LIQUID CRYSTAL DISPLAYS

Fundamental Physics and Technology

Robert H. Chen

WILEY

SID Series in Display Technology

Liquid Crystal Displays

Wiley-SID Series in Display Technology

Series Editor:
Anthony C. Lowe

Consultant Editor:
Michael A. Kriss

Display Systems: Design and Applications
Lindsay W. MacDonald and Anthony C. Lowe (Eds.)

Electronic Display Measurement: Concepts, Techniques, and Instrumentation
Peter A. Keller

Reflective Liquid Crystal Displays
Shin-Tson Wu and Deng-Ke Yang

Colour Engineering: Achieving Device Independent Colour
Phil Green and Lindsay MacDonald (Eds.)

Display Interfaces: Fundamentals and Standards
Robert L. Myers

Digital Image Display: Algorithms and Implementation
Gheorghe Berbecel

Flexible Flat Panel Displays
Gregory Crawford (Ed.)

Polarization Engineering for LCD Projection
Michael G. Robinson, Jianmin Chen, and Gary D. Sharp

Fundamentals of Liquid Crystal Devices
Deng-Ke Yang and Shin-Tson Wu

Introduction to Microdisplays
David Armitage, Ian Underwood, and Shin-Tson Wu

Mobile Displays: Technology and Applications
Achintya K. Bhowmik, Zili Li, and Philip Bos (Eds.)

Photoalignment of Liquid Crystalline Materials: Physics and Applications
Vladimir G. Chigrinov, Vladimir M. Kozenkov and Hoi-Sing Kwok

Projection Displays, Second Edition
Matthew S. Brennesholtz and Edward H. Stupp

Introduction to Flat Panel Displays
Jiun-Haw Lee, David N. Liu and Shin-Tson Wu

LCD Backlights
Shunsuke Kobayashi, shigeo Mikoshiba and Sungkyoo Lim (Eds.)

Liquid Crystal Displays: Addressing Schemes and Electro-Optical Effects, Second Edition
Ernst Lueder

Transflective Liquid Crystal Displays
Zhibing Ge and Shin-Tson Wu

Liquid Crystal Displays: Fundamental Physics and Technology
Robert H. Chen

Liquid Crystal Displays

Fundamental Physics and Technology

Robert H. Chen

National Taiwan University

WILEY

A John Wiley & Sons, Inc., Publication

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Chen, Robert H., 1947-
Liquid crystal displays : fundamental physics & technology / Robert H. Chen.
p. cm.
Includes index.
ISBN 978-0-470-93087-8 (cloth)
1. Liquid crystal displays. 2. Liquid crystal devices. I. Title.
TK7872.L56C44 2011
621.3815'422–dc22

2010045220

Printed in the United States of America

Obook ISBN 978-1-118-08435-9
ePDF ISBN 978-1-118-08433-5
ePub ISBN 978-1-118-08434-2

10 9 8 7 6 5 4 3 2 1

Contents

Series Editor's Foreword

For once, I found it difficult to know how to begin. Writing forewords for the Wiley-SID series (this is my twentieth) is a demanding but extremely pleasurable task. In a qualitative sense this foreword is no different; it is the book that is different. Let me explain.

On reading two sample chapters of Robert Chen's manuscript, I realized that this would be like no other book in the series. Not only was its intended scope to cover the entirety of liquid crystal display (LCD) science and technology from the fundamentals of mathematics and physics to the production of products, but it was written by an author who has not only the academic background but also the experience as an executive in several major companies to provide first-hand insight and understanding of the global development of what is now a predominantly Asia-based industry.

The author has covered his subject matter with great proficiency and style. But there is more: the book is filled with interesting footnotes, often witty, of technical or historical relevance or a combination of all three. The most significant references are cited, but this is not a book where the reader will find a comprehensive list of all relevant publications. Other books in the series which address specific aspects of the technology provide that.

The unique feature of this book is that when discussing the global industrial development of the LCD industry, the author provides an account which is unprecedented—certainly in this series—in its level of detail, its understanding of cultural influences, and its degree of frankness. I believe that few will disagree with his arguments, but some will find it uncomfortable reading.

So, as the author aspires, this book may be read at several different levels. Anyone who reads it will find it rewarding as a technical introduction to the field replete with a sense of history. They will realize that this industry, which has made most of its growth in the last two decades, is built on the shoulders of scientific progress going back two centuries. Last, but certainly not least, I hope that they will find it a first-rate literary experience.

Anthony C. Lowe
Series Editor

Braishfield, UK

Preface

The liquid crystal display (LCD) has become the principal modern medium for visual information and image appreciation. It is now a pervasive and increasingly indispensable part of our everyday lives. Apart from its utility, this marvelous device relies on a science and technology that I believe makes the device all the more attractive and interesting.

This book is organized to highlight the basic physics, chemistry, and technology behind this intriguing product, and while describing the LCD, I attempt to provide some insight into that physics, chemistry, and technology. I believe that the history of the development of the LCD is equally intriguing, and thus I make excursions into tales of the principal contributors and their achievements and thinking in their research. Finally, the allure of liquid crystal television has made it a coveted symbol of modern life worldwide, and so apart from the technical descriptions, I also describe how the LCD business has become a global enterprise.

I attempt to describe the physics and technology in a clear and simple manner understandable to an educated reader. Further, I have endeavored to pay attention to literary exposition as far as I am able, in the hope that, in addition to describing the technology, the book may also provide some literary enjoyment. Of course whether I have succeeded here depends on the reader's assessment.

This book is written at an introductory level suitable for advanced undergraduates and first-year graduate students in physics and engineering, and as a reference for basic concepts for researchers. I also have tried to make the scientific and technical descriptions intuitively clear so that any educated person who has studied calculus can easily understand the exposition and thereby understand and appreciate liquid crystal displays and the science behind them.

Readers new to the field should read this book in chapter sequence to understand the gradual development of the LCD and the science and engineering involved; advanced researchers and practitioners can select the chapters and sections to find descriptions of the background of those selected topics.

Robert H. Chen

Taipei, Taiwan
June 2011

Acknowledgments

I would like to thank Professor Paul Nahin, for his books on mathematics and engineering from which I learned a great deal and borrowed liberally, and for his kind encouragement; Simone Taylor, Editorial Director at Wiley, who saw the potential of the manuscript and undertook the task of getting this book published while guiding me along the way; and most gratefully Dr. Anthony C. Lowe, the Editor of the Wiley-SID Series, who corrected mistakes and blocked metaphors (I am of course solely responsible for any that have gotten through). Further thanks are due to my wife Fonda, for her patient understanding; my daughter Chelsea, for cheerful enthusiasm; and my cat Amao, for accompanying me all the while. For my technical education, I would like to thank Dr. Hsu Chenjung, whose intelligence inspired me; Professor Andrew Nagy of Michigan and Professor Von Eshleman of Stanford, who supported me; and Chimei Optoelectronics Corporation where I learned about LCDs. Many of the drawings were done by Ingrid Hung at Chimei and Tsai Hsin-Huei of the National Taiwan University of Art.

About the Author

Robert Hsin Chen

Robert Hsin Chen is an adjunct professor at National Taiwan University and also teaches at Tsinghua and Jiaotong Universities in Taiwan. He was formerly a Senior Vice-President at Chimei Optoelectronics, a Director at Taiwan Semiconductor Manufacturing Company, Vice-President at Acer Corporation, and Of Counsel at the law firm Baker & McKenzie. Dr. Chen has a PhD from the University of Michigan (Space Physics Research Lab), a postdoctorate from Stanford University (Center for Radar Astronomy), and a JD from the University of California at Berkeley. He is a member of many scientific organizations, as well as the California Bar, and is a registered patent attorney; he has written many articles for international scientific and intellectual property journals, and is the author of *Made in Taiwan* (1997) and *Crystals, Physics, and Law* (in Chinese, 2010).

1

Double Refraction

The operation of liquid crystal displays is founded on the phenomenon of the double refraction of light as first recorded in Denmark by Erasmus Bartholinus in 1670. A piece of translucent calcite apparently divides incident light into two streams, producing a double image. This is depicted in Figure 1.1, as shown by the offset of the word "calcite." At about the same time in the Netherlands, Christian Huygens discovered that the light rays through the calcite could be extinguished by passing them through a second piece of calcite if that piece were rotated about the direction of the ray; this is depicted in Figure 1.2. This may be observed by taking two pairs of polarizing sunglasses and rotating them relative to each other.

One hundred and thirty-eight years later, in 1808, a protégé of the famous French mathematician Fourier, Etienne Louis Malus, observed that light reflected from a window, when passing through a piece of calcite also would change intensity as the calcite was rotated, apparently showing that reflected light was also altered in some way. The intensity of the light changed in both cases because the molecules of calcite have a crystal order that affects the light in an intricate but very understandable way called *polarization*.

Liquid Crystal Displays, First Edition. Robert H. Chen.

Figure 1.1 Double refraction in calcite. From http://www.physics.gatech.edu/gcuo/lectures.

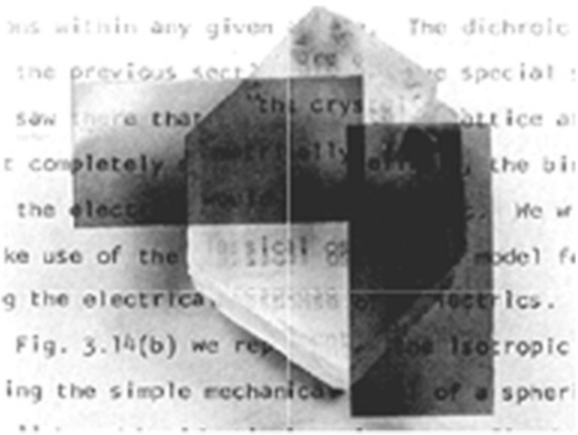

Figure 1.2 Two pieces of calcite at an angle. From http://www.physics.gatech.edu/gcuo/lectures.

It would be another 80 years later in Austria that double refraction, also called *birefringence*, and light polarization would be observed, not in crystalline rocks, but in a viscous liquid, later to be called a "liquid crystal." Although no doubt intriguing to natural scientists, intensive investigation of liquid crystals had to wait for yet another 80 years, when commercial interests provided the impetus for further study.

Briefly, a liquid crystal display can reproduce an image of a scene through the use of a video camera that, upon receiving the light reflected from the scene through its lens, in accord with the photoelectric effect first explained by Einstein, an electric current is generated in a metal when struck by light of sufficient energy, the current being proportional to the intensity of that light. That current is then transmitted to transistors that control an analog voltage that is applied to a pair of transparent electrode plates. Those plates enclose a thin layer of liquid crystal between them, and the voltage on the plates generates an electric field that is used to control the orientation of the electric dipole moment of the liquid crystal molecules, causing them to turn. Then light from a light source placed behind the liquid crystal layer, after being linearly polarized by a polarizer, will have its polarization states altered by the different orientations of the liquid crystal molecules, in accord with the liquid crystal's degree of birefringence. The beauty of the liquid crystal display is that the birefringence effected by a liquid crystal is precisely controllable by that electric field. The different polarization states of the light in conjunction with a second polarizer changes the brightness of the light emanating from the backlight source, and that modulated brightness can represent the light intensity of the original scene; the millions of picture elements so produced then combine to form an image that replicates the original scene.

Liquid crystal displays thus are based on an optical phenomena of electrically controlled birefringence and polarization, which can only be understood through knowledge of the interaction of light and matter.

However, light may be familiar to everybody, but Samuel Johnson succinctly observed that [1]*

> We all know what light is, but it is not easy to tell what it is.

* Samuel Johnson (1709–1784), English lexicographer, critic, poet, and moralist who completed the *Dictionary of the English Language* in 1755; Johnson is one of the preeminent authorities on the English language.

The understanding of light can gainfully begin at the outset with an appreciation of light as described by the Maxwell equations.

Reference

[1] Johnson, S. 1755. *Boswell's Life; Dictionary of the English Language*; quoted in Clegg, B. 2001. *Light Years*. Piatkus, London.

2

Electromagnetism

The scientific study of light has more than 1500 years of illustrious history. Beginning with Euclid and his geometrical study of light beams, the list of luminaries includes the great scientist/mathematicians Descartes, Galileo, Snell, Fermat, Boyle, Hooke, Newton, Euler, Fourier, Bartholinus, Huygens, Malus, Gauss, Laplace, Fresnel, Hamilton, Cauchy, Poisson, Faraday, and Maxwell. From those classical beginnings, the theories have evolved into atomic and quantum mechanical theories of light, developed by the great physicists Planck, Bohr, Heisenberg, Schrodinger, Born, Dirac, and Einstein. With such brainpower as driving force, the subsequent profound understanding of light should not have been unexpected.

The first mathematical treatments of light however quickly became mired in an ineluctable *æther*; that is, the early physical theory of *action at a distance* required the presence of an all-pervasive, elastic, and very subtle material to serve as the medium through which forces could transfer their effect. Simply put, although often not easy to apply, the interaction between two separate bodies is determined by a mechanical transfer of force acting along a line connecting the bodies, that force weakening with the distance between the bodies. The action at a distance theory could successfully describe many observations in common experience, the most cogent example being sea waves. But this “æthereal” view of Nature confounded even its proponents

Liquid Crystal Displays, First Edition. Robert H. Chen.

when faced with the equally naturally observed electromagnetic phenomena, such as the effects of a magnet on a current-carrying wire and the invisible transfer of electromagnetic forces through a vacuum.

The great mathematical physicist Maxwell too was caught up in the æthereal action at a distance and a physics based on mechanics and fluid dynamics, so his initial efforts to mathematically describe the observed electromagnetic phenomena were based on such conceptualizations of electrical energy as the stored energy in a spring, and magnetic energy as the kinetic energy of a flywheel, and of course, electric current was seen as flowing water (an analogy nonetheless still used today). When Maxwell faced the *interaction* between electricity and magnetism, however, he was confounded: how would an electric current in a wire produce a concentric circulating magnetic force, and how would a moving magnet near a wire coil produce an electric current in that coil? The description of all the parts and the mutual interactions among them using purely mechanistic and fluid formulations would result in some strange machines [1].

For example, the *deus ex machina* sketched in Figure 2.1 consisting of an interconnected contraption of balls, wheels, gears, and tubes. Solidly ingenious as it was, in order to explain what the experimentalists Oersted, Ampere, and Faraday had observed in Nature and experiments, it also was clear that this mechanical beast was going to be very difficult to tame.

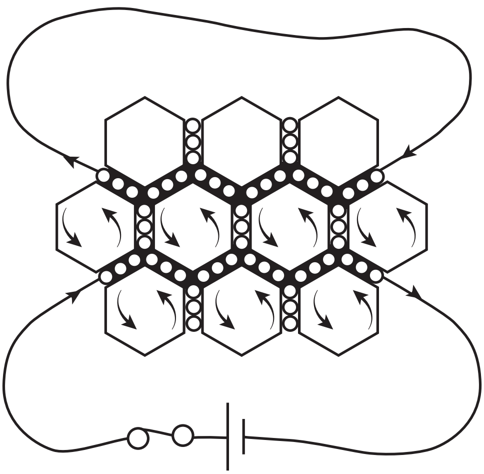

Figure 2.1 Maxwell's electromagnetic mechanical machine. From Mahon, B. 2003. *The Man Who Changed Everything, The Life and Times of James Clerk Maxwell*, Wiley, p. 100.

Indeed, the intricate *pas de deux* of electromagnetic forces at the time was clearly observed but only murkily understood. One force apparently engenders another force, but the generation clearly was not acting in the line through the distance between the bodies producing those forces. In a vain attempt to tie the forces, the construction of springs, flywheels, balls, and interconnecting water pipes, ropes, pulleys, and gears became just too complicated and contrived to attain the simplicity and elegance sought by a mathematical theoretician like Maxwell. But worst of all, the bits and pieces could not hope to operate to produce electromagnetic forces in a vacuum; the mechanical theory still relied upon the ethereal yet ubiquitous *æther* and all its attendant mystery. If Maxwell was to overcome the *æther's* dark art, he needed the power of mathematical physics to smite that *ævil* witch.

Faraday's Intuitive Field

The untenable complications wrought by the purely mechanistic and æther-laden action at a distance were unraveled by the great experimentalist Faraday. Having had little formal education, Faraday was not equipped to use mathematical physics to describe what he observed; instead he depended on his (considerable) powers of intuition.

To start off, a point charge (q) acted upon by an electric force (E) will experience a mechanical force (F) described simply by the equation $F = qE$, where the force is directly proportional to, and in the same direction as, the electric force. But Faraday observed that the effect that a magnet has on a current-carrying wire is to move it, as shown in the schematic drawing in Figure 2.2 as the dashed line. That is, when the current is turned on, the wire near the magnet will move horizontally in a direction perpendicular to the direction of the South to North poles of the magnet, so mathematically the magnetic force emanating from the magnet produces a mechanical force F that can be described by the vector equation $F = qv \times B$. The equation says that a point charge traveling in the wire at a velocity (v) will be subject to a force (F) that is proportional and perpendicular to both v and B (the *cross product* in the vector calculus). The electric and magnetic forces combined in a single equation is the well-known Lorentz force,

$$F = q(E + v \times B).$$

From the above equation, it is clear that while there is a force (E) associated directly with an electric charge (q), a magnetic force requires motion (v) to act.

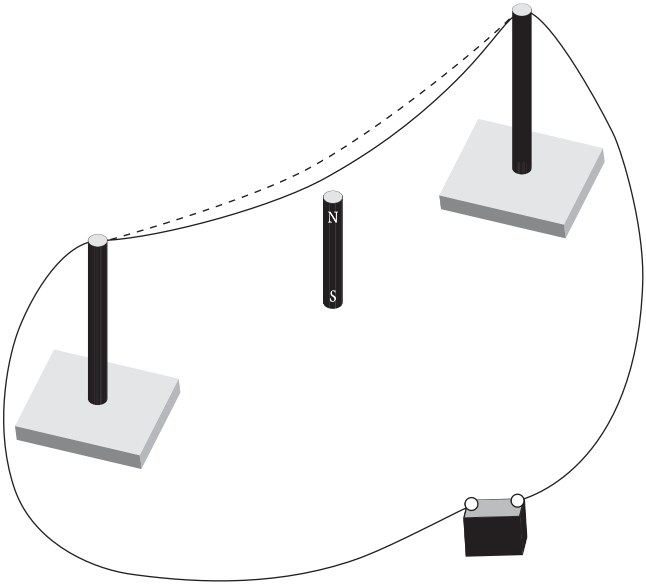

Figure 2.2 Magnetic force acting on a current in a wire moves the wire.

Other observations were not so simply describable, however; for example, the subsequent mutual interaction of the current, the generated magnetic force, and the magnet's magnetic force.

To help matters along, Faraday here visualized the force effect of the magnet as a pattern of *lines of force*, the grouping together of which constituted a *flux* of force lines, the number and closeness of the lines representing the density of the flux, and that flux density indicating the strength or intensity of the magnetic force. Faraday's own drawing of the lines of force emanating from a bar magnet is shown in Figure 2.3, where he described the flux lines as a *field*. This then was the basic idea of a field to intuitively conceptualize electromagnetism.

The idea of lines of force constituting a field to describe the electric and magnetic effects was not the only pivotal concept invented by Faraday; another critical idea was that the field lines could be superimposed to describe the cumulative effect from many different sources of electric and magnetic force. This *principle of superposition* can reduce a very complicated collection of electromagnetic sources of force into a simple addition of the different contributions from the various sources. That is, at a given point in space, no matter what the distribution of the other electric or magnetic