholesteric mesophase, exhibited by materials composed of optically active molecules, is essentially a nematic except that its structure has spontaneous twist about an axis normal to the director (Figure 1.1b). The spiral arrangement of the molecules in the cholesteric phase is responsible for its unique optical properties like selective reflexion of circularly polarized light, very high optical rotatory power etc. Certain compounds showing the cholesteric phase also show additional phases called the blue phases. These phases exist over a small temperature range ($\sim 1^\circ\text{C}$) between the cholesteric phase and the isotropic liquid.⁵

1.1.3 Smectic

Smectic liquid crystals have a stratified (layered) structure but a variety of phases are possible with different inter- and intra-molecular correlations.

In the simplest case, smectic A phase (Sm A), the molecules are upright in each layer with their centres irregularly spaced in a liquid-like fashion (see figure 1.2).

The smectic A phase is best described as an orientationally ordered fluid on which is superposed a one-dimensional density wave along the optic axis, namely the layer normal.⁶⁻⁸ This one-dimensional mass density wave can be expressed as

$$\rho(r) = \rho_o \left[1 + \text{Re} \left(|\psi| e^{i(q_o z + \phi)} \right) \right] \quad (1.1)$$

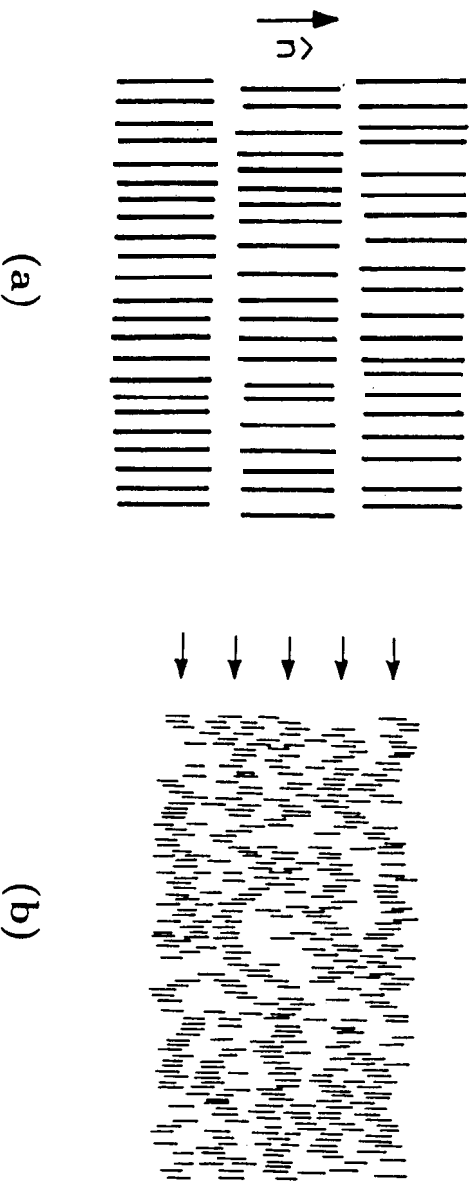


Figure 1.2: Molecular arrangement in the smectic A phase. (b) A realistic distribution of molecules in the smectic A phase. The arrows indicate the crests of the density wave. From R.Schaezting and J.D.Litster, *Advances in Liquid Crystals*, 4, Ed. G.H.Brown (Academic Press, 1979), p.147. \hat{n} denotes the director.

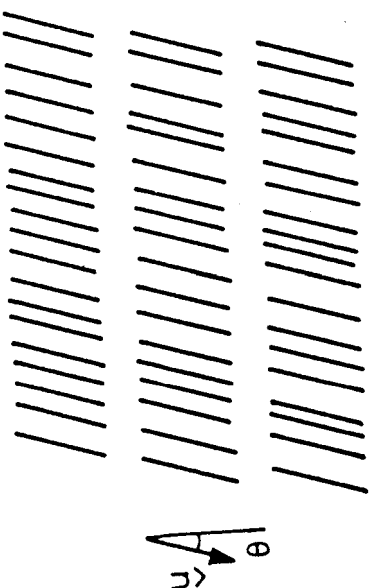


Figure 1.3: Molecular arrangement in the smectic C phase.

Here, ρ_o is the average density, $q_o = 2\pi/d$ where d is the layer thickness, ϕ is the phase factor fixing the position of the layers, $|\psi|$ is the amplitude of the density wave which is a measure of the strength of the smectic order.

Smectic C (Sm C) is the tilted form of Sm A, i.e., the molecules are tilted with respect to the layer normal (see figure 1.3). Arrangement of the molecules within a layer is liquid-like as in Sm A. The direction of the wave vector of the mass density wave is at an angle with respect to the layer normal. If the molecules are optically active then they form chiral smectic C or Sm C* phase. Due to the presence of chirality the azimuthal angle of the tilted molecules precesses from one layer to another giving rise to a helicoidal structure (Figure 1.4). The resulting structure shows ferroelectric properties.⁹

Smectic C phase is described by a two component complex order parameter,¹⁰ $\Theta = Be^{i\phi}$, where, θ is the tilt angle and ϕ is the azimuthal angle. Since ϕ can be chosen arbitrarily, θ is taken as the order parameter of the Sm C phase.

For a long time it was believed that only one type of smectic A phase exists, viz., the monolayer Sm A phase in which the layer spacing $d \sim l$, the length of the molecule. However with the synthesis of molecules having strong polar end groups several types of smectic A phases have been observed, referred to as partially bilayer Sm A_d, bilayer Sm A₂ and monolayer Sm A₁ depending on the extent: of interdigitation of the molecules in the neighbouring layers.¹¹ These phases are identified on the basis of the X-ray diffraction patterns exhibited by monodomain samples. (The molecular arrangement and the characteristic X-ray diffraction pattern of different smectic A phases are described in chapter 4). The

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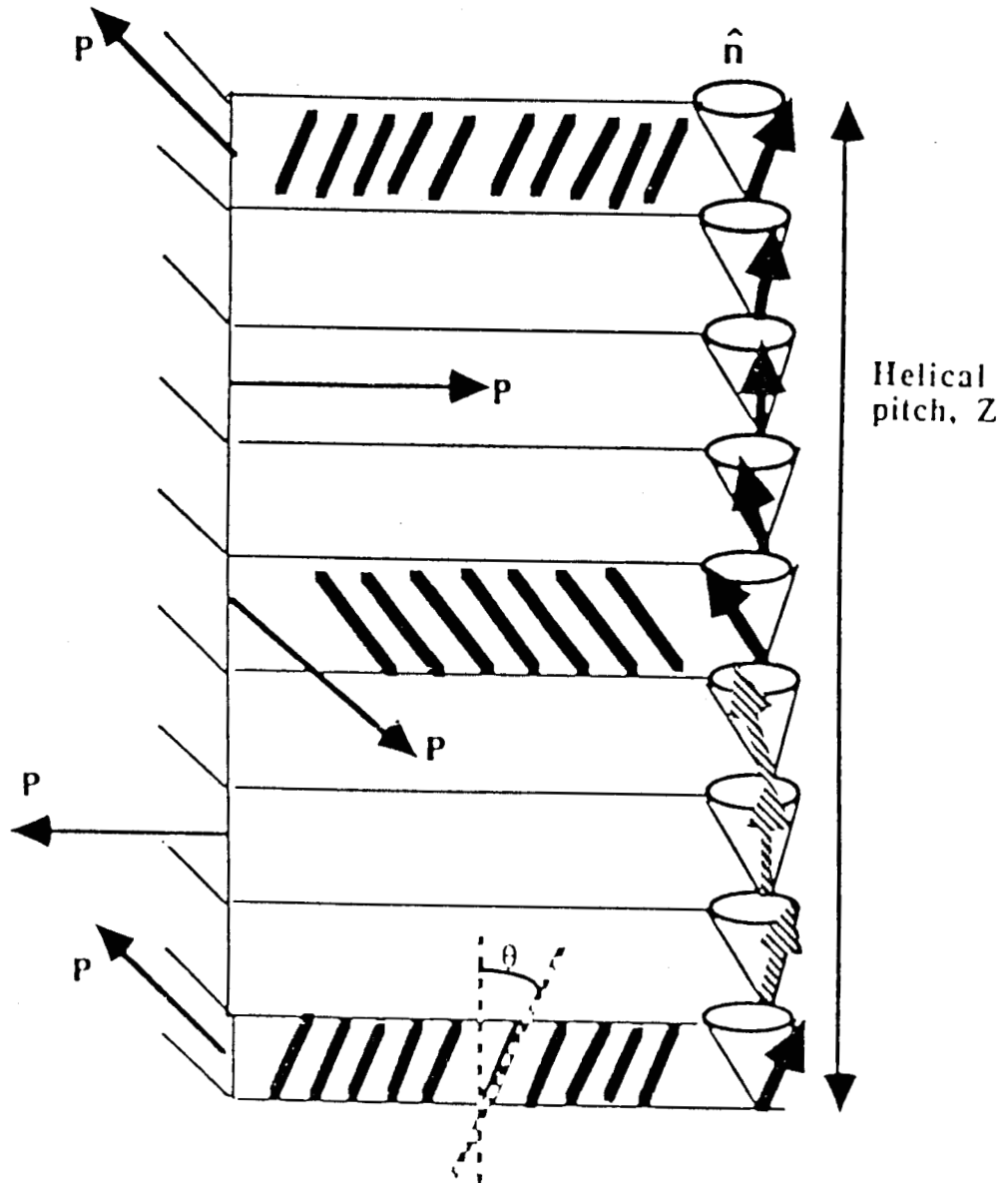


Figure 1.4: Molecular arrangement in the smectic C* phase.

corresponding tilted modifications are referred to as Sm C_d, Sm C₂ and Sm C₁ phases respectively.

Depending on the molecular arrangements within the layer and the extent of inter-layer correlations smectic mesophases are further classified into different types.¹² Over a dozen smectic modifications have been identified. Some of them (smectic B, smectic G, smectic J etc.,) have three-dimensional long range order as in a crystal, though with weak interlayer interactions, while others referred to as hexatic phases (hexatic B (hex B), smectic F (Sm F), smectic I (Sm I) etc.), possess three-dimensional long-range bond *orientational* order, but without any long-range positional order. (Bond orientational order (BOO) arises due to correlations in the orientation of the centres of neighbouring molecules).

1.1.4 Sequence of transitions

When a compound exhibits both nematic and smectic phases, then generally the nematic phase occurs at a higher temperature. Exceptions to this were discovered by Cladis¹³ in certain strongly polar materials. The first observations were on a binary mixture of two cyano compounds: over a range of composition the sequence of transitions on cooling was as follows:

isotropic+ N \longrightarrow Sm A \longrightarrow N_R \longrightarrow crystal

where N stands for the usual higher temperature nematic and N_R for a second nematic, called the *re-entrant* nematic which appears at a lower temperature. Later, a similar effect was observed in pure compounds at elevated pressures¹⁴ as well as at atmospheric pressure.¹⁵

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1.1.5 Nature of the phase transitions

Transition between these different mesophases can be either first order or second order. The change in the structure of the system when it passes through a phase transition is described quantitatively by the order parameter. It is defined in such a way that it takes a non-zero value in the ordered (or unsymmetrical) phase and zero in the disordered (or symmetrical) phase. For e.g., spontaneous polarisation is the order parameter for paraelectric-ferroelectric transition, magnetisation in the case of paramagnetic-ferromagnetic transition. A first order transition is characterised by the order parameter changing discontinuously, whereas across a second order transition it varies continuously from zero. Another interesting point is that a second order phase transition involves a change in symmetry between the two phases. This necessitates the condition that the symmetry of one phase is higher than that of the other. In other words, the *higher symmetry phase* has all symmetry elements of the lower *symmetry phase*, together with additional elements. Whereas in a phase transition of the first kind the change in symmetry of the body is subject to no such restrictions. Consequently the symmetries of the two phases could be unrelated or even same.

This thesis deals mainly with experimental studies across special types of points viz., critical point, tricritical point. In some cases a first order phase transition ends at a *critical* point beyond which there is no transition with one phase evolving continuously into another when parameters like temperature, concentration etc are varied. This situation is realised when the symmetry of the two phases involved are identical, as for e.g., in a gas-liquid type of

transition or in a paramagnetic-ferromagnetic transition in the presence of a nonzero applied field. A tricritical point is a point at which a second order phase transition crosses over to a first order one. Tricritical points have been found in He³-He⁴ mixtures,¹⁶ metamagnets,¹⁷ ammonium halides,¹⁸ ferroelectrics¹⁹ etc. Idcritical situations where a first order phase boundary ends up at a critical *point* followed by a continuous evolution region or crosses-over to a second order one with a concomitant tricritical point are realised in transitions involving different mesophases, some of which are described in this thesis. The overall contents of the six chapters are summarised in the following sections.

1.2 Phase diagram exhibiting smectic A - smectic C - smectic F meeting point

Since the proposal of dislocation-mediated melting in two dimensions by Kosterlitz and Thouless²⁰ there has been considerable activity in this field. Extending this two stage melting theory to liquid crystals, Birgeneau and Litster²¹ predicted a stacked hexatic phase, the existence of which was experimentally confirmed by Pindak et al.²² This phase referred to as hexatic B (hex B) exhibits long range bond *orientational* order (BOO) as in solids but short range positional order like a liquid. Smectic F (Sm F) and smectic I (Sm I) are tilted forms of hex B.¹² Theoretically²³⁻²⁵ a number of topologies for the phase diagram involving different hexatic phases have been worked out. Experimentally,²⁶ however, only a few have been studied. But no phase diagram with Sm A, Sm C and tilted hexatic phases have been studied so far. Chapter 2 presents optical and X-ray diffraction studies on a binary liquid crystalline system which led to the first

observation of a Sm A-Sm C-Sm F meeting point. Detailed description of the X-ray diffraction set up used is also given in this chapter.

High precision layer spacing measurements carried out on several mixtures showed that all the three phase boundaries, namely, Sm A-Sm C, Sm C-Sm F and Sm A-Sm F are first order near the Sm A-Sm C-Sm F meeting point. Hence the Sm A-Sm C-Sm F meeting point, a meeting point of three first order phase boundaries, is a triple *point*. An interesting offshoot of this feature is the observation of *tricritical point* on the Sm A-Sm C phase boundary. The Sm A-Sm C transition is first order for concentrations close to the Sm A-Sm C-Sm F meeting point. Whereas from earlier studies the Sm A-Sm C phase transition is known to become first order only when the range of Sm A phase is small²⁷ and/or the strength of the transverse dipole moment of the constituent molecule is large,²⁸ neither of these two factors seem to play a role in the present system. One possible reason for this could be the influence of the tilt field arising from the coupling between the BOO and the molecular tilt order parameter.

1.3 Effect of the smectic I* phase temperature range on the nature of the tilted fluid to hexatic transition

Owing to the existence of tilt, Sm C phase has induced BOO²⁴ albeit of small amplitude. Thus Sm C and Sm I (or Sm F) phases have identical symmetry. Consequently Sm C should transform to Sm I (Sm F) either through a first order phase transition or evolve continuously from one phase to another without a phase transition. This situation is similar to a gas-liquid transition or the paramagnetic-ferromagnetic transition in the presence of nonzero applied field.

It is very well known that in these cases, the first order phase boundary terminates at a *critical point* followed by a continuous evolution region. But such a critical point has not been seen in $S_m C$ -tilted hexatic ($S_m F$ or $S_m I$) systems. Chapter 3 discusses experiments carried out to search for a $S_m C$ - $S_m I$ critical point. Layer spacing measurements in the vicinity of $S_m C$ - $S_m I$ transition have been done on a number of compounds, three of them belonging to the same homologous series. Results showed that in these compounds for smaller ranges of the $S_m I$ phase, $S_m C$ phase evolves continuously into the $S_m I$ phase. With increase in the temperature range of $S_m I$ phase, both the total variation in layer spacing (Δd) and the strength of the variation $\Delta d/\Delta T$ increases. Extrapolating the results of the three homologues, it appears that with further increase in the temperature range of $S_m I$ phase, a *critical point* is likely to be reached followed by a region of first order phase transition. Measurements on other compounds indicate that the presence of a second hexatic phase i.e., $S_m F$ phase below the $S_m I$ phase also influences the nature of the transition. Thus the temperature range of the $S_m I$ (or hexatic) phase plays an important role in deciding the nature of $S_m C$ - $S_m I$ transition. A comparison between this scenario and a similar one proposed by Aharony et al.,²³ is also discussed.

1.4 Studies on smectic A - smectic A phase boundaries

Materials with strong polar end groups exhibit several types of smectic A phases with different periodicities, viz., $S_m A_d$ and $S_m A_2$, in addition to the monolayer smectic A ($S_m A_1$) phase which is also seen in non-polar molecules." The occurrence of these polymorphic forms of smectic A phases is successfully explained by

the phenomenological model proposed by Prost and coworkers.²⁹ They used this model within the framework of mean field theory to work out various theoretical phase diagrams.³⁰ One of the important predictions of these phase diagrams is the termination of the first order Sm A_d -Sm A_2 phase boundary at a *critical point*. The fact that Sm A_d and Sm A_2 have identical symmetry does not allow a second order transition between these phases. The first observation of a Sm A_d -Sm A_2 *critical point* was in a binary liquid crystalline system (11OPCBOB and 9OBCB) employing high resolution X-ray technique.³¹

Since the constituent molecules are polar and the extent of interdigitation of molecules in the neighbouring layers vary from one phase to another, one can expect the changes to be reflected in the dielectric measurements also. Earlier studies on materials having different smectic A phases have shown this to be true.³² Chapter 4 presents high precision dielectric measurements in the vicinity of Sm A_d -Sm A_2 critical point in the same binary system (as in Ref. 31). Results show that at the transition both ϵ_{\parallel} and ϵ_{\perp} , the dielectric constants parallel and perpendicular to the director, as well as the dielectric anisotropy $\Delta\epsilon (= \epsilon_{\parallel} - \epsilon_{\perp})$ exhibit sharp variation for a first order transition but a smoother change in the continuous evolution region. Detailed analysis of the data for several mixtures has enabled precise identification of the critical point.

Similar to the Sm A_d -Sm A_2 transition the Sm A_d -Sm A_1 transition can be either first order or of continuous evolution type without a phase transition.³³⁻³⁴ In this case the theory³⁴ predicts two different situations. The first order Sm A_d -Sm A_1 phase boundary can end either at a critical point similar to the Sm A_d -

Sm A_2 critical point or at a nematic island. Despite having the same symmetry, a transformation between Sm A_1 and Sm A_2 phases can be either first order or second order: the latter is possible due to the exact doubling of the layer periodicity.^{29–30,33–36} However, theoretical studies of Park et al.,³³ showed the possibility of a continuous path between Sm A_1 and Sm A_2 phases. The second part of Chapter 4 demonstrates the existence of such a *continuous thermodynamic path* between Sm A_1 and Sm A_2 phases. X-ray and optical studies show that this path, observed in the temperature-concentration plane of a binary liquid crystalline system, follows a continuous evolution from Sm A_1 to Sm A_2 via Sm A_d phase, thereby establishing that the global symmetry of Sm A_1 , Sm A_d and Sm A_2 are the same.

1.5 High precision density studies near the smectic A - nematic tricritical point

The N-Sm A transition is one of the most widely studied transitions in liquid crystals. It involves the development of a one dimensional density modulation in an orientationally ordered fluid. Transition between these two can be either first order or second order with a *tricritical point* separating the two regions. It is very well established that for a sufficiently large temperature range of the nematic phase, the nematic order is saturated and the transition is second order. When the nematic temperature range is reduced, the coupling between nematic and smectic A order parameter increases and drives the second order N-Sm A transition to first order. McMillan⁷ using a mean field theory predicted that a tricritical point should occur when $r = T_{NA}/T_{NI} = 0.87$, where, T_{NA} and T_{NI}

correspond to the N-Sm A and N-isotropic transition temperatures respectively. Earlier experiments³⁷⁻⁴⁰ have shown that a crossover from second to first order occurs at $r \sim 0.99$, a value much higher than theoretically predicted value of 0.87.

The measurement of density is a fundamental property in understanding the phase behaviour, and the continuity or discontinuity of the transition. Chapter 5 presents high precision density measurements (with a precision of $5 \times 10^{-5} \text{ g/cm}^3$) near the N-Sm A transition. Measurements were made using an Anton Paar instrument consisting of a microcell (DMA 602MH) and a processing unit (DMA 60). The principle of determining density involves measuring the period of oscillation of a hollow glass tuning fork filled with the sample to be studied. The compounds used were 9CB and its mixtures of different concentrations with the higher homologue 10CB, $X=0.04, 0.2$ and 0.3 where X is the mole fraction of 10CB in the mixture. 9CB has a small temperature range of the nematic phase viz., 2°C . This nematic range decreases on increasing X and finally it ceases to exist for $X > 0.35$. The results show that the thermal variation of the density (ρ) shows a slow decrease within the phase and changes abruptly at the transition. Although the variation of ρ across Sm A-N transition shows a concentration dependence, it was not significant enough to locate the tricritical point accurately. In order to achieve this, the critical part of density variation ($\Delta\rho$) was fitted to a power-law^{38-39,41} of the form

$$|\Delta\rho| = |\rho - \rho_0| = A_{\pm}|t|^{1-\alpha} \quad (1.2)$$

where $t = (T - T_{AN})/T_{AN}$ and ρ_0 is the value of ρ at T_{AN} , α is the exponent equal

to the heat capacity exponent.⁴² It was observed that equation 1.2 describes the data very well for 9CB and $X=0.04$ suggesting that the nature of the transition is second order. The observed exponents are $a = 0.43 \pm 0.01$ for 9CB with $r=0.994$ and $a = 0.5 \pm 0.01$ for $X=0.04$ with $r=0.995$. For $X=0.2$ and 0.3 with much smaller range of nematic phase, the data showed a clear deviation from the power law indicating that the transition is first order^{36,38} in these two mixtures. Thus the N-Sm A transition is first order for $X=0.2$ and second order for $X=0.04$ with $\alpha=0.5$, a tricritical value.^{1,43} Thus we conclude that $X=0.04$ is at or in the immediate vicinity of a tricritical point with $r = 0.995$, in excellent agreement with studies carried out using other probes.³⁷⁻³⁸

1.6 An experimental study of smectic A - smectic C transitions in monolayer, partially bilayer and bilayer systems

From symmetry considerations the transition between Sm A- Sm C can be either first order or second order. de Gennes¹⁰ described the Sm A- Sm C transition using a two component complex order parameter and proposed that it may belong to the 3D XY universality class. Subsequent studies¹¹ showed that the transition is mean-field like with a large sixth order term in the Landau free energy expansion. The presence of the sixth order term implies that the transition is always close to a mean-field tricritical point. Further, it is known that the tricritical influence is controlled by the temperature range of the smectic A phase²⁷ and/or by the strength of the transverse dipole moment of the constituent molecule.²⁸

Recent heat capacity measurements of Garland et al⁴⁵ have shown that for

two compounds exhibiting bilayer Sm A₂-Sm C₂ transition the behaviour is simple mean-field like, i.e., the contribution of the sixth order term is negligible. In the light of this it was felt that it would be interesting to *see* whether such a behaviour can be observed for materials exhibiting partially bilayer and monolayer phases also. Chapter 6 describes systematic order parameter (tilt angle) measurements in the vicinity of Sm A₁-Sm C₁, Sm A_d-Sm C_d and Sm A₂-Sm C₂ transitions. Thermal variation of layer spacing *d* has been measured in both Sm A and Sm C phases. The tilt angle θ in the Sm C phase was calculated using the expression $\theta = \cos^{-1}(d_C/d_A)$, where d_C and d_A are the layer spacing values in the Sm C and Sm A phases respectively. The temperature dependent tilt angle has been fitted to an extended mean-field model which incorporates a sixth order term in the Landau free energy expression. The analysis gives a remarkably high value of t_o ; $t_o = 1.5 \times 10^{-2}$, 9.45×10^{-2} and 1.57×10^{-1} in compounds having bilayer, partially bilayer and monolayer transitions respectively. t_o has been considered as an all important parameter in characterising the Sm A-Sm C transition. It defines the temperature range upto which mean field behaviour can be seen. Large t_o observed in all the three cases suggests negligible contribution from the 6th order term (i.e., a simple mean field behaviour). Data analysis shows that this is indeed true in all the three compounds. Another interesting feature is the observation of simple mean-field behaviour in a compound with a very small temperature range of smectic A phase ($\sim 3^\circ\text{C}$). In view of these studies a more general scenario can be predicted. If the material possesses bilayer phases then simple mean field behaviour can be observed for a small temperature of the Sm A phase while in the case of partially bilayer

Sm A_d-Sm C_d and monolayer Sm A₁-Sm C₁ transitions, the range has to be large to observe such a behaviour.

1.7 High pressure studies on materials exhibiting fluid to hexatic phase transitions in liquid crystals

High pressure studies on liquid crystals have enabled the study of a rich variety of phases and phase transition in liquid crystal systems. Some of the important results of these studies are pressure-induced mesomorphism, the appearance of re-entrant phases, observations of multicritical points etc., in single component systems.⁴⁶ But high pressure studies on systems involving the hexatic phase are very few (Ref. 47, 48 and G.G.Nair et al., of Ref. 26). Chapter 7 presents measurements performed with a view to investigating the effect of pressure on materials exhibiting fluid (Sm A, Sm C) to hexatic (Sm I, Sm F etc) phase transitions. An optical high pressure cell⁴⁹ was used for the experiments.

Results showed that Sm A and hex B phases are stable at high pressure in a compound with isotropic-Sm A-hex B phase sequence. With a tilted fluid-hexatic sequence at room pressure, the fluid (Sm C*) phase is seen to be unstable at high pressure. The increase in the stability of Sm A and Sm I* phases and the decrease in the stability of Sm C* phase at high pressure appears to lead to a Sm A-Sm C*-Sm I* meeting point.

Pressure induced mesomorphism has been observed in a compound with Sm A-Sm F-Cry G sequence at 1 bar. An induced phase ('X'-yet to be identified smectic phase) is seen beyond a pressure of 0.6 kbar between Sm F and Cry G

phases. With further increase in pressure Sm A and X phases were seen to be unstable leading to two triple points, viz., Sm A-Sm F-X and isotropic-Sm A-X. In an other compound with Sm A-Sm C-Sm F phase sequence the destabilisation of the Sm C phase at high pressure appears to lead to a Sm A-Sm C-Sm F meeting point.

These studies indicate that the type of bridging group in the molecular structure plays a role in the relative stability of different phases. In particular the Sm A and hexatic phases are observed to be more stable in materials with an ester linkage group in agreement with earlier experiments of Cladis et al.,⁴⁷⁻⁴⁸ whereas Sm A phase is unstable at high pressure in compounds with schiff base linkage group e.g., in 90.4, 50.6⁵⁰ and 40.8.⁴⁷

The results described in this thesis have been published in the following papers.

1. Phase diagram exhibiting a smectic A-smectic C- smectic F meeting point (in collaboration with V.N.Raja and S.Krishna Prasad), *Phys.Rev. A* 46, 726, (1992).
2. Effect of the I* phase temperature range on the nature of tilted fluid to hexatic transition (in collaboration with V.N.Raja, S.Krishna Prasad, J.W.Goodby and M.E.Neubert), *Ferroelectrics*, **121**, 235 (1991).

3. Dielectric behavior near a smectic A_d - smectic A_2 critical point (in collaboration with S.Krishna Prasad, V.N.Raja, S.Pfeiffer, S.Quentel and G. Heppke), *Mol.Cryst.Liq.Cryst.*, **198**, 291 (1991).
4. Continuous thermodynamic path between three smectic A phases of the same symmetry (in collaboration with S.Pfeiffer, G.Heppke and R.Shashidhar), *Phys.Rev. A* 46, 6166 (1992).
5. High precision density studies near the smectic A - nematic tricritical point (in collaboration with V.N.Raja, S.Krishna Prasad and S.Chandrasekhar), *Liquid Crystals*, **12**, 239 (1992).
6. An experimental study of the smectic A - smectic C transitions in monolayer, partially bilayer and bilayer systems (in collaboration with S.Krishna Prasad, V.N.Raja and S.Chandrasekhar), *Mol. Cryst. Liq. Cryst. Lett.* (in press)
7. High pressure studies of materials exhibiting fluid to hexatic phase transitions in liquid crystals (in collaboration with V.N.Raja, S.Krishna Prasad and S.Chandrasekhar), *Proceedings of 13th AIRAPT International Conference on High Pressure Sciences and Technology*, Bangalore, Ed. A. K. Singh (Oxford and IBH Publishing Company) p 520 (1992).

Other publications

1. Temperature range of the smectic **A** phase and its effect on the smectic **A** - smectic **C** transition (in collaboration with S.Krishna Prasad, V.N.Raja, Geetha G.Nair and M.E.Neubert), *Phys.Rev. A* 42, 2479 (1990).
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