

## CHAPTER. 2 REVIEW OF PREVIOUS WORK

- 2.1. Introduction.
- 2.2. Synthesis
- 2.3. Review of evaluation of material constants.
  - 2.3.1. Spontaneous polarisation.(Ps).
    - 2.3.1.1. Measurement of spontaneous polarisation.
      - 2.3.1.1.1. Electrical reversal of spontaneous polarisation.
  - 2.3.2. Rotational viscosity.
    - 2.3.2.1. Measurement of rotational viscosity.
  - 2.3.3. Dielectric constant.
    - 2.3.3.1. Measurement of dielectric constant.
  - 2.3.4. Tilt angle.
- 2.4. Electro-optic switching studies.
- 2.5. FLC light valves and modulators.

## REVIEW OF PREVIOUS WORK

### 2.1. INTRODUCTION.

This chapter gives a summary of major works related to the characterisation and electro-optical switching studies of ferroelectric liquid crystals. The discovery of ferroelectricity in tilted smectic phase by Meyer in 1975 [5] confirmed that as in solids, molecules can have spontaneous polarisation in the liquid crystalline phases also. This has stimulated many studies from both fundamental and practical points of view. The ultimate aim of all these efforts is the realisation of a ferroelectric liquid crystal display which can meet the stringent requirements such as quick response, good grey scale capability and contrast so that their performance is comparable to that of cathode ray tubes.

The main steps involved in the fabrication of such a ferroelectric liquid crystal device are

1. Synthesis of a ferroelectric liquid crystal compound that shows ferroelectricity at room temperature and has comparatively high value of spontaneous polarisation, low rotational viscosity. The identification of phases is also done at this stage .

2. Evaluation of material constants such as spontaneous polarisation, dielectric constant, rotational viscosity and tilt angle as well as designing a suitable cell geometry and developing an aligning technique to orient the molecules in the desired configuration forms the next step.

3. A detailed study of the dynamic electro-optic characteristics of the material such as rise time, decay time, bistability and grey scale capability under varying signal conditions are also carried out in this stage.

4. Finally an addressing technique which depends on the particular application and the material properties will be arrived at.

In the last seventeen years many results have been published in each of the above categories by a number of workers. Some of these important contributions, which are relevant to the present work, are reviewed in this chapter.

## 2.2. SYNTHESIS.

Display operation requires a chemically and photochemically stable ferroelectric liquid crystal with wide temperature range around room temperature. For individual compounds the range of ferroelectric liquid crystal phase is small and most of them are at higher temperatures. This problem was solved by making eutectic

mixtures of different compounds [8,9 & 10]. The dependence of material constants of these mixtures on the magnitude and direction of the spontaneous polarisation ( $P_s$ ) and pitch values were studied by Goodby and Leslie [11].

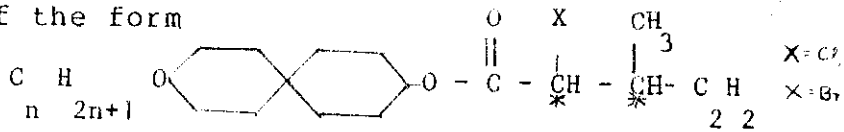
From Meyers arguments of occurrence of ferroelectricity in liquid crystals itself, it is understood that the extent of hindrance to the molecular rotation along its long axis is a measure of the magnitude of spontaneous polarisation. Based on this fact Uemoto et al. [12] synthesised a series of DOBAMBC type ferroelectric liquid crystal with higher number of carbon atoms ( $n$ ) in the alkoxy chain. They observed that for molecules with  $n < 5$ , value of spontaneous polarisation is very small. For  $n > 6$ , spontaneous polarisation was found to increase with the number  $n$  of carbon atoms, as the molecular rotation is reduced very much for these compounds.

Sakurai et al. [13] obtained high spontaneous polarisation values by using secondary alcohols as the chiral source of DOBAMBC type ferroelectric liquid crystal instead of primary active alcohols.

The increase in the value of spontaneous polarisation of these compounds is mainly due to the proximity of the chiral centre to the dipole.

Yoshino et al. [14] synthesised a series of

compounds of the form



The magnitude of spontaneous polarisation is 250 nC/sq.cm ie 20 orders of magnitude higher than that of DOBAMBC.

Recently R.J.Twieg et al. [15] synthesised a series of new ferroelectric liquid crystals characterised by the presence of a thioester core and an alkoxy carbonyl tail derived from a chiral 2-alkanol. Some of them shows spontaneous polarisation values of 220 nC/sq.cm at near room temperatures.

New ferroelectric smectic thiadaxosle derivatives synthesised by Tschieske et al. [16] gave spontaneous polarisation values of 350 nC/sq.cm. Due to the high value of spontaneous polarisation these ferroelectric liquid crystals can find application in high speed displays.

### 2.3. REVIEW OF EVALUATION OF MATERIAL CONSTANTS.

#### 2.3.1. Spontaneous Polarisation.

The potential application of ferroelectric liquid crystal materials in any device depends on the strength of spontaneous polarisation because an external field applied to such a material can couple with this polarisation. This interaction provides an additional driving force for the

molecular orientation other than the forces due to dielectric anisotropy.

### 2.3.1.1. Measurement of Spontaneous Polarisation.

The first estimate of magnitude of spontaneous polarisation was obtained from the measurement of the dc field ( $E_c$ ) necessary to unwind the helical structure [5].

$E_c$  is given by the equilibrium between the electrical energy and the elastic energy.

$$E_c = \frac{\frac{1}{2} K \theta^2 + \frac{1}{2} P_s q^2}{16 P_s}$$

where  $q$  is the helical wave vector. The value of  $K$ , an elastic constant is not known accurately. Hysteresis of unwinding and ionic screening of applied field causes errors in actual experiments.

To obtain a direct measurement of spontaneous polarisation, the sample is prepared in the planar configuration. On reversing the dipoles, which are perpendicular to the electrodes in this case, by some external fields and observing the current profile, then the integral of the induced current is  $2PA$  ( $A$  is the area of the specimen).

But difficulties arise from the large conductive and capacitive currents evolving along with the current due to spontaneous polarisation reversal. The total current  $I$  on the upper electrode can be written as

$$I = A \frac{dp}{dt} + \frac{A}{d} \frac{d(\epsilon U)}{dt} + I_{\text{ionic}} = I_p + I_c + I_i$$

$t$  is the time,  $\epsilon$  is the permittivity of the compound and  $U$  is the applied voltage.

The different electrical methods employed to evaluate spontaneous polarisation either compensate the capacitative current or separate the spontaneous polarisation current from the other components in time or shape. The shear and pyroelectric methods keep  $U=0$  so that  $I_i = 0$  and  $I_c = 0$ .

Yu et al. [17] and Blinov et al. [18] used pyroelectrical method for evaluating spontaneous polarisation. The sample is subjected to small periodic temperature jumps by means of laser pulses.

$$\text{Then } \int I dt = - A \frac{dp}{dt} \int dt$$

Where  $I$  is the current during one pulse.

This method avoids errors due to the induced polarisation and ionic currents. But for good results a perfect alignment is required and it is very difficult to determine the temperature dependence of spontaneous polarisation.

#### 2.3.1.1.1. Electrical reversal of spontaneous polarisation.

In these methods, an alternating voltage (pulse or

continuous wave) is applied to the specimen to reverse the spontaneous polarisation. It was first introduced by Martinot-Lagarde [19]. He applied a square wave voltage to the specimen in SmC\* state and the integral of the bump due to spontaneous polarisation reversal was calculated. The square wave produces a quick reversal of dipoles and hence a good time separation between the different current components. But due to the non-linearity of the ionic current it is very difficult to fix a base line as a reference for the measurement of the spontaneous polarisation current. Hence the values obtained are not matching with theoretical and other experimental values.

This ambiguity in fixing a base line was later solved mainly by two methods.

Miyasato et al. [7] showed that the non-linear behaviour of the background current can be avoided by using a triangular wave instead of a square wave. In this case the rate of variation of the applied voltage is low. Hence the bump due to the polarisation reversal appears on a straight base line. So the background current due to capacitative and ionic contributions can be directly subtracted to obtain the current due to polarisation reversal. Further it is easy to obtain a good high voltage triangular wave than a square one.



Sometimes, depending upon the alignment method and thickness, two or three bumps [20] are obtained due to the spontaneous polarisation reversal itself. In this case the integral of these bumps gives the spontaneous polarisation.

Skarp et al. [6] solved the problem of separation of the background current in a more rigorous method. They first considered a model of the ferroelectric liquid crystals placed between two electrodes. In the absence of spontaneous polarisation, it can be regarded as a capacitor (C) in parallel to a resistor ( $R_p$ ). (Fig.2.1).

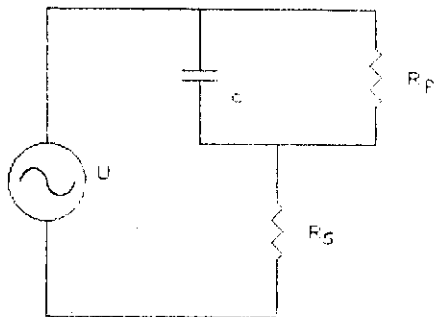


Fig. 2.1 Equivalent circuit of a FLC between two electrodes in the absence of  $P_s$

Hence when a square wave voltage  $U$  is applied the background current should obey the equation

$$C R_s \frac{dI}{dt} + (R_s + R_p) I / R_p = U / R_p + C \frac{dU}{dt}$$

This equation is solved numerically to obtain the value of  $I$  at any instant for a given  $U$ . It is then subtracted from the measured value to get the current due to polarisation reversal, which is then integrated to get the charge  $Q$  on the electrodes.

Then  $Q = 2PA$

Ferroelectric liquid crystals synthesised recently have a very high value of spontaneous polarisation (350 nC/sq.cm). The methods to measure the spontaneous polarisation in these compounds have to take into account their high ionic conductivity and permittivity. This is achieved in differential measurements or by using rectangular or triangular voltages to separate the current components by their time behaviour.

### 2.3.2. Rotational Viscosity.

The application prospects of liquid crystals in any device relies on the possibility to induce structural changes by an externally applied electric field. The dynamical behaviour of the related switching process may often be described by introducing a suitable viscosity term in the equation of motion.

In nematic liquid crystals the viscous forces are estimated using the Leslie-Erickson model [21]. In ferroelectric liquid crystals we have to introduce two rotational viscosities denoted by  $\gamma_\phi$  &  $\gamma_\theta$  [22]. At very high fields, magnitude of the tilt angle  $\theta$  can be changed appreciably. Hence to account for the viscosity at high fields (softmode effect) the coefficient  $\gamma_\theta$  is introduced. But for moderate fields the motion of the director is along

a cone of angle  $\theta$  (Goldstone mode). Hence only the direction of  $\theta$  varies. Hence it is the rotational viscosity  $\gamma_{\phi}$  which influences the ferroelectric switching process involving comparatively lower electric fields. Therefore the determination of  $\gamma_{\phi}$  is of prime interest in response time studies related to dynamical switching in ferroelectric liquid crystals.

#### 2.3.2.1. Measurement of Rotational viscosity

Measurement of rotational viscosity for nematics have been carried out for a long time using several methods. Some of these methods were applied to smectic C\* also. But many new methods, which take advantage of the ferroelectricity have additionally been developed in recent years.

Pieransky et al. [23] evaluated rotational viscosity by studies of dynamic conosopic picture and by disturbing the helix in the SmC\* phase by an alternating shear or Poisseuille flow and measuring the current. The complicated experimental setups and inconsistent results render these methods obsolete.

One of the most convenient ways for evaluating rotational viscosity is to measure the optical response time in thin samples [24 & 25] on an applied voltage step. The

time measured from 10 to 90 % of the transmission between crossed polarisers is related to rotational viscosity by the equation:

$$\gamma_{\phi} = 1 / 1.8 \tau_{10-90} \cdot P_s \cdot E$$

The switching model holds good for the region of the electric field high enough so as to neglect the elastic effects. Though the method is simple, it requires a separate setup for the measurement of spontaneous polarisation. Further the extraction of rotational viscosity from the measurements is influenced by several factors such as wavelength dependence of the light transmission and dielectric anisotropy.

The polarisation reversal methods started by M. Lagarde [19] overcomes some of the drawbacks of earlier methods. Originally used to evaluate spontaneous polarisation, it was later found to be a very good method to measure rotational viscosity also [25,26,27]. Now several simplified analytic switching models exist enabling a detailed evaluation of such polarisation reversal experiments.

In earlier studies rotational viscosities were calculated from the position of the current peak on the time axis. But this peak position depends on the elastic effects

and hence the evaluation becomes difficult.

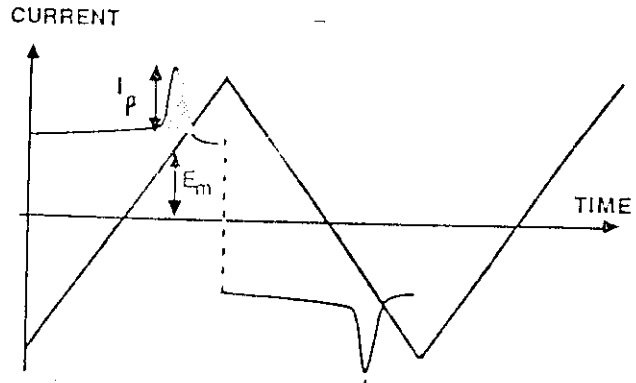
Later it was established that the most important parameter of relevance for rotational viscosity measurements is the width of the half height of the current peak. They are related by the equation

$$\gamma_{\phi} = 1 / 1.8 T_w P_s E$$

Geelhar et.al [28] evaluated viscosity by analysing the current response of a triangular voltage to the ferroelectric liquid crystal. The evaluation method is shown in Fig.2.2. In the current peak the maximum height  $I_p$  at the electric field  $E_m$  is noted. Then

$$\gamma_{\phi} = A P_s^2 E_m / I_p$$

Fig. 2.2



where  $A$  is the area of electrodes.

But the question remains whether viscosity measured in thin cells corresponds to the bulk viscosity of the system, or it is influenced by boundary effects.

Levstik et al. [29] demonstrated a method by which the rotational viscosity can be determined for bulk samples by measuring the dielectric constant of the system together with polarisation and tilt angle. Their results also showed that the variation of viscosity with temperature obeys

Arrhenius law. The advantage of this method over electro-optic and spontaneous polarisation reversal methods is that the director is excited to small oscillations and the use of bulk samples reduces the boundary effects.

Skarp et al. [25] measured the rotational viscosities of four ferroelectric liquid crystals with varying structure and macroscopic characteristics. They compared the results obtained by ac bridge, electro-optical, triangular and square wave methods. All methods were found to be sensitive to cell preparation, especially on the alignment of smectic layers.

### 2.3.3. DIELECTRIC CONSTANT.

The dielectric response of materials has been of great interest to scientists and technologists for a long time. This is especially true for ferroelectric materials. In the case of liquid crystals the investigation of dielectric behaviour of SmC\* materials near the phase transition from high temperature SmA phase can contribute to the understanding of mechanism of phase transition. Further, the sign of the dielectric anisotropy decides the speed of electro-optic switching and bistability of switched states in an applied electric field.

The complex permittivity of a dielectric material

is expressed as  $\epsilon^*(\omega) = \epsilon'(\omega) - j \frac{\epsilon''}{\omega}$

where  $\omega$  is the angular frequency of the measuring field.

The real part  $\epsilon'$  of the permittivity is the usual dielectric constant while the imaginary part  $\epsilon''$  accounts for dielectric losses.

The dielectric behaviour of chiral smectic C phase and its dependence on temperature and frequency, measuring field strength, pressure, sample thickness and electric bias field has been studied by several groups during the last few years. The main outcome has been the characterisation of the dielectric properties of the Goldstone mode in the C\* phase and the soft mode in the A\* and C\* phases. The first is related to the rotations of the molecules along the smectic cone while the second mode is related to rotations in which the tilt of the molecules get changed.

#### 2.3.3.1. Measurement of dielectric constant.

The dielectric constant of ferroelectric liquid crystals is usually measured either by the capacitance bridge or an impedance analyser or by a lock-in amplifier.

Temperature dependence of dielectric constant of p-decyloxybenzylidene-p-amino-2-methylbutylcinnamate (DOBAMBC) in the planar oriented samples of thickness 250,

100, 50 and 30 microns were studied by Yoshino et al. [30]. For low frequencies ( $< 1\text{ kHz}$ ), they obtained a maximum value of dielectric constant at a temperature near the phase transition temperature  $T_c$  from the smectic A to the  $\text{SmC}^*$  phase. Frequency dependence of dielectric constant at various thicknesses were also measured at different temperatures. The results showed that at high frequencies ( $> 10\text{ kHz}$ ), there is no appreciable change of permittivity in the  $\text{SmC}^*$  state.

Sakurai et al. [13] prepared a new series of ferroelectric liquid crystals and the dielectric measurements at low frequencies (30 Hz) showed a sharp increase in value in the  $\text{SmC}^*$  state.

Using a mixture of compounds Levstik et al. [29] produced a room temperature ferroelectric liquid crystal with the  $\text{SmC}^*$  phase from  $15^\circ\text{C}$  to  $44^\circ\text{C}$ . For a 130 micron thick planar sample dielectric constant was determined in the smectic A and  $\text{SmC}^*$  phase for frequencies from 20 Hz to 8 kHz.

Glogarova et al. [31] measured the temperature dependence of dielectric constant in planar samples of DOBAMBC with simultaneously observing the structure. They repeated the experiments using samples unwound by a dc electric field. At high fields no appreciable change in



dielectric constant was observed on passing from the smectic A to SmC\* phase. Their results also showed that dielectric constant showed a relaxation behaviour at higher frequencies (>200 Hz). Far above this frequency the value of dielectric constant is comparable to the value obtained at high biasing fields and in the smectic A phase.

Applied field dependence of static dielectric constant and also dc bias field dependence of high frequency dielectric constant for 1 MHz to 100 MHz were measured in the helicoidal smectic C phase of DOBAMBC by Maruyama et al. [32] using lock-in amplifier, thermal noise and bridge method. He observed a very low characteristic threshold field in the static dielectric constant measurement by lock-in amplifier. This corresponds to the minimum excitation field of the Goldstone mode. The high frequency dielectric constant was found to be temperature independent above 10 MHz.

The static dielectric constant ( $\epsilon$ ) in the smectic A and SmC\* phase of the ferroelectric liquid crystal 4(3-methyl-2-chlorobutanoyloxy)-4-heptyloxybiphenyl was determined by Bahr et al. [33]. They observed strong pre-transitional effects in the smectic A phase. When the Goldstone mode contribution in the SmC\* phase was quenched

by an applied electric field, a cusp like behaviour of dielectric constant at the C\*- A transition, similar to solid ferroelectrics were observed.

The soft mode behaviour of ferroelectric liquid crystal 4-octyloxy-4-(2-methyl butyloxy) carbonyl phenylester was investigated by Pavel and Glagarova [34]. For this they measured the complex permittivity of the material in the vicinity of smectic A-- SmC\* phase transition with a dc field applied to the specimen to unwind the helix. This helped them to eliminate the contribution to dielectric constant from the Goldstone mode.

They found that at 100 Hz the temperature dependence of the soft mode contribution had the form of the Currie-Weiss law on both smectic A and SmC\* phase. At higher frequencies the maximum of dielectric constant at T<sub>c</sub> is lowered and at about 40 kHz a minimum appeared. Similar results were obtained by Legrand et al. [35] for large range of frequencies.

In all the above measurements of dielectric constant in SmC\* phase means the dielectric constant perpendicular to the helix. However for the calculation of dielectric torque, the important information lies in the anisotropy of dielectric constant. ie

$$\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$$

where  $\epsilon_{\parallel}$  relates to an electric field applied along the molecular axis and  $\epsilon_{\perp}$ , to the field perpendicular to the axis. In the smectic A and smectic A\* phase the field directions are in accordance with this definition. But in the SmC\* phase, in the homeotropic configuration the measuring field makes an angle  $\theta$  (the tilt angle) with the director. In spite of this the measured dielectric constant was noted as  $\epsilon_{\parallel}$ . Similarly in the planar geometry also, due to the presence of the tilt the measuring field is no longer perpendicular to the director. But the measured dielectric constant was denoted as  $\epsilon_{\perp}$ .

This discrepancy was realised by Hoffmann et al. [36]. By a transform of the tensor from the coordinate frame related to the main axes of molecule to the laboratory frame, they calculated the actual dielectric anisotropy of DOBAMBC samples.

Such measurements of dielectric anisotropy for a series of commercially available ferroelectric liquid crystals were conducted by Gouda et al. [37] for frequencies from kHz to MHz ranges. Their results are useful in calculations of dielectric torque in applied devices.

#### 2.3.4. TILT ANGLE.

The tilt angle  $\theta$  of molecules inside the smectic

layers is the order parameter of smectic phase. It is the order parameter of the SmC\* phase also since the polarisation itself is proportional to the tilt angle. Further the tilt angle represents the tilt of the long axis of any second rank tensor associated with the molecules like the diamagnetic susceptibility, the dielectric constant and optical indices. Hence the measurement of tilt and the investigation of its dependence on the molecular structure, temperature and the composition of mixtures is necessary for selecting and tailoring new ferroelectric materials for electro-optic devices.

Two important methods usually employed for measuring tilt angle are the X-ray method and the optical method. If  $l$  is the length of the molecule of ferroelectric liquid crystal and  $d$  the thickness of the tilted smectic layers, then

$$d = l \cos\theta .$$

In X-ray method [38]  $d$  is derived from the layer periodicity of the sample in the SmC\* phase and  $l$  from that in the smectic A phase close to the smectic A- SmC\* phase transition temperature. The periodicity is obtained from X-ray photographs by measuring the separation between the lines formed by the beams scattered and non scattered by the

smectic layers. Then using the Bragg relation

$$n \lambda = 2d \sin \theta$$

where  $\lambda$  is the wavelength of the X-ray radiation and  $\theta$  the Bragg reflection angle.

Martinot-Lagarde et al. [38] studied the variation of tilt angle with temperature for ferroelectric liquid crystals like DOBAMBC, OOBAMBMC, OOBMBCC and TDOBAMBCC using the X-ray method and obtained good results.

In optical measurements, the tilt angle of the main axis of optical dielectric tensor gives the angle  $\theta$ . Martinot Lagarde et al. [38] measured this angle after unwinding the helix using an electric field. In the unwound state, all the molecules are tilted across the normal to the layers by the tilt angle  $\theta$ . By reversing the field direction the molecules are tilted by an angle  $-\theta$ . Thus the angle between two extinction positions, under crossed polarisers is  $2\theta$ . Their experiments in planar and homeotropic geometries gave accurate values of tilt angle at different temperatures.

One disadvantage of optical method compared to optical method is the necessity of a strong electric field. But the X-ray method is inadequate when the molecules possess long end chains.

Takezoe et al. [39] measured the tilt angle for different sample thickness of DOBAMBC in which the helix was unwound by glass surfaces. The apparent value of tilt angle increased with decreasing thickness and reached a constant when sample thickness was less than the pitch of the helix. This value is taken as the true value of tilt angle.

#### 2.4. ELECTRO-OPTIC SWITCHING CHARACTERISTICS.

The choice of an ferroelectric liquid crystal material for any particular application depends on its electro-optical switching characteristics like rise time, decay time, grey scale capability and bistability. The geometry (configuration) of the cell is the most important factor that decides these characteristics, other than the material constants. Since ferroelectric liquid crystals have a layered structure, many types of configurations, making use of different mechanisms such as helical unwinding, domain switching and optical birefringence have been studied by many workers.

From an application point of view a broad classification of these configurations is based on the thickness of the material ( $d$ ) compared to its pitch ( $P_0$ ). For thick cells ( $d \gg P_0$ ) the optical effects are explained

on the basis of winding and unwinding of the helix. In this case if the pitch is comparable to the wave length of light used, then strong scattering is the mechanism of optical effect. When pitch is less than wave length, scattering decreases and the incident light sees an apparent refractive index averaged over the helix (Deformed helix FLC ). Since the helix is easily distorted by electric fields, it is possible to modify electrically the average optic axis to obtain electrical contrast.

For thick cells (10 microns to 250 microns) experiments were conducted by Yoshino et al. [40] with an aim to establish bistability in thick cells of DOBAMBC, by utilising the change in light scattering that follows the transition between wound and unwound states of the helix of the ferroelectric liquid crystal. But the unwound, uniformly aligned monodomain structure regained its original helical form on removal of applied field. Moreover the threshold voltage was high and the response was slow.

Another method tried by this group is based on the transient light scattering at the instant of domain switching due to the polarity reversal of the applied field [41]. Here for both polarities of applied voltage, the medium is transparent whereas during the reversal of the

field it is opaque. There is an improvement in response, as both winding and unwinding are controlled by the applied field. But bistability is not achieved in this case also.

In the deformed helix ferroelectric effect suggested by Ostrovski et al. [42] a ferroelectric liquid crystal with a very short pitch is used. When the pitch is shorter than the wave length of the incident beam, they showed that an average optical indicatrix can be considered. Initially the optic axis of the helical structure coincides with the helical axis. The distortion of the helix by an applied field leads to a change of refractive index and hence to a change in optical transmission through the material. A low voltage, high response liquid crystal--photoconductor structure with a spatial resolution of 40 lines per millimeter and reversible memory was developed by Bersenev et al.[43] based on this effect. Recently Funfschilling and Schadt proposed a highly multiplexible deformed helix ferroelectric liquid crystal device [44] with response time in 10 micro seconds region and good grey scale capability. A major drawback of this effect is the unwinding of the helix under slightly higher voltages.

For thin cells ( $d \ll P_0$ ) the helix can be unwound by means of surface forces. Clark & Lagerwall [45] was able



to arrive at such a geometry (SSFLC) in which the UP and DOWN states are stabilised by surface interactions. The change in birefringence due to the transition between these two uniformly aligned states, on reversing the polarity of the applied field, is utilised for getting optical switching. They obtained sub-microsecond switching speeds at very low fields (2 V/micron).

Patel [46] studied the switching behaviour of such SSFLC cells and established bistability and the presence of a dynamic threshold in cells of 1 to 2 microns thickness. He obtained a linear relation between inverse of pulse width and voltage for a particular transmission level.

Patel and Goodby [47] examined the temperature and pulse shape dependence of optical switching in these surface stabilised configurations using simple and complex waveforms.

AC field stabilisation is another method [48] used to stabilise the switched state of an ferroelectric liquid crystal with negative dielectric anisotropy. The ac should alternate the field polarity in a time shorter than liquid crystals response time. Theoretical studies on this effect has been carried out by Schiller et al. [49] and Jiu Zhi et al.[24]. Detailed experimental studies regarding influence

of spontaneous polarisation and  $\gamma\phi$  on this effect have been done by Nagata et al. [50].

A drawback in all these thin cell configurations is the lack of inherent grey scales. This has been solved to an extent by using the technique of multiple frequency addressing and making use of the phenomena of multidomain switching [51].

The soft mode effect, first suggested and studied by Garoff and Meyer [52] utilises the electroclinic response of chiral orthogonal smectic phases. (  $A^*$ ,  $B^*$  and  $E^*$  ) in bookshelf geometry. In addition to a submicrosecond response time and wide continuous dynamic range the devices based on this effect has full grey scale capability [53]. Very small temperature dependence and good linearity of response are further advantages of this effect.

## 2.5. FLC LIGHT VALVES AND MODULATORS.

Modulation essentially consists in imprinting an information on a carrier wave. In image converters, projection displays and transmitters of optical communication systems, light is the carrier. So in optical modulation, phase or intensity of a light beam is to be modified according to the modulating signal.

The modulation can be obtained either by direct

switching of the light source or by using an external modulator. The use of an external modulator has a distinct advantage over direct modulation as it relieves the burden imposed on the light source. By passing a carrier wave through a modulator, a sub carrier that contains information can be generated by applying the signal on the modulator crystals, which can be electro-optic, magneto-optic or acousto-optic.

The electro-optic modulation of light is based on a linear electro-optic effect in crystals whose refractive index is changed upon the application of an electric field. Liquid crystals thus offer a natural choice of such materials as the orientation of the molecules and hence the refractive index can be easily changed by an external electric field. Nematic liquid crystal based optical modulators have been fabricated by many workers. The increased response time and improved bistability of ferroelectric liquid crystals make them more attractive as materials in these devices.

Presently two types of modulating mechanisms are suggested in ferroelectric liquid crystal based modulators. When the thickness of the liquid crystal layer is much higher than the pitch ( $d \gg P_0$ ) and applied field is less than

the critical unwinding field ( $E < E_c$ ) and light beam aperture is greater than the pitch ( $a > P_0$ ), then the light modulation is due to the helix deformation (DHF effect) [42].

On the basis of this effect a low voltage light modulator with switching time of 250 micro seconds was fabricated by Bersenev et al. [43]. Funfschilling and Schadt obtained 10 micro seconds response time by applying high voltage pulses of short duration before the low voltage probe pulse [44].

In a recent paper Panarin et al. studied dependence of switching time of such deformed helix ferroelectric devices on driving voltages and frequencies [54]. A nonlinearity of response characteristics was observed at higher voltages and frequencies.

Using chiral dopants and multicomponent mixtures ferroelectric liquid crystals of very small pitch are available now. This offers good chances for developing modulators using this effect.

When the major concerns are response time and bistability, thin cells are superior to thick ones. Both the SSFLC and SMFLC configurations have been used to construct high frequency low-voltage modulators. In applications like optical processing, photoaddressed

ferroelectric liquid crystal- spatial light modulators (FLC-SLM) are of particular interest as it offers parallel optical addressing with a potentially high frame rate. Armitage et al. obtained write and erase speeds of 100 micro seconds for an imaging test device using ferroelectric liquid crystals [55].

For binary operations SSFLC effect is more suitable due to its good bistability. But for continuous gradations (grey scales) the linear electroclinic effect of SMFLC configuration is superior.

A FLC-SLM using a hydrogenated amorphous silicon as photoconductor was constructed by Yamamoto et al. [56] using SmC\* ferroelectric liquid crystal in a coupled configuration. Response times of 500 micro seconds for 1 micro seconds pulses, a contrast ratio of 200:1 and a resolution of 80 lines per millimeter are achieved in this model.

Mao et al. [57] demonstrated that optically addressed spatial light modulators with SmA\* and SmC\* materials and an amorphous silicon photosensor can be used to perform high speed low power optical phase conjugation. Frequency response of 10 k Hz were achieved by them.

Electro-optic modulators in the polarisation mode

using materials in the SmA\* and SmC\* phase were fabricated by Karppinan et al. [58]. In the SmA\* configuration 3 micro seconds time were attained for 40 volts (peak to peak).

Using a mixture of ferroelectric liquid crystal compounds Anderson et al. [59] obtained a tilt of 11.25 for a SmA\* phase at room temperature and at moderate field strengths. By means of multiple cell technique good grey scale generation and response times of 10 micro seconds were obtained.

To summarise, ferroelectric liquid crystal based electro-optic modulators can be used as choppers, function generators and optical power controllers with better efficiency and speed. Reset pulse techniques in thick cells and electroclinic effects in thin cells can be effectively exploited for improving response times. If SmC\* material with high spontaneous polarisation and low viscosity and SmA\* materials with large tilt are available, high speed requirements of light valves for applications in spatial light modulators in image converters and optical processors can be realised.