Liquid Crystal Displays

ADDRESSING SCHEMES AND ELECTRO-OPTICAL EFFECTS,
SECOND EDITION

Ernst Lueder
University of Stuttgart, Germany
and Electro-Optical Consultancy, LLC, USA

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Liquid Crystal Displays

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To Helen

Whose assistance and patience made this book possible

Contents

Foreword

Since publication of the first edition of this book nine years ago, much has happened. Dominance of the CRT has been replaced by dominance of LCDs not only for computer monitors but also for television, control room and signage applications. The need for faster response, wider viewing angles, better colour rendition, thinner displays and lower energy consumption has motivated extraordinary developments and this last decade has been one of unprecedented change. A fact known just to a few is that the first edition of this book was the Wiley-SID series' best seller. I am therefore delighted that Ernst Lueder has agreed to write a second edition.

The following new sections have been added: fast blue phase materials, which have the sub-millisecond switching times required for 240Hz refresh rate TVs; multidomain VA cells for TV applications; the addressing requirements of VA cells to achieve TV speeds (which often requires parallel addressing); motion blur and its remedies and last, transfer techniques of TFTs fabricated at high temperature on to flexible substrates.

The sections on components for LCDs, flexographic printing, ink jet printing, surface properties for printing and cell building by lamination have been updated.

Thus the original purpose stated by Professor Lueder in his preface to the first edition – to condense into one volume all the basic information that is needed to understand the operation and the building of liquid crystal displays – will now be met by this second edition, which I am confident will see equal success.

Anthony Lowe
Braishfield, UK, 2009

Preface to the First Edition

The overriding purpose of this book, as further outlined in the Introduction (Chapter 1), is to condense in one single volume all the basic information that is needed to understand the operation and the building of liquid crystal displays. This requires a treatment of a wealth of electro-optical effects as well as a description of the rich variety of addressing schemes. The latter has not been done for more than a decade.

In the pursuit of this ambitious goal I was very fortunate to have a number of experts at my side who offered advice and assistance for writing this book. Dr. Tony Lowe, the editor of this SID- series, lent his experience in selecting the contents of this book and in focusing on special topics. His most valuable assistance is gratefully appreciated. Dr. Mike Lee from Imperial College in London enriched the chapters on addressing techniques with some most helpful suggestions and enlightening discussions. I am very grateful for his support. I am also indebted to my co-worker at Stuttgart University, Dr. Christoph Zeile, who contributed to the sections about electro-optical effects by numerous discussions and his helpful observations. I thank Mrs. Heidi Schuehle very much for typing the manuscript with competence and patience and for alerting me to various inconsistencies. Mr. Rene Troeger has skillfully drawn the figures for which I am very grateful.

Finally, I wish to thank John Wiley for their always pleasant cooperation as well as for the attractive production of the book.

Ernst Lueder
Scottsdale, Arizona, 2000

Preface to the Second Edition

The second edition of *Liquid Crystal Displays* focuses on the latest LCDs with wide viewing characteristics, short optical response times and accelerated relaxation, the suppression of motion blur, thin LED backlights and printed layers replacing costly photolithography.

I very much appreciate the valuable suggestions by Dr. Tony Lowe, the editor of the Wiley SID series in Display Technology, and expert insights from my colleagues Dan Schott and Dr. Bob Melcher covering the wide area of current display activities. I am grateful for the diligent and skilled proofreading by Lyn Hicks and Kim Stringer. As in the first edition, I am greatly indebted to Heidi Schuehle for observantly and attentively typing the manuscript and to Rene Troeger for the accomplished and professional drawing of the figures.

About the Author

Ernst Lueder was born in 1932. At his graduation from High School he was awarded the 'Scheffel'-prize for literary achievements.

In 1962 he received his doctorate in electrical engineering, and in 1966 his Habilitation, which qualified him to teach in the area of theoretical electrical engineering.

From 1968 to 1971 he worked for Bell Telephone Laboratories in Holmdel, New Jersey, USA, undertaking research into the design of miniaturized filters and communication systems, especially in thin film technology. He established laws for optimizing the dynamic range and the signal-to-noise ratio of two-ports.

In 1971 he was appointed a full professor at the Department of Electrical Communications, and named Director of the Institute of Network and System's Theory at Stuttgart University. He specialized in the design of hybrid thin and thick film circuits, the development of sensors, thin film transistors and flat panel liquid crystal displays, in the synthesis of circuits, in the theory of communication systems and in the optimization of systems.

Since spring 1991 he has also headed a new DM 80 million laboratory for the fabrication of flat panel displays. Research activities in this laboratory include TFT- and MIM-addressed TN-, PDLC- and GH-displays, as well as bistable FLC- and PSCT-displays.

He retired in 1999.

He was a member of the IEEE, and became an IEEE Fellow in 1985. As a member of the German Society for Information Technology, ITG, he was for two years a member of the society's board of directors. He served in the Scientific Advisory group for the Heinrich- Hertz Institute in Berlin, and was chairman of this group for four years. Starting in 1994 he participated as a member of the SID board of directors, as a director of the Mid-Europe chapter, and as vice-president for Europe. Further, he was a member of the SPIE, ISHM, FKTG, the German society for broadcast and television technology, and the New York Academy of Sciences (NYAS).

In 1991 he was awarded the order of merit 1st Class of the Federal Republic of Germany, and in 1998 he became a Fellow of SID.

In 2009 he received SID's Slottow-Owaki Award.

1

Introduction

Liquid Crystal Displays (LCDs) have established a firm foothold on the market as flat panel displays for computers, transportation, communication (especially in its mobile version), instrumentation and, in the future, with increasing importance for television. The understanding of LCDs requires knowledge about the various electro-optical effects of liquid crystal cells, and about the control of the grey shades and colours in the picture elements (pixels, or pels) by addressing circuits.

The electro-optical effects are based either on the propagation of polarized light through anisotropic liquid crystal cells, or on the propagation of unpolarized light through scattering cells.

The grey shade controlling voltage across each pixel is provided mainly by either passive matrix or active matrix addressing. In passive matrix addressing, the voltage in each pixel is generated by voltages at the end of the rows (or lines) and the columns of the display, whereas active matrix addressing uses Thin Film Transistors (TFTs) or Metal Insulator Metal (MIMs) devices as switches in each pixel.

Further topics are the fabrication of conductors, transparent electrodes, TFTs and MIMs with thin film technology, the generation of colour filters, and the assembly and bonding of liquid crystal cells.

It is not only manufacturers of LCDs but also the vast community of users which need to grasp the essence of the physics and engineering of LCDs. The understanding of these topics enables users to select the appropriate LCD for their application, to tailor the optic performance to their needs (e.g. by optimizing the waveform at the addressing circuit by the addition of performance-enhancing sheets, or by selecting the appropriate location of the external ICs for signal processing), as well as for storing and feeding in of the picture information.

Further, manufacturers and users should be enabled to judge the suitability of future developments and trends for their purposes.

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2 INTRODUCTION

The first section of this book presents an overview of the properties of liquid crystal materials and a phenomenological description of the most frequently used type of LCDs, the TFT-addressed twisted nematic (TN) LCD. The aim is to familiarize readers with the main aspects of LCDs, to introduce most of the terminology, to establish an understanding without doing calculations, and to alleviate the subsequent more detailed discussion without losing the overall picture in which the details are embedded.

The remaining portions of the book are devoted to an analytical investigation of the electro-optic effects, and to an elaboration of the addressing schemes complemented by the manufacture of the thin film components.

Applications are centred around transmissive and reflective displays and light valves for projectors. Plastic substrates and printing of layers replacing vacuum processes are examples of an emerging new display technology.

2

Liquid Crystal Materials and Liquid Crystal Cells

2.1 Properties of Liquid Crystals

2.1.1 Shape and phases of liquid crystals

Most liquid crystals consist of molecules shaped like the rod in Figure 2.1(a). The direction of the long axis is called the *director*, given by the vector $\vec{n}$, which is an apolar vector as $\vec{n}$ and $-\vec{n}$ are equivalent. Rod-shaped molecules are also termed *calamitic*. Other shapes of molecules are disc-like or discotic, as in Figure 2.1(b), and lath-like.

We focus on calamitic (Bahadur, 1990; Demus *et al.*, 1998a,b) liquid crystals as they are the most important for applications. Below the melting point T_m they are solid, crystalline and anisotropic, whereas above the clearing point with temperature $T_c > T_m$ they are a clear isotropic liquid. In the mesophase in Figure 2.2 in between T_m and T_c, the material has the appearance of a milky liquid, but still exhibits the ordered phases shown in Figure 2.2. These phases are now described in the sequence given by increasing temperature. The first phase above T_m is the smectic *C* phase (smectic is derived from the Greek word for soap). As all smectic phases, it is ordered in two dimensions. The molecules are arranged with random deviations tilted to the plane of the layer. In the smectic *A* phase the directors of the molecules are again with random deviations perpendicular to the plane of the layer. Next to the clearing point, the nematic phase appears with only a one-dimensional order (nematic in Greek means a thread, indicating the thread-like defects in the material). All members of the mesophase are anisotropic, as is the solid phase.

Some more phases of minor importance for display applications are below the smectic *C* phase, the smectic B_{hex} phase (hexatic *B* phase), with the same layers as smectic *C* but a short

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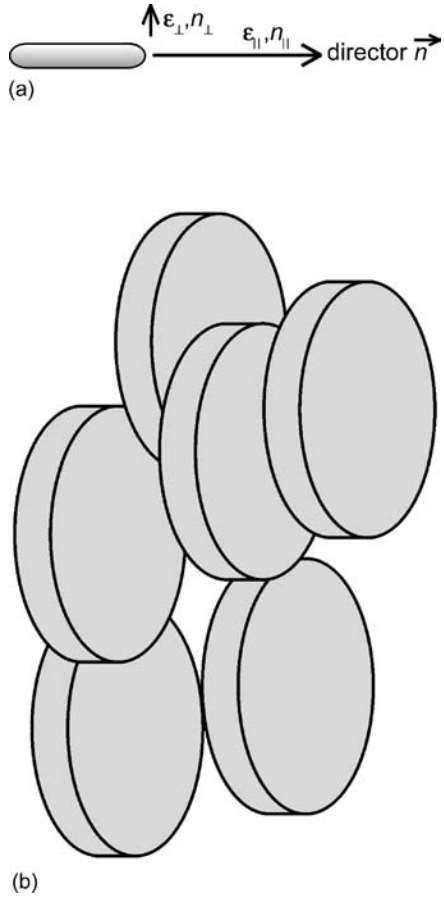

Figure 2.1 (a) Rod-like or calamitic liquid crystal molecule with director n; (b) disc-like or discotic liquid crystal molecules

range close packed hexagonal structure, in Figure 2.3(a) seen against the director $\vec{n}$; in this direction, the smectic C phase exhibits the irregular structure in Figure 2.3(b). The phases J, G, E, K and H are located above T_m, and are smectic-like soft crystals with a long range order.

The smectic C^* phase (chiral smectic C phase) in Figure 2.4 possesses a layered smectic structure in which the parallel directors of the molecules are rotated from layer to layer on the surface of a cone, resulting in a helix.

If chiral compounds such as cholesterol esters are added, the nematic phase changes to the cholesteric phase in Figure 2.5, which exhibits a helical structure in which, again, the director is rotated from layer to layer.

An as yet poorly understood peculiarity are the blue phases which occur in a small temperature range between the cholesteric and solid anisotropic phase.

More than 20 000 calamitic compounds are known.

Liquid crystals, the phases of which change with temperature, are called *thermotropic*. Those which change with the concentration of solvents and temperature are *lyotropic*.

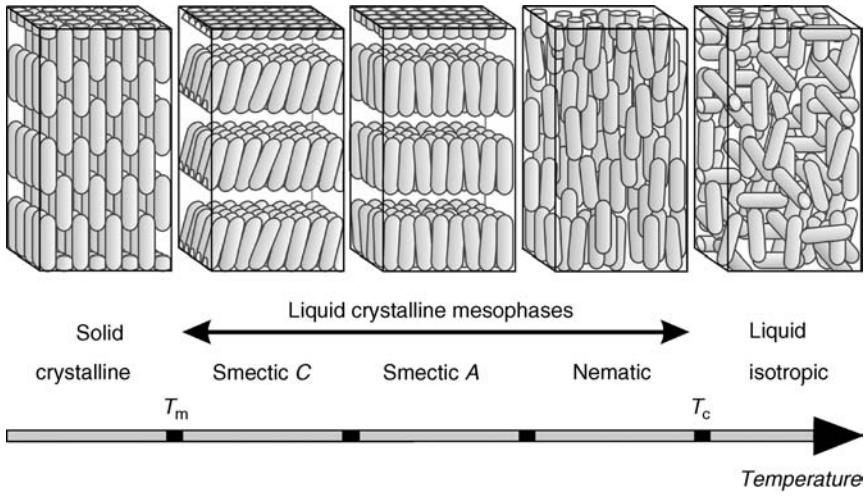

Figure 2.2 Phases of LC materials versus temperature

Calamitic and thermotropic liquid crystals are important for LCDs. Their nematic phase is the basis for both the most widely used Twisted Nematic (TN) cell with active matrix addressing, and for the SuperTwist Nematic (STN) cell with passive matrix addressing. Further LCDs based on calamitic and thermotropic nematic phases are Polymer Dispersed Liquid Crystals (PDLCs) and guest-host-LCDs. The smectic *A* and smectic C^* phases provide bistable ferroelectric LCDs with passive matrix addressing. The cholesteric phase gave rise to the Stabilized Cholesteric Texture (SCT) with bistability at zero field. LCDs based on these phases will be discussed later.

To better understand electro-optical effects and electronic addressing, some materials properties have to be presented (Bahadur, 1990; Demus *et al.*, 1998a,b).

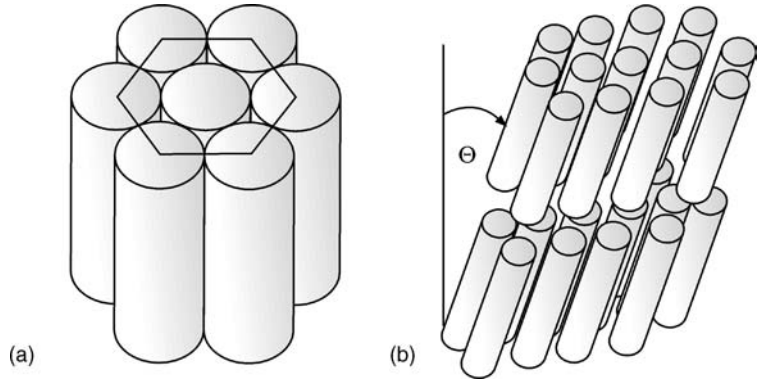

Figure 2.3 Top view of (a) the close packed hexagonal structure of the smectic B_{hex} phase, and (b) of the smectic *C* phase

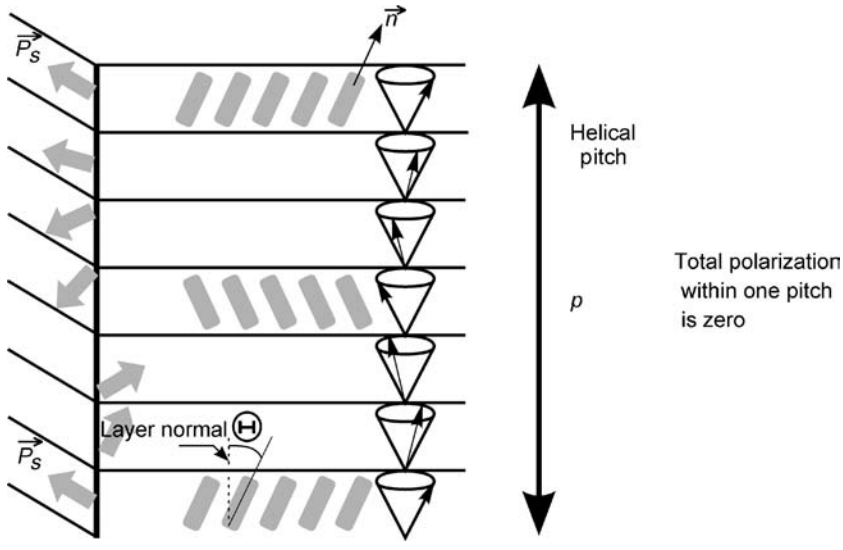

Figure 2.4 The helix in a layered structure of chiral smectic *C* liquid crystals with polarization $\vec{P}_s$ perpendicular to $\vec{n}$

2.1.2 Material properties of anisotropic liquid crystals

The rod-like molecules have a head and a tail, which is, however, not taken into account by the direction of $\vec{n}$. Molecules in an unordered alignment exhibit an average director.

The individual molecules have an angle Θ to this average director. The order parameter S of a phase is defined by (Tsvetkov, 1942)

$$S = \frac{1}{2}\langle 3\cos^2 \Theta - 1\rangle, \tag{2.1}$$

where the bracket indicates that the average over a large number of molecules with angles Θ is taken. In a perfectly ordered state, $\Theta = 0$, and hence $S = 1$. A completely unordered phase has $S = 0$. In typical nematic phases, S lies in the region of 0.4 to 0.7, indicating that the molecules are rather disordered.

The energy needed for a phase transition, e.g., from smectic *A* to smectic *C*, is characterized by a transition enthalpy in kJ/mol. Extensive investigations of phase transitions have revealed the temperature dependence of physical parameters such as the helical pitch, the viscosity or the elastic coefficients.

Due to the ordered structure, all phases between T_m and T_c are anisotropic, meaning that all dielectric, optical and mechanical properties depend upon the direction.

The dielectric constant is $\varepsilon = \varepsilon_r \varepsilon_0$, where $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m stands for the permittivity in vacuum and ε_r for the relative dielectric constant. This means, as shown in Figure 2.1, $\varepsilon_r = \varepsilon_{\|}$

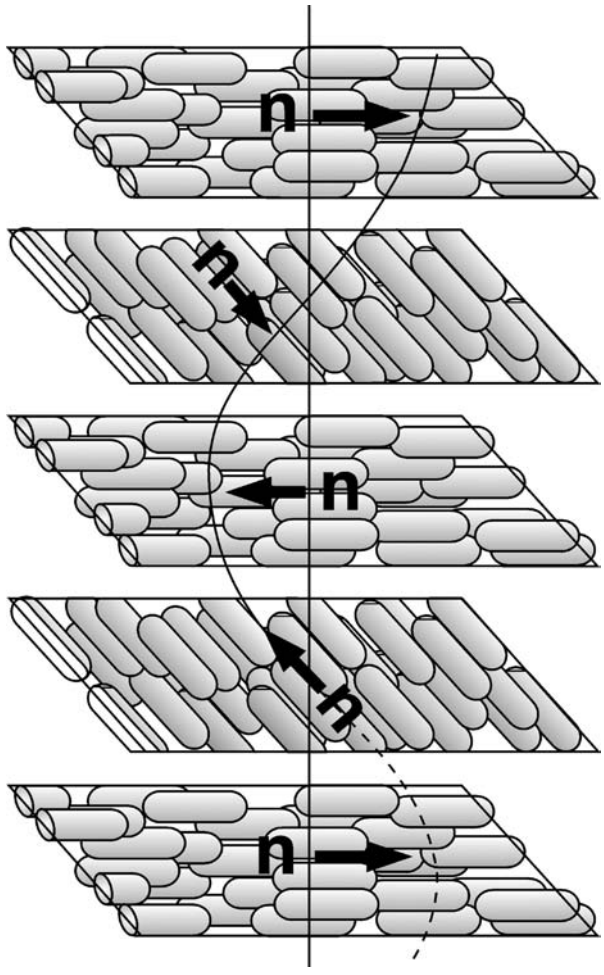

Figure 2.5 Helix of the cholesteric phase

in the direction parallel to the director and $\varepsilon_r = \varepsilon_\perp$ perpendicular to the director, leading to the dielectric anisotropy

$$\Delta\varepsilon = \varepsilon_{||} - \varepsilon_\perp. \tag{2.2}$$

Materials with $\Delta\varepsilon > 0$ are called *p*-type; their molecules align with the director parallel to the electric field, whereas in *n*-type materials with $\Delta\varepsilon < 0$, they align perpendicular to the field. This holds independent of the direction of the field vector. Values for $\Delta\varepsilon$ are found in the range from -0.8 to -6 and from 2 to 20. The addition of cyanogroups enlarges $\Delta\varepsilon$, whereas fluorine atoms in materials with $\Delta\varepsilon < 0$ lower $\Delta\varepsilon$ even further. Values for four materials are listed in Table 2.1.

The optical anisotropy Δn concerns the refractive indices n_0 for the ordinary beam of light, where the vector of the electrical field oscillates perpendicular to the optical axis that is

Table 2.1 Properties of liquid crystal materials

	ZLI-3125	14616	ZLI-2585	14627
T_C[°C]	63	54	70	48
$\Delta\varepsilon$ (1 kHz, 20 °C)	+2.4	+2.3	−4.4	−3.5
η [mm^2/s] (20 °C)	20	32	45	45
$n_0 = n_\perp$	1.4672	1.4554	1.469	1.4551
$n_e = n_\parallel$	1.5188	1.5034	1.506	1.4893
Δn (589 nm, 20 °C)	0.0516	0.0480	0.037	0.0342

perpendicular to the director and the refractive index n_e for the extraordinary beam of light, where the field vector oscillates in parallel to the director. Hence we obtain

$$n_0 = n_\perp, \tag{2.3}$$

and

$$n_e = n_{||}, \tag{2.4}$$

and the optical anisotropy

$$\Delta n = n_{||} - n_\perp = n_e - n_0. \tag{2.5}$$

More explanation about the optic axis and the ordinary beam will be given in Chapter 6. The refractive index n is based on optical frequencies which are very high. Therefore, the equation known from Maxwell's theory (Born and Wolf, 1980)

$$n = \sqrt{\varepsilon_r} \quad \text{for} \quad \mu_r = 1 \tag{2.6}$$

provides for frequencies approaching infinity:

$$\varepsilon_{r||\infty} = n_{||}^2, \tag{2.7}$$

$$\varepsilon_{r\perp\infty} = n_\perp^2 \tag{2.8}$$

and

$$\Delta\varepsilon_{r\infty} = n_{||}^2 - n_\perp^2. \tag{2.9}$$

The refractive indices depend upon the wavelength λ. Values for Δn lie in the range Δn [0.04, 0.45]; some values are listed in Table 2.1. As a rule, materials with a high Δn are not stable to UV light. Due to the optical anisotropy, the material is birefringent. The speed of light is (Born and Wolf, 1980)

$$v = c/n(\lambda), \tag{2.10}$$