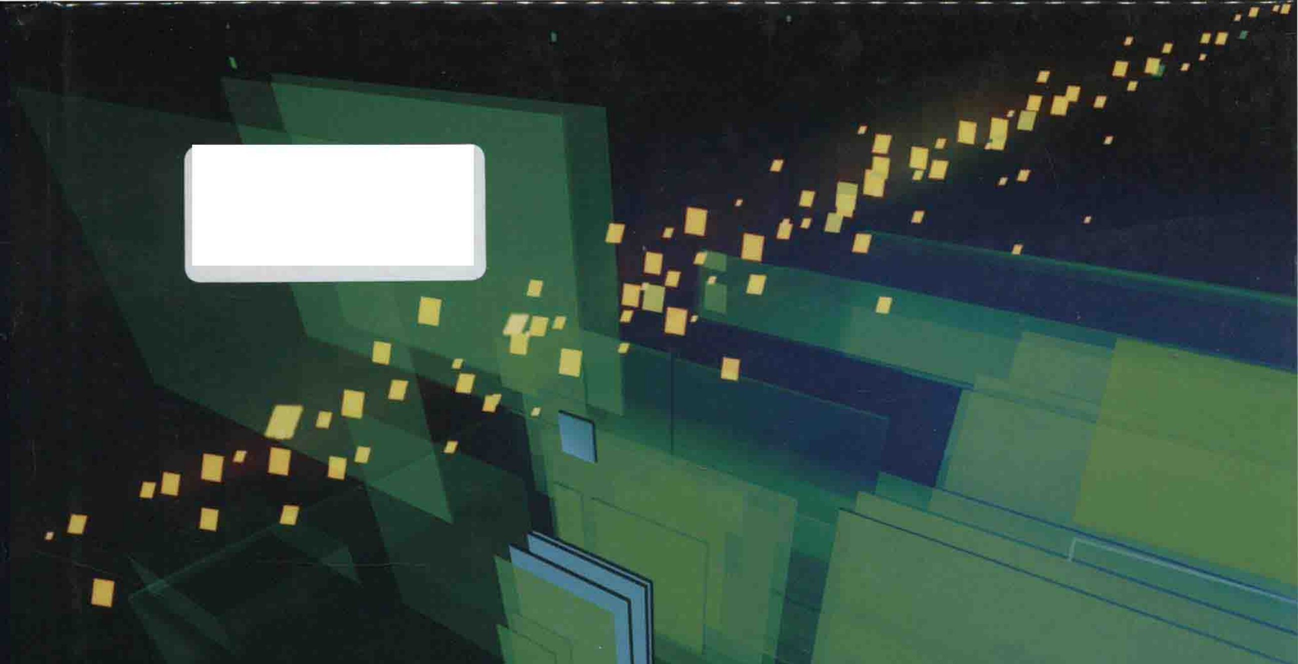

DMITRY A. YAKOVLEV
VLADIMIR G. CHIGRINOV
HOI-SING KWOK

Modeling and Optimization of LCD Optical Performance

WILEY SID Series in Display Technology

MODELING AND OPTIMIZATION OF LCD OPTICAL PERFORMANCE

Dmitry A. Yakovlev
Saratov State University, Russia

Vladimir G. Chigrinov
Hong Kong University of Science & Technology, Hong Kong

Hoi-Sing Kwok
Hong Kong University of Science & Technology, Hong Kong

WILEY

This edition first published 2015

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Yakovlev, Dmitry A.
Modeling and optimization of LCD optical performance / Dmitry A. Yakovlev, Vladimir G. Chigrinov, Hoi-Sing Kwok.
pages cm
Includes bibliographical references and index.
ISBN 978-0-470-68914-1 (hardback)
1. Liquid crystal displays. I. Chigrinov, V. G. (Vladimir G.) II. Kwok, Hoi-Sing. III. Title.
TK7872.L56Y35 2014
621.3815′422–dc23

2014001761

A catalogue record for this book is available from the British Library.

ISBN: 9780470689141

Set in 9/11pt Times by Aptara Inc., New Delhi, India

Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2015

MODELING AND OPTIMIZATION OF LCD OPTICAL PERFORMANCE

Wiley-SID Series in Display Technology

Series Editors:
Anthony C. Lowe and Ian Sage

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

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

3D Displays
Ernst Lueder

OLED Display Fundamentals and Applications
Takatoshi Tsujimura

Illumination, Color and Imaging: Evaluation and Optimization of Visual Displays
Peter Bodrogi and Tran Quoc Khanh

Interactive Displays: Natural Human-Interface Technologies
Achintya K. Bhowmik (Ed.)

Addressing Techniques of Liquid Crystal Displays
Temkar N. Ruckmongathan

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

Modeling and Optimization of LCD Optical Performance
Dmitry A. Yakovlev, Vladimir G. Chigrinov, and Hoi-Sing Kwok

To our beloved wives: Larisa, Larisa, and Ying-Hung

Series Editor's Foreword

Liquid crystal displays are the bedrock of the flat panel display industry. Their success and their continued improvement in all aspects of performance are due in substantial part to improvements in the fundamental understanding of how liquid crystal structures interact with forces applied by external electrical fields and by the intrinsic potential differences which exist at boundaries between dissimilar materials.

Several computer modelling systems are commercially available. They enable users to predict the properties of displays, avoiding the necessity to test every new idea by experiment. They are essentially black boxes into which are inputted the properties of materials, cell dimensions, applied voltage and other data, and which output the optical properties of a display as functions of time, applied voltage, wavelength and viewing angle. Their use requires no fundamental understanding of the thermodynamics or mechanics of liquid crystal (LC) interactions and therein lies a potential problem. For reasons of efficiency and minimising computer time, most, if not all modelling routines operate on simplified and approximated formulæ. Under some circumstances these approximations can lead to unforeseen errors and this is a topic which is addressed in unprecedented detail in this volume. But first it contains an exposition of the fundamentals from a description of polarized light through the calculation of its interaction with LC layers by the Jones calculus to predict the properties of cell structures. Next are presented worked examples of different transmissive and reflective nematic and ferroelectric modes using modelling software developed by the authors. The second part of the book provides a more detailed analysis of mathematical methods, starting from the basic mathematics and matrix algebra specific to LC modelling. It then progresses from describing relatively simple models to a description of rigorous electromagnetic methods to describe the optics of 1D inhomogeneous media and their use for numerical modelling of LC optics. The impact of approximations on computational accuracy is discussed throughout. The final chapter of the book touches on layers which are anisotropic in two dimensions, an important topic for LCDs which increasingly use multi-domain pixel structures.

The detailed contents of each chapter are described by the authors in their introduction, but my purpose in presenting this briefer description here is to show what a comprehensive book this is. It goes even further because a companion website http://www.wiley.com/go/yakovlev/modelinglcd contains the well commented source code of the program library LMOPTICS, which is a collection of routines for calculating the optical characteristics of multilayer systems, based on the methods described in this book. It also contains a set of sample programs which exemplify the application of this library and the methods described in this book to modelling LCDs.

This book and its companion website provide a comprehensive operational base for scientists and engineers who wish to make reliable modelling experiments. It provides a wealth of information for academic researchers and students engaged in condensed matter physics which is of relevance not just to displays but to LC-based photonic devices in general.

Anthony Lowe
Braishfield, UK, 2014

Preface

Liquid crystal displays (LCDs) are ubiquitous nowadays. They are used in almost all electronic devices and information systems. This is the result of many years of research and development by dedicated scientists and technologists. Despite the relative maturity of LCD technologies, many improvements are still needed and research is being performed. For example, issues such as energy efficiency, simpler methods of achieving large viewing angles, lower manufacturing cost, and LC alignment techniques still have a lot of room for improvement. In this regard, computer modeling of LCDs is a very useful tool for designing new display modes and improving their performance.

Many monographs and textbooks have been written about LCDs. Some are at the pedagogical level, while others are at the more advanced engineering level. Some involve more physics, while others concentrate on the engineering aspects. It is our desire to add to this collection with a book devoted to computer modeling and optimization of the optical performance of LCDs. It is believed that there is a need for a book that is devoted to an in-depth treatment of this subject. Many useful methods and techniques as well as fine points not covered in previous books are considered here.

For three decades, the authors of this book have been dealing with the problems related to the practical application of liquid crystals, in particular, developing software for numerical modeling and optimization of LCDs. Wishing to make our software sufficiently versatile (applicable to most kinds of LCDs) and efficient (providing a high accuracy of modeling, fast, and provided with convenient optimization tools) and dealing with specific optimization problems, we have examined a great number of approaches, methods, and techniques. In this book we have tried to present a unified approach to the optical modeling of LCDs, which unites the most theoretically rigorous and efficient methods and determines how these methods should be used in different situations. We describe efficient algorithms for solving typical problems of LCD optics and give recommendations as to how to build a basic theoretical model and choose the mathematical tools to solve the problem at hand, considering the problem geometry, factors to be accounted for, and required accuracy. Much attention is given to analytical approaches to solving optimization and inverse problems.

Chapter 1 provides the basic knowledge necessary to proceed to optics of LCDs. Basic notions and concepts of polarization optics and optics of anisotropic media are presented. Particular attention is given to the classical Jones calculus, a method with the aid of which a great number of optical problems for LCDs were solved. The classical Jones calculus has many advantages and disadvantages. The main disadvantage is its conflict with electromagnetic theory in many respects. The main advantages are its simplicity, reliability in many important cases, and rich mathematical apparatus allowing one to analyze polarization-optical systems and solve many problems semi-analytically or analytically. This method is eminently suitable for demonstrating the benefits of using matrices and matrix analysis in polarization optics to the newcomer to this field. In Chapters 2 and 3 the Jones calculus is used for the analysis of the optical operation of LC layers and LCDs in terms of the simplest models. Applications of a parameter space approach and an optical equivalence theorem in LCD optics are demonstrated; these techniques provide a comprehensive picture of LC modes suitable for LCDs and LC photonic devices.

In Chapter 4 we consider various electro-optical effects used in LC displays as well as different kinds of LCDs, the features of their numerical modeling, and typical optimization problems. We give many examples of solving particular optimization problems with the help of computer modeling.

Chapter 5 begins with a brief review of notions and relations of matrix algebra as a foundation to understanding much of the theoretical material of this book. We purposely postponed the regular presentation of this mathematical material to this chapter, preferring to demonstrate first its usefulness, which we do in previous chapters. We included this material to make the book self-contained for the reader. Moreover, in this mathematical review we consider a specific kind of matrices, which is rarely considered in mathematical books but is important in our consideration of LCD optics. This is followed by definitions of some radiometric quantities, a summary of the optical conventions adopted in this book, and a section introducing several important notions concerning the characterization of wave fields by Stokes and Jones vectors.

In Chapter 6 we present a set of relatively simple approaches and representations useful in solving optimization and inverse problems for LCDs when normal incidence of light is considered. In typical situations, the approaches presented in this chapter have no contradictions with electromagnetic theory and can be used in conjunction with rigorous methods. The discussion is illustrated by experimental examples, which give a clear idea of the actual effect of various factors that are taken into account or neglected in different kinds of optical models of LCDs.

Chapters 7 through 10 are devoted to rigorous electromagnetic (EM) methods of optics of 1D-inhomogeneous media and their use for numerical modeling of the optical properties of LCDs.

In Chapter 7 we discuss different physical models used in modeling the LCD optics, models which determine the choice of EM methods and ways of their use. This chapter also presents two general algorithms for calculating transmission and reflection characteristics of layered structures with allowance for multiple reflections, namely, transfer matrix technique and adding technique. These techniques are employed in some EM methods considered in subsequent chapters. In the last section of Chapter 7, optical models of some basic elements of LCDs are considered.

In Chapters 8, 9, and 10 rigorous EM methods of optics of stratified media are discussed in detail. Along with the discussion of the EM methods, these chapters contain a description of the authors' program library LMOPTICS (Fortran 90), a collection of routines for calculating optical characteristics of stratified media based on these methods. This library, available on the companion website, greatly simplifies the development of program modules for accurate evaluation of the optical characteristics of LCDs, and we hope it will be useful to the reader.

One of the EM methods presented in Chapter 8 is a method referred to in this book as the eigenwave (EW) Jones matrix method. This is a rigorous method using transmission and reflection operators, represented by 2×2 matrices, to describe the optical effect of constituents of the layered system under consideration. One of the advantages of this method over the extended Jones matrix method variants described in earlier books on LCDs is better accuracy, especially in the case of oblique incidence. The EW Jones matrix method supplemented with a set of numerical techniques and approximate representations, which are considered in Chapters 11 and 12, is a convenient tool for solving optimization problems for LCDs and inverse problems for inhomogeneous LC layers. We show that in most practically interesting cases, this method provides nearly the same level of mathematical simplicity and the same possibilities to analyze as the classical Jones calculus does. Chapter 11 considers various ways of calculating transmission operators for inhomogeneous liquid crystal layers used in different variants of the Jones matrix method. Application of the EW Jones matrix method to inhomogeneous LC layers is discussed in detail. In Chapter 12 we consider some useful approximations and give examples of application of the EW Jones matrix method in solving optimization and inverse problems.

In Chapter 13 we discuss the potential and limitations of the EM methods of optics of inhomogeneous media in modeling LC displays with fine intra-pixel structure and demonstrate some capabilities of more general EM methods.

Appendix A provides examples of LCD modeling performed over the years by students at Hong Kong University of Science and Technology. Appendix B contains supplementary theoretical material.

Chapter 1 was written by D.A. Yakovlev (D.A.Y.) and H.S. Kwok (H.S.K.). Chapters 2 and 3 were written by H.S.K. Chapter 4 and Appendix A were written by V.G. Chigrinov. Chapters 5 through 13 and Appendix B were written by D.A.Y.

This book is mainly intended for engineers and researchers dealing with the development and application of LC devices. University researchers and students who are specialized in condensed matter physics and engaged in fundamental and applied research of liquid crystals may also find much useful information here.

It is our hope that this book will be helpful to developers of new generations of LC displays.

Vladimir G. Chigrinov
Hoi-Sing Kwok
Dmitry A. Yakovlev

Acknowledgments

We would like to thank Alex King, Genna Manaog, Baljinder Kaur, Thomas Tang, Anatoli A. Murauski, Evgeny Pozhidaev, Sergiy Valyukh, Xu Peizhi, Valery V. Tuchin, Alexander B. Pravdin, Dmitry D. Yakovlev, and Svetlana M. Moiseeva for their invaluable help in preparing this book.

Vladimir G. Chigrinov
Hoi-Sing Kwok
Dmitry A. Yakovlev

List of Abbreviations

AMM	approximating multilayer method
AR	antireflective
CJMM	classical Jones matrix method
DM	discretization method
DRA	direct-ray approximation
EAS	electrode–alignment layer system
ECB	electrically controlled birefringence
EJMM	extended Jones matrix method
EW	eigenwave
EWB	eigenwave basis
FLC	ferroelectric LC
FLCD	ferroelectric LCD
FP	Fabry–Perot
FPI	Fabry–Perot interference
GM	grating method
GOA	geometrical optics approximation
IPS	in-plane switching
JC	Jones calculus
LC	liquid crystal
LCD	liquid crystal display
MEF	modulation efficiency factor
MPW	monochromatic plane wave
NB	normally black
NBR	negligible bulk reflection (approximation)
NBRA	negligible-bulk-reflection approximation
NW	normally white
PBS	polarizing beam splitter
PCS	polarization-converting system
PDLC	polymer dispersed liquid crystal
PSM	power series method
QAA	quasiadiabatic approximation
QMPW	quasimonochromatic plane wave
QWP	quarter-wave plate
RVC	reflection–voltage curve, reflectance–voltage curve
SBA	small-birefringence approximation
SOP	state of polarization
STN	supertwisted nematic

TIR	total internal reflection
TN	twisted nematic
TVC	transmission–voltage curve, transmittance–voltage curve
VA	vertical alignment
WP	wave plate