

Chapter 2

Liquid Crystal Material for Microwave Applications

Liquid crystal (LC) molecules feature an additional state of matter, which exists between a liquid and a solid state. In this state, the LC molecules can flow even though they have orientational order. The molecules can be formed in plenty of different forms depending on how the constituents are bonded. These forms are mainly in a rod- or disk-like shape. The shape anisotropy results in different physical phenomena such as the liquid crystal mesophase (from Greek, *mesos* = middle), anisotropies in the refractive index, in the magnetic susceptibility and in the dielectric properties. These fundamental properties of rod-like shape nematic liquid crystals are presented in the first section in accordance with the scope of this work. In the second section, it is aimed to give reader insights into LC based planar microwave devices. Hence, required technology and working principle of a variable delay line are presented.

2.1 Fundamentals of Liquid Crystal Materials

The most common states of matter on Earth are solid, liquid and gas depending on the temperature and pressure. In the solid state, the molecules are strongly bonded by intermolecular forces either in a regular order, so called crystalline solid, or in an irregular order. In the crystalline solid state, the molecules can only vibrate at their well defined positions (positional order) and have a tendency to align in a specific direction (orientational order). As the temperature of the matter increases to a certain *melting point* T_m , the solid state transforms into a liquid state, where the molecules can move freely and feature no more positional and orientational orders.

The strengths of the intermolecular forces in the LC materials are not homogenous in all directions because the material is formed by anisotropic molecules. When the temperature of the solid LC material is increased, the molecules vibrate excessively and breakdown the weak intermolecular bonds, leading to a drop off in the positional order [DEM+98]. This middle state is defined as the liquid crystal state, where the

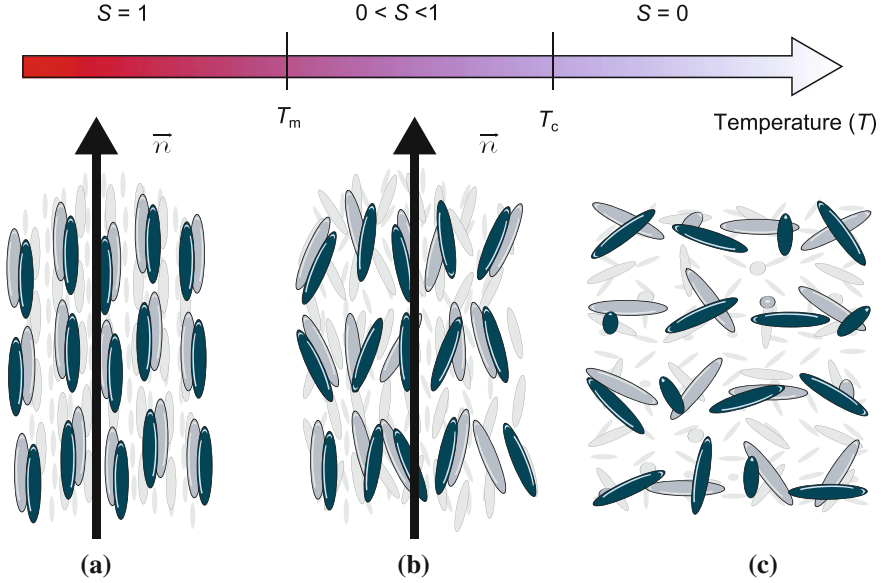


Fig. 2.1 Schematic of a nematic liquid crystal material depending on the temperature. **a** Crystalline solid state with perfect alignment with the order parameter $S = 1$. Director $\vec{n}$ is parallel to the molecular *long axis*. **b** Nematic phase, where $\vec{n}$ indicates the time-average directions of the molecules. **c** Liquid phase with the lowest molecular ordering like $S = 0$

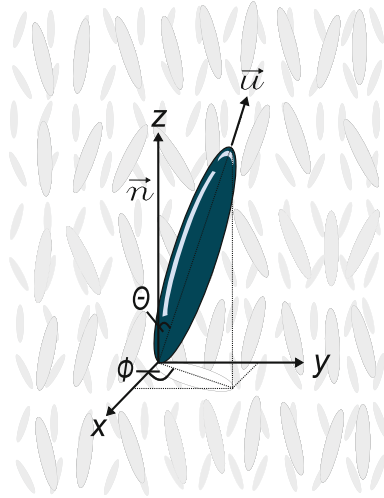
molecules still exhibit orientational order like of a solid crystalline and the material can additionally flow like a liquid [YW06].

Figure 2.1 shows the schematic representation of a nematic liquid crystal. In an LC bulk, the molecules are aligned parallel to their long axes because of the shape anisotropy. In the macroscopic scale, the time-averaged direction of the molecules is denoted by a director $\vec{n}$, which is along the long axes of the molecules. Such a preferred direction is not defined for the short axes since the nematic liquid crystals are usually uniaxial [YW06]. In the both solid and nematic phases, a director can be assigned whereas the level of molecular ordering is different. This is quantitatively defined by an order parameter S [Goe09]. At temperature T_c , so called the *clearing point*, the transition into the liquid phase occurs and the opacity clears. 5CB¹ is a well-known commercially available LC and frequently used in the LC display applications. The clearing point of this material is about 38 °C [Goe09] (also see Appendix A.2.1), which is low for an application. Recently, both experimental [Goe09] and commercial LC mixtures (GT3 series from Merck KGaA, Germany), which are synthesized especially for microwave applications, show an increased nematic range, i.e. from $T_m = -20$ °C to $T_c = 100$ °C for GT3-23001.

Arrangement of the LC molecules in a bulk is determine quantitatively by using the order parameter S [GP93]. Figure 2.2 shows a snapshot of a single rod-like shape

¹ Distributed under the trade name K15 from Merck KGaA, Germany.

Fig. 2.2 The coordinate system for a single liquid crystal molecule. The material is in the nematic phase. The director $\vec{n}$ is aligned along the z axis. The molecule *long axis* is parallel to the unit vector $\vec{u}$ at the given observation time



LC molecule. The single molecule points in $\vec{u}$ direction at the moment of observation and the director is parallel to the z axis. This means that the average direction of the molecules is in the z direction or the molecules spend more time when pointing in the z direction than other directions [CH97].

The probability of directing the unit vector $\vec{u}$ within the solid angle $d\Omega$ that is $d\Omega = \sin\theta d\theta d\phi$ is given by $f(\theta, \phi)d\Omega$ [YW06]. Here, $f(\theta, \phi)$ is an orientational distribution function. Since the nematic LCs are uniaxial, there is no preferred direction along ϕ and therefore, $f(\theta, \phi)d\Omega$ can be rewritten as $f(\theta)d\Omega$ with $d\Omega = \sin\theta d\theta$. The order parameter S can be determined by averaging $f(\theta)d\Omega$ over the time and over the space. A commonly used expression for S is obtained by using the average of the $2nd$ order Legendre polynomial [CH97, YW06], which is given by

$$S = \langle P_2(\cos\theta) \rangle = \left\langle \frac{3}{2} \cos^2\theta - \frac{1}{2} \right\rangle = \frac{\int_0^\pi \left(\frac{3}{2} \cos^2\theta - \frac{1}{2} \right) f(\theta) \sin\theta d\theta}{\int_0^\pi f(\theta) \sin\theta d\theta}. \quad (2.1)$$

When the molecules are perfectly aligned, $f(\theta) = \delta(\theta)$ and the order parameter $S = 1$ [CH97] according to Eq. (2.1). For a completely unordered case, on the other hand, the molecules direct to all directions with an equal probability. Thus, $f(\theta)$ is constant, resulting to $S = 0$ [YW06]. In the nematic phase, the order parameter is in the range of 0–1 depending on the temperature. To calculate S in the nematic phase, $f(\theta)$ can be described in details by using *Maier-Saupe* or *Landau-de Gennes theory* [GP93, CH97, YW06]. The first considers the temperature dependency of S and the distribution function is determined by the Boltzmann distribution. The second accounts additional effects and enables to fit the respective function to a measurement by use of additional parameters [Goe09]. Further details of these theories are not

discussed here since this work focus on the usage of LC materials in microwave applications.

2.1.1 Response of Liquid Crystal Molecules in Electromagnetic Fields

Owing to the shape anisotropy, liquid crystals are diamagnetic and dielectric materials [BC94, CH97, GP93]. They feature either anisotropic magnetic susceptibility $\Delta\chi_m$ or anisotropic relative permittivity $\Delta\epsilon_r$ if they are exposed to a magnetic or an electric field, respectively. This section presents responses of the LC materials to an applied electromagnetic field.

Anisotropic Magnetic Susceptibility $\Delta\chi_m$

The liquid crystal molecules have magnetic polarizability κ when they are exposed to a magnetic field $\vec{H}$. The magnetic polarizability κ of the molecules differs depending on the angle between $\vec{H}$ and $\vec{u}$ [YW06]. It can be decomposed into $\kappa_{\parallel}$ and $\kappa_{\perp}$, where the terms $\parallel$ and $\perp$ stand for the directions parallel and perpendicular to the molecule long axis, respectively. A diagonal tensor of the magnetic polarizability $\overleftrightarrow{\kappa}$, which is

$$\overleftrightarrow{\kappa} = \begin{pmatrix} \kappa_{\perp} & 0 & 0 \\ 0 & \kappa_{\perp} & 0 \\ 0 & 0 & \kappa_{\parallel} \end{pmatrix}, \quad (2.2)$$

can be written for a uniaxial LC material along $\vec{u}$ [Goe09]. The unit vector $\vec{u}$ is given in the spherical coordinate system with $\vec{u} = \vec{u}_{\theta} + \vec{u}_{\phi} + \vec{u}_r$. $\overleftrightarrow{\kappa}$ is transformed into the cartesian coordinate system xyz in Fig. 2.2 by using a rotation matrix R [CH97]. The resultant magnetic polarizability tensor $\overleftrightarrow{\kappa}$ is

$$\overleftrightarrow{\kappa} = R \overleftrightarrow{\kappa} R^{-1} \quad (2.3)$$

with

$$R = \begin{pmatrix} \cos \theta \cos \phi - \sin \phi \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix}. \quad (2.4)$$

The magnetic susceptibility χ_m is a macroscopic property. It can be obtained by multiplying the magnetic polarizability κ by the molecular number density N [YW06, Goe09]. The magnetic susceptibility is written as $\overleftrightarrow{\chi}_m = N \overleftrightarrow{\kappa}$ in the tensorial form. The derivations up to here are carried out only for one molecule. As described in Sect. 2.1, the averaged magnetic susceptibility of an LC bulk can be obtained by using $\langle \rangle$ operator element by element. By calculating $\langle \overleftrightarrow{\chi}_m \rangle = N \langle \overleftrightarrow{\kappa} \rangle$, one obtains [YW06]

$$\begin{aligned}
\langle \overleftrightarrow{\chi}_m \rangle &= \begin{pmatrix} \chi_{m,\perp} & 0 & 0 \\ 0 & \chi_{m,\perp} & 0 \\ 0 & 0 & \chi_{m,\parallel} \end{pmatrix} \\
&= N \begin{pmatrix} \kappa_{\perp} + \frac{1}{3}(1-S)\Delta\kappa & 0 & 0 \\ 0 & \kappa_{\perp} + \frac{1}{3}(1-S)\Delta\kappa & 0 \\ 0 & 0 & \kappa_{\perp} + \frac{1}{3}(2S+1)\Delta\kappa \end{pmatrix}. \quad (2.5)
\end{aligned}$$

The anisotropic magnetic susceptibility $\Delta\chi_m$ is

$$\Delta\chi_m = \chi_{m,\parallel} - \chi_{m,\perp} = NS\Delta\kappa. \quad (2.6)$$

The magnetic susceptibilities of the LC material are negative and close to zero (in the order of 10^{-5} in SI units) [CH97, YW06] and therefore, it is not considered in this work. Nevertheless, as will be given in 2.1.2, the anisotropic magnetic response of the material, although being low, is exploited consciously to control the orientation of the LC molecules.

Anisotropic Relative Permittivity $\Delta\epsilon_r$

In the presence of an external electrical field $\vec{E}$, a dielectric dipole moment $\vec{p}$ is induced on the LC molecules since the molecules are polarizable. Similar to the magnetic case, the polarizability α_p of the LC molecules differs depending on the angle between $\vec{E}$ and $\vec{u}$. The tensorial material polarizability $\overleftrightarrow{\alpha}_p$ is

$$\overleftrightarrow{\alpha}_p = \begin{pmatrix} \alpha_{p,\perp} & 0 & 0 \\ 0 & \alpha_{p,\perp} & 0 \\ 0 & 0 & \alpha_{p,\parallel} \end{pmatrix} \quad (2.7)$$

according to the molecular axis $\vec{u}$. The dipole moment $\vec{p}$ is actually induced by the local electrical field on a molecule $\vec{E}_{local}$, which is produced by the external field and by the dipole moments of the other molecules [YW06]. Here, $\vec{E}_{local}$ is not equal to the applied external field unlike to the magnetic case because of the strong dipole-dipole interactions between the molecules. The relationship between $\vec{E}_{local}$ and $\vec{E}$ is given as

$$\vec{E}_{local} = \overleftrightarrow{K} \vec{E}, \quad (2.8)$$

where $\overleftrightarrow{K}$ is so called the tensorial internal field constant [YW06, Goe09]. It is defined by $\overleftrightarrow{K} = 1 / \left(1 - N \overleftrightarrow{\alpha}_p / 3\epsilon_0 \right)$ with the permittivity of free space ϵ_0 (8.85×10^{-12} F/m) and the molecular number density n . The induced dipole moment is obtained by

$$\vec{p} = \overleftrightarrow{\alpha}_p \vec{E}_{local} = \overleftrightarrow{\alpha}_p \overleftrightarrow{K} \vec{E}. \quad (2.9)$$

The corresponding macroscopic polarization $\vec{P}$ is

$$\vec{P} = N\vec{p} = N\overleftrightarrow{\alpha}_p \overleftrightarrow{K} \vec{E} \quad (2.10)$$

along to molecular axis $\vec{u}$ is [YW06]. The tensors in Eq. (2.10) can be transformed into the laboratory coordinates xyz (see Fig. 2.2) by using the rotation matrix R . Then, the Eq. (2.10) can be rewritten for the laboratory frame as

$$\begin{aligned} \vec{P} &= NR\overleftrightarrow{\alpha}_p \overleftrightarrow{K} R^{-1} \vec{E} \\ &= \overleftrightarrow{\chi}_e \vec{E}. \end{aligned} \quad (2.11)$$

where χ_e and $\overleftrightarrow{\chi}_e$ are the electric susceptibility and its tensor, respectively. Averaging $\overleftrightarrow{\chi}_e$ by using $\langle \rangle$ operator, one obtains the effective susceptibility tensor as [YW06]

$$\langle \overleftrightarrow{\chi}_e \rangle = \frac{N}{3} \begin{pmatrix} \alpha_{\perp} K_{\perp} (2 + S) & 0 & 0 \\ +\alpha_{\parallel} K_{\parallel} (1 - S) & & \\ 0 & \alpha_{\perp} K_{\perp} (2 + S) & 0 \\ & +\alpha_{\parallel} K_{\parallel} (1 - S) & \\ 0 & 0 & \alpha_{\perp} K_{\perp} (2 - 2S) \\ & & +\alpha_{\parallel} K_{\parallel} (1 + 2S) \end{pmatrix} \quad (2.12)$$

The dielectric displacement $\vec{D}$ is defined as [CH97]

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = (\varepsilon_0 + \overleftrightarrow{\chi}_e) \vec{E} = \varepsilon_0 \overleftrightarrow{\varepsilon}_r \vec{E}, \quad (2.13)$$

In Eq. (2.13), the complex relative permittivity tensor $\overleftrightarrow{\varepsilon}_r$ is defined by $\overleftrightarrow{\varepsilon}_r = \overleftrightarrow{I} + \overleftrightarrow{\chi}_e / \varepsilon_0$ with the identity matrix tensor $\overleftrightarrow{I}$. By using Eq. (2.12), one can obtain the complex effective perpendicular and parallel relative permittivity

$$\varepsilon_{r,\perp} = 1 + \frac{N}{3\varepsilon_0} [\alpha_{\perp} K_{\perp} (2 + S) + \alpha_{\parallel} K_{\parallel} (1 - S)] \quad (2.14)$$

and

$$\varepsilon_{r,\parallel} = 1 + \frac{N}{3\varepsilon_0} [\alpha_{\perp} K_{\perp} (2 - 2S) + \alpha_{\parallel} K_{\parallel} (1 + 2S)], \quad (2.15)$$

respectively. The resultant anisotropic relative permittivity $\Delta\varepsilon_r$ is calculated by

$$\Delta\varepsilon_r = \varepsilon_{r,\parallel} - \varepsilon_{r,\perp} = \frac{N}{\varepsilon_0} (\alpha_{\parallel} K_{\parallel} - \alpha_{\perp} K_{\perp}) \quad (2.16)$$

and analogously, the anisotropic refractive can be written as

$$\Delta n = n_{\parallel} - n_{\perp} = \sqrt{\varepsilon_{r,\parallel}} - \sqrt{\varepsilon_{r,\perp}} \quad (2.17)$$

since the complex relative permeability is $\underline{\mu}_r \approx 1$. The dielectric anisotropy is proportional to the order parameter and can be either positive or negative. Nevertheless, as will be described in Chap. 3, all LC samples used in this work have positive dielectric anisotropy.

The electrical characteristics of the LC materials are characterized by using two quantities. These are so called the material tunability τ_{LC} and the material efficiency η_{LC} . The first is related to the real part of the complex relative permittivity and the second accounts dielectric losses. The complex relative permittivity can be rewritten as

$$\begin{aligned}\underline{\varepsilon}_{r,i} &= \Re(\underline{\varepsilon}_{r,i}) - j\Im(\underline{\varepsilon}_{r,i}) \\ &= \Re(\underline{\varepsilon}_{r,i}) \left(1 - j \frac{\Im(\underline{\varepsilon}_{r,i})}{\Re(\underline{\varepsilon}_{r,i})} \right) \\ &= \varepsilon_{r,i} (1 - j \tan \delta_i),\end{aligned}\tag{2.18}$$

where, i represents the orientation of the LC molecules, i.e $\parallel$ or $\perp$. In Eq. (2.19), ε_r is the relative permittivity and $\tan \delta$ is the material loss tangent. The corresponding τ_{LC} and η_{LC} are determined by

$$\tau_{LC} = \frac{\varepsilon_{r,\parallel} - \varepsilon_{r,\perp}}{\varepsilon_{r,\parallel}} = \frac{\Delta \varepsilon_r}{\varepsilon_{r,\parallel}}\tag{2.19}$$

and

$$\eta_{LC} = \tau_{LC} / \max(\tan \delta),\tag{2.20}$$

respectively. As will be shown in Chap. 3, the $\tan \delta$ experienced by the electromagnetic field is higher if the field is perpendicular to the molecules. This refers that $\tan \delta_{\perp} > \tan \delta_{\parallel}$ at the microwave frequencies [Mue07, Goe09]. Thus, in calculations of η_{LC} , $\tan \delta_{\perp}$ is utilized because it defines the minimum material efficiency.

2.1.2 Alignment Methods

The polarizability α_p and therefore, the macroscopic relative permittivity $\underline{\varepsilon}_r$ of the LC material depend on the angle between the director $\vec{n}$ and the electric field $\vec{E}$ (see Sect. 2.1.1). In a tunable device, the direction of $\vec{n}$ has to be controlled to exploit the LC material as a tunable dielectric. Possible methods to align the LC molecules are described in this section. Before doing so, it is essential to explain briefly total free energy in an LC bulk and the terms contributing to this energy.

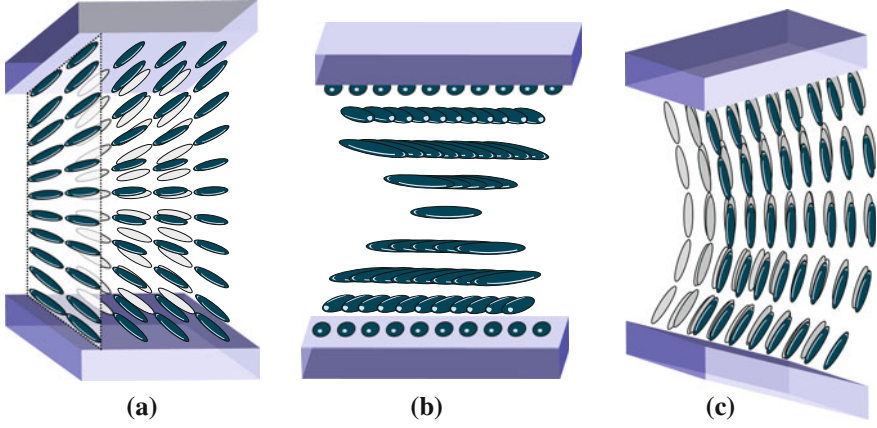


Fig. 2.3 Possible deformations of an oriented LC layer. **a** Splay, **b** twist and **c** bend types of deformations

Total Free Energy in an LC Bulk

The continuum theory [Dem+99, YW06] is a commonly used method for modelling the LC material in a device. Any kind of local or complete change in the direction of $\vec{n}$ increases the energy of the system, which is formulated by the Gibbs free type of energy. The system achieves an equilibrium state when the Gibbs free energy has its minimum at constant temperature and pressure [YW06]. This also means that if the system's energy is increased, the molecular orientation (and $\vec{n}$) changes to find a new equilibrium state, resulting in again a minimum free energy. The factors having impact on the system's energy are elastic deformations, external electromagnetic fields and anchoring effects.

In reality, even the molecules are aligned in a specific direction, the director $\vec{n}$ may vary in the volume depending on the position [YW06]. This phenomenon is called the elastic deformation of the director. Three possible deformations can be observed in an oriented LC material. These are splay, twist and bend as shown in Fig. 2.3. The contributions of the deformations to the energy of the system per unit volume can be computed as [CH97, Dem+99]:

$$\begin{aligned} df_{\text{elastic}} &= df_{\text{splay}} + df_{\text{twist}} + df_{\text{bend}} \\ &= \frac{1}{2} K_{11} (\nabla \cdot \vec{n})^2 + \frac{1}{2} K_{22} [\vec{n} \cdot (\nabla \times \vec{n})]^2 + \frac{1}{2} K_{33} [\vec{n} \times (\nabla \times \vec{n})]^2, \end{aligned} \quad (2.21)$$

where K_{11} , K_{22} and K_{33} are elastic constants for the splay, twist and bend types of deformations, respectively. These values are characteristics for an LC sample and can be determined by performing measurements as in [Ong91].

Beside elastic distortions, the energy of the system changes in the presence of an external electromagnetic field. In case of an external electric field $\vec{E}$, the energy per unit volume is given by [CH97]

$$f_{\text{electric}} = \frac{1}{2} \vec{D} \cdot \vec{E} \quad (2.22)$$

for a parallel plate varactor, where the LC material is contained between two conducting electrodes as a tunable dielectric. Such a simple device models the working principle of the hardware realized in this work. An incremental change in the director $d\vec{n}$ leads to a change in the polarization $\vec{P}$ because of the anisotropic behaviour of the material. One can also write that $d\vec{P} = d\vec{D}$ according to (2.13) since the applied voltage across the electrodes and therefore, the applied bias field are constant [CH97]. Thus, the small change in the energy per unit volume is

$$df_{\text{electric},1} = \frac{1}{2} d\vec{P} \cdot \vec{E}. \quad (2.23)$$

On the other hand, the amount of the charge on the electrodes has to be adopted to keep the applied voltage constant because of the changing polarization. The corresponding small change in the energy per unit volume is [CH97]

$$df_{\text{electric},2} = -d\vec{P} \cdot \vec{E}. \quad (2.24)$$

One can add Eqs. (2.23) and (2.24) to obtain the total change in the energy per unit volume caused by the electric field. This is negative and equal to

$$df_{\text{electric}} = df_{\text{electric},1} + df_{\text{electric},2} = -\frac{1}{2} d\vec{P} \cdot \vec{E}. \quad (2.25)$$

Equation (2.25) is given in terms of the relative permittivity and the director as [Goe09]

$$df_{\text{electric}} = -\frac{1}{2} \varepsilon_0 (\langle \vec{E}^2 \rangle \varepsilon_{r,\perp} + \Delta \varepsilon_r \langle (\vec{n} \cdot \vec{E})^2 \rangle). \quad (2.26)$$

Similarly, the change in the energy per unit volume caused by the magnetic field $\vec{H}$ is [Mue07]

$$df_{\text{magnetic}} = -\frac{1}{2} \mu_0 (\langle \vec{H}^2 \rangle \mu_{r,\perp} + \Delta \mu_r \langle (\vec{n} \cdot \vec{H})^2 \rangle) \quad (2.27)$$

with μ_0 is permeability of free space ($4\pi \times 10^{-7}$ N/A²) and μ_r is relative permeability.

Another factor affecting the system's energy is anchoring forces because of the boundaries. In many liquid crystal devices, the viscous LC material is contained between two substrates. These substrates are coated with an alignment layer. When

the anisotropic LC material has a contact with the anisotropic surface (because of the alignment layer) interaction energy occurs. This is called the anchoring energy. According to *Rapini-Papoular Model*, this energy density is determined as [YW06]

$$df_{\text{surface}} = \frac{1}{2} W_p \sin^2(\theta - \theta_0) + \frac{1}{2} W_a \sin^2(\phi - \phi_0). \quad (2.28)$$

In Eq. (2.28), W_p and W_a are polar and azimuthal anchoring strengths, respectively; (θ, ϕ) specify the director $\vec{n}$ and (θ_0, ϕ_0) specify the preferred alignment direction for the polar and azimuthal angles, respectively.

The total free energy W_f of the system can be written as

$$W_f = \int_{\text{Volume}} df = \int_{\text{Volume}} (df_{\text{elastic}} + df_{\text{electric}} + df_{\text{magnetic}} + df_{\text{surface}}). \quad (2.29)$$

Alignment by Surface Anchoring

The preferred alignment direction defined by the alignment layer can be either in parallel (homogenous alignment) or perpendicular (homeotropic alignment) to the surface [YW06]. The alignment principal can be explained in the light of the energy considerations. The system's total energy is proportional to the anchoring surface energy f_{surface} (see Eq. (2.29)) and therewith f_{surface} has to be minimized for an equilibrium state of the molecules. According to Eq. (2.28), f_{surface} is minimized when $\sin(\theta - \theta_0)$ and $\sin(\phi - \phi_0)$ terms are zero for an ideal case. This results in $\theta = \theta_0$ and $\phi = \phi_0$, which means that $\vec{n}$ (specified by θ and ϕ) is aligned parallel to the preferred direction (specified by θ_0 and ϕ_0).

In this work, a homogenous alignment layer is utilized that is made of Nylon 6. It aligns the molecules parallel to the surfaces at a zero biasing case, which refers that no external field is applied. The alignment layer is spin coated, cured and then mechanically rubbed [Goe09] to have microscopic grooves on the surface. The coating parameters of the alignment layer are crucial for the device performance. A thick alignment layer in the order of a few mm affects the radio frequency (RF) performance of the device. On the other hand, a thin alignment layer results in light and nonuniform grooves having a low anchoring force. Several different coating parameters for the alignment layer are tested and these results are given in Appendix A.1.2.

Alignment by Electromagnetic Fields

In the presence of an external electric $\vec{E}$ or magnetic $\vec{H}$ field, the liquid crystal molecules are aligned to minimize the total free energy.

The energy contributed by an external electrical field f_{electric} is negative (see Eq. (2.26)) and therefore, increasing its absolute value decreases the total free

energy. LC materials used for the microwave applications feature a positive anisotropy [Mue07, Goe09] that is $\Delta\epsilon_r = \epsilon_{r,\parallel} - \epsilon_{r,\perp} > 0$. Hence, $|f_{\text{electric}}|$ is maximized when the director is aligned parallel to the applied field. This can be seen in the second term of Eq. (2.26).

A similar alignment can be accomplished by using the magnetic fields (see Eq. (2.27)). However, this method is rarely used, especially for LC devices, because of the heavy and bulky magnets. Nevertheless, for the experimental setups, i.e. for characterization of the material parameters, the molecules can be aligned parallel to an applied magnetic field.

2.2 Fundamentals of Tunable Inverted Microstrip Lines

This section aims to give reader insights into fundamentals of LC based microwave devices. For this purpose, an LC based planar variable delay line is presented including required technology and its working principal. Here the term planar device refers a microwave device, which is implemented by using a printed transmission line such as microstrip line, slotline or coplanar waveguide. In this context, the variable delay line is chosen in inverted microstrip line (IMSL) topology since it is a well-known application of LCs for microwaves [KFN02, Mue07].

2.2.1 Technology

Figure 2.4 shows a schematic of the fabrication process of the IMSL. Similar to liquid crystal displays (LCDs), glass substrates are preferred for microwave device realization. The reasons are that the glass is mechanically stable, which is essential to achieve a uniform LC layer thickness, and it is transparent, so different glass substrates can be aligned and stacked on top of each other. The manufactures delivers dielectric properties only for low frequency, i.e. for 1 MHz. The characterization of glass substrates are given in Sect. 3.2 for microwave frequencies (see also Appendix A.2.2).

Electrodes of the IMSL are implemented on the glass substrates by using photolithography processes. Technological details can be found in Appendix A.1.1. A seed layer, which is made of Nickel–Chromium (Ni–Cr) and gold (Au) metals, is evaporated on the glass substrate. The Ni–Cr layer is utilized as an adhesive layer between the substrate and Au layer. Typical thicknesses are 15 nm for Ni–Cr layer and 60 nm for the Au layer. A positive photoresist is spin coated on top of the seed layer. The photoresist is exposed with UV light and subsequently developed by using a convenient developer (see Appendix A.1.1). The signal and ground electrodes of the IMSL are formed inside the well-defined valleys by using electroplating of the gold metal. The thickness of the plated gold is specified to be 3 times of the skin depth at the device's operating frequency. This value is chosen as a compromise between a

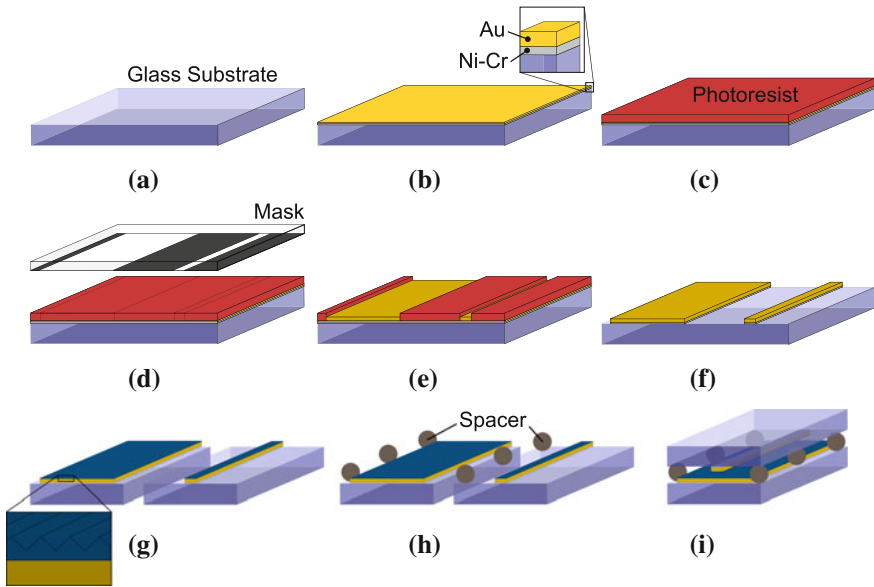


Fig. 2.4 A schematic overview of the fabrication processes of LC based inverted microstrip line. **a** Top of a glass substrate is covered by **b** nickel–chromium (Ni–Cr)/gold (Au) seed layer by using thermal evaporation. **c** A positive photoresist is spin coated, **d** exposed with UV light and developed. **e** The electrodes of the IMSL are formed inside the valleys by electroplating of the gold electrode. **f** The photoresist is removed and the seed layer is etched. **g** The substrate is diced into two pieces and each substrate is coated with an alignment layer. **h** Spacers are formed on the top of the substrates. **i** Finally, the two substrates are aligned and bonded by UV curable adhesive

lower electrode thickness, causing a high metallic loss, and a higher electrode thickness, raising the fabrication costs. During the plating, two types of marker are also formed on the glass substrate whereas they are not shown in Fig. 2.4. These markers are used in the next steps for cutting and aligning purposes. After the plating, the photoresist is stripped and the seed layer is etched first by using a Au etchant and then by using a Ni–Cr etchant. The substrate is diced into two pieces by means of the cutting markers. Each piece is coated with an alignment layer made of Nylon 6 and rubbed mechanically to form grooves on the surfaces (see Appendix A.1.2). The substrates are covered with spherical glass spacers having 100 mm diameter. The spacers are commercially available from Sekisui Chemical Co., Ltd. In LC displays, similar spacer are used with lower dimensions. The substrate carrying the signal electrode is inverted and aligned on top of the ground electrode by using the complementary alignment marks. The aligned substrates are bonded with UV curable adhesive that is Ablestik A4086T. The resultant structure is that the signal electrode is on the bottom side of the front glass substrate and the ground electrode is on the top side of the back glass substrate. In between, a cavity with 100 mm height is formed because of the spacers. The LC material is filled into the cavity by means of adhesion forces

and subsequently. Finally, the structure is sealed either by using UV sensitive glue or any kind of nonconductive two-component glues.

2.2.2 Working Principle

Cross-sectional views of the IMSL is shown in Fig. 2.5. Owing to the alignment layer, the entire LC bulk is oriented parallel to the surfaces initially. The director $\vec{n}$ is perpendicular to the RF field distribution of the IMSL. The electric field, propagating in the LC layer, experiences the complex perpendicular relative permittivity $\epsilon_{r,\perp}$, which is along the molecule's short axis. This is given as

$$\epsilon_{r,\perp} = \epsilon_{r,\perp}(1 - j \tan \delta_{\perp}). \quad (2.30)$$

according to Eq. (2.18). Indeed, the main part of the field propagates in the LC layer and only some in the front glass, which is called as fringing field. Hence, the propagating wave experiences an *effective permittivity* depending on the device geometry and the electrical parameters of the glass substrates [Bal05]. The challenge is to force the field to propagate only through the LC layer by reducing the fringing field. This enhances the tuning efficiency of the IMSL. Methods reducing the fringing field are presented in Sect. 4.1.1. Nonetheless, the corresponding complex perpendicular effective permittivity $\epsilon_{r,\text{eff},\perp}$ is mainly defined by $\epsilon_{r,\perp}$.

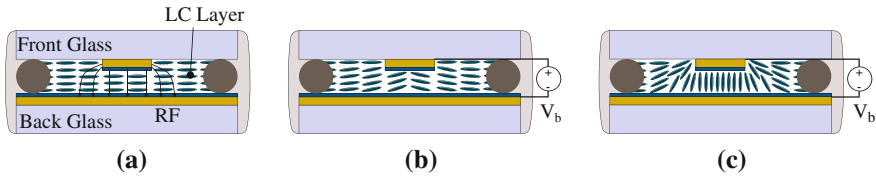


Fig. 2.5 Cross-sectional views of the variable IMSL. **a** The LC molecules are parallel to the surface ($\epsilon_{r,\text{eff}} = \epsilon_{r,\text{eff},\perp}$) and perpendicular to the radio frequency (RF) field. **b** The molecules are aligned as equilibrium between the applied field and the anchoring force of the alignment layer ($V_b > V_{\text{th}}$ and $\epsilon_{r,\text{eff},\perp} < \epsilon_{r,\text{eff}} < \epsilon_{r,\text{eff},\parallel}$). **c** The LC molecules are oriented parallel to the electric field of the IMSL ($V_b > V_{\text{sat}}$ and $\epsilon_{r,\text{eff}} = \epsilon_{r,\text{eff},\parallel}$)

The director can be realigned by applying an external bias voltage V_b across the signal and the ground electrodes (see Sect. 2.1.2). However, the surface anchoring resists to the realignment caused by the electrical field [YW06]. Only after a threshold voltage is exceeded the molecules are realigned as equilibrium between the applied field and the anchoring force of the alignment layer. This threshold phenomenon is well-known as *Fréedericksz transition* [CH97, YW06]. For the IMSL type LC devices, where the splay deformation is dominant, the required threshold voltage V_{th} is [Goe09]

$$V_{th} = \pi \sqrt{\frac{K_{11}}{\varepsilon_0 \Delta \varepsilon_r}}. \quad (2.31)$$

Increasing the applied bias voltage dominates the alignment by the external field and therefore, the angle between $\vec{n}$ and the electric field of the IMSL decreases. Eventually, a saturation state is achieved [Goe09], where the molecules are parallel to the electric field of the IMSL. In this case, $\varepsilon_{r,\parallel}$ and $\tan \delta_{\parallel}$ (see Eq. (2.30)) are effective and define the complex parallel effective permittivity $\underline{\varepsilon}_{r,\text{eff},\parallel}$ (see Appendix A.3.3).

Response Times

Time interval required for the transition from an equilibrium state into another is defined as *response time* of the LC devices [Mar08, Goe09]. The response time depends on the height of the LC layer h_{LC} , alignment method and the LC material itself. In this work, two different response times are frequently used. These are given for two extreme alignments of the director, which are either from perpendicular to parallel or parallel to perpendicular alignments with respect to the electric field of the IMSL. For the first one ($\perp$ to $\parallel$), a bias voltage V_b is applied and the time interval is denoted as t_{on} . For the second one ($\parallel$ to $\perp$), the applied voltage is released and the desired molecular orientation is forced by the alignment layer. This is denoted as t_{off} . The formulas for t_{on} and t_{off} are [Mar08]

$$t_{on} \propto \frac{\gamma_{LC} h_{LC}^2}{\Delta \varepsilon_r (V_b^2 - V_{th}^2)} \quad \text{and} \quad t_{off} \propto \frac{\gamma_{LC} h_{LC}^2}{\Delta \varepsilon_r V_{th}^2}. \quad (2.32)$$

In Eq. (2.32) γ_{LC} is rotational viscosity of the LC molecules. As can be seen from Eq. (2.32), the response times are linearly dependent to the material parameter and quadratic dependent to the LC layer thickness. Hence, the challenge is to propose novel device topologies allowing to lower LC layer thickness to reduce the response times of the LC devices.

Electrical Properties of the IMSL

The electrical length ϕ_ℓ of the variable IMSL can be written as [Che94]

$$\begin{aligned} j\phi_\ell &= \underline{\gamma} \ell_{\text{physical}} \\ &= (\alpha + j\beta) \ell_{\text{physical}} \\ &\approx \frac{j2\pi f_0}{c_0} \sqrt{\varepsilon_{r,\text{eff}}} \left(1 - j \frac{\tan \delta_{\text{eff}}}{2} + \frac{(\tan \delta_{\text{eff}})^2}{8} \right) \ell_{\text{physical}} \end{aligned} \quad (2.33)$$

since the effective relative permeability of LC is $\underline{\mu}_{r,\text{eff}} \approx 1$ and LC is a low-loss dielectric that is $\Im(\underline{\varepsilon}_{r,\text{eff}}) \ll \Re(\underline{\varepsilon}_{r,\text{eff}})$. In Eq. (2.33), $\underline{\gamma}$ is complex propagation constant of the IMSL, including the attenuation α and propagation β constants, ℓ_{physical} is physical length of the IMSL, f_0 is operating frequency and c_0 is speed of light in vacuum ($\approx 3 \times 10^8$ m/s). The resultant phase shift ϕ_β can be written as

$$\phi_\beta = \Im(j\phi_\ell) = \beta\ell_{\text{physical}} \approx \frac{360^\circ}{c_0} f_0 \ell_{\text{physical}} \sqrt{\varepsilon_{r,\text{eff}}} \quad (2.34)$$

since $(\tan \delta_{\text{eff}})^2/8 \ll 1$ in Eq. (2.33) for the low-loss LC material. It should be noted that $\varepsilon_{r,\text{eff}}$ is a voltage tunable quantity, leading to a voltage dependent phase shift. Therefore, a differential phase shift $\Delta\phi_\beta$ can be defined depending on the applied voltage V_b . This is given by, $\Delta\phi_\beta$ is

$$\begin{aligned} \Delta\phi_\beta &= \phi_\beta(V_b > V_{\text{th}}) - \phi_\beta(V_b = 0) \\ &= \frac{360^\circ}{c_0} f_0 \ell_{\text{physical}} \sqrt{\varepsilon_{r,\text{eff}}(V_b > V_{\text{th}}) - \varepsilon_{r,\text{eff}}(V_b = 0)}. \end{aligned} \quad (2.35)$$

A maximum differential phase shift $\Delta\phi_{\beta,\text{max}}$ is achieved when $V_b \geq V_{\text{Sat}}$, where V_{Sat} is so called the saturation voltage. Meantime, the voltage dependent insertion loss IL of the IMSL is calculated by [Mue07]

$$\text{IL}(V_b) \approx 4.343 \tan \delta_{\text{eff}} \frac{2\pi f_0}{c_0} \ell_{\text{physical}} \sqrt{\varepsilon_{r,\text{eff}}(V_b)} \quad [\text{dB}]. \quad (2.36)$$

As can be seen in Eq. (2.35) and (2.36), both differential phase shift and the insertion loss are proportional to ℓ_{physical} . The common parameter for quantifying the RF performance of a variable delay line is a frequency dependent variable delay line efficiency (or phase shifter efficiency) η_{VDL} . It is defined by the ratio of the maximum differential phase shift and the highest insertion loss in all tuning states. This can be formulated by

$$\eta_{\text{VDL}} = \Delta\phi_{\beta,\text{max}} / \text{IL}_{\text{max}} \quad [^\circ/\text{dB}] \quad (2.37)$$

In general, the aim is to achieve the highest possible differential phase shift accompanied by the lowest insertion loss which leads to a high η_{VDL} .

2.3 Summary

This section presented the fundamental material properties of LCs and their usage in a variable delay line (VDL) as tunable dielectric. In Sect. 2.1, it was explained that the LC molecules are uniaxial anisotropic materials, which is originated from its rod-like

shape. This results in orientation dependent responses of the molecules to several physical phenomena. In particular, their special responses to the electromagnetic fields were described. In case of an electrical field only, such a response refers that the LC molecules feature different polarization depending on how the field is incident on the molecules. This results in different macroscopic permittivities. Given that, the orientation between the electric field and the molecules has to be controlled to exploit LCs as tunable dielectrics. For this manner, system's total free energy was described. The factors contributing to this energy were the elastic forces, external electromagnetic fields and surface anchoring forces. In the second part, the LC based inverted microstrip delay line was introduced. Especially, the technology required and working principle of the device were presented. In an application, the LC molecules are aligned by using two methods simultaneously. First, an alignment layer anchors the molecules parallel to the surfaces. Second, the molecules are oriented parallel to the applied biasing field, which is perpendicular to the surfaces. In relation to the first part, the both surface anchoring and bias field increase the system's total free energy initially. Then the molecules reach its equilibrium state gradually while minimizing the total free energy. Therefore, a continuous tunability of the LC material is possible depending on the applied bias voltage. Finally, an essential parameter was defined to measure the quality of different delay lines. This was the delay line efficiency η_{VDL} , which was determined by the ratio of the maximum differential phase shift and the highest insertion loss.

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