Introduction to Complex Mediums for Optics and Electromagnetics

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About the cover: The advances made in the last 150 years in the field of electromagnetics are connected to the ideas seeded by the 24 people depicted. These stalwart scientists are A.M. Ampere, J.C. Bose, C.A. Coulomb, A. Einstein, B. Franklin, A.J. Fresnel (top row); K.F. Gauss, O. Heaviside, H. von Helmholtz, H. Hertz, J. Larmor, M. von Laue (second row); H.A. Lorentz, G. Marconi, J.C. Maxwell, A.A. Michelson, H.C. Oersted, C.V. Raman (third row); W.H. Bragg, W.L. Bragg, J.W. Strutt (Rayleigh), J.J. Thomson, A. Volta, L. Onsager (bottom row).

Dedicated to pristine mountains and cheerful childhoods

Contents

Foreword

Richard P. McNitt

Engineers/scientists are oft exposed to the concept that the half-life of one's useful scientific knowledge is of the order of a decade, that those not *keeping up* will quickly be left behind. The contents of this book are proof, to me, that—if anything—a decade may well overstate the length of scientific half-life in the realm of electromagnetic/material interactions. I vividly recall a graduate course in physics (taught by a well-known physicist) four decades ago where we were exposed, more or less in passing, to some *second-order* effects: Peltier, Seebeck, and Thompson. As most of the students were engineers with strong interest in devices, some suggestions for utilization were quickly put forward—for instance, a possible direct-current refrigerator—but the professor noted that the effects were "small" for extant materials and thus unsatisfactory for such use. Similarly, we were given some rudimentary information about liquid crystals (possible thermometers), and birefringence of some strained materials, the latter an area of active research at that time for photoelasticians. As to electromagnetic waves, the "Maxwell equations of the time" were considered adequate, providing solutions in free space, isotropic homogenous materials, and waveguides. Most mathematical requirements were satisfied by the utilization of linear partial differential equations with constant coefficients.

This book presents many aspects of what is essentially a brave new engineering/scientist world, presenting major findings of the last decade, current research activity, speculations, and suggestions for future attack. There are powerful and general (we certainly had not been exposed to "Diffeo(4)", or to Monte

Carlo simulations) mathematical methods presented, *generalized* Maxwell's equations are suggested and then utilized to resolve complex situations, a plethora of new *effects* are described and explained, and rather exotic materials and materials systems are presented. Instead of being confined to existing materials and materials systems, engineers are now able to work with materials scientists to design systems (composites, thin films, etc.) they need even to the nano-level. One author points out that the cause-and-effect orientation of the past is now integrated into a systems approach that has a goal-and-means orientation. Further, in the new realm of nanomaterials, quantum effects also come to the fore.

It is illuminating to list just some of the named *effects* (some of which are *third-* and *fourth-order*, but of increasing engineering significance) listed in this tome, effects that are available for exploitation by the informed and contemporary engineer: Faraday (rotation), Fresnel-Fizeau, Kerr, Matteuci, Mockels, Sagnac, Villari, Voigt (Cotton-Mouton), and Wiedemann. Topics such as natural optical rotation, electro-magnetic- and piezo-toroidics, magnetoelectric, magnetoimpedance, paramagnetoelectric, piezomagnetoelectric, whistler waves, and others are examined. Concepts such as excitons, light-assisted tunneling, photonic crystals, spatial solitons, semiconductor quantum wells, superlattices (metamaterials), and negative phase-velocity materials are considered, particularly as to how they will be effective in new materials with names such as Permalloy, Terfenol-D, and Yablonovite. Faced with such evidence of so many things that were not generally known four decades ago, it is tempting to validate a decade half-life, and to acknowledge that many engineers who thought they were well trained, had only mastered $(1/2)^4 =$ one sixteenth of the information presented in this book!

The broad and exceptionally well-explained contents should be of significant value to three very different populations:

(i) The engineering scientist whose formal education occurred some decades ago and who wishes to be brought *up-to-date*. ... The chapters are comprehensive, well written, and informative. Although not condescending, each chapter starts with fundamentals and completely develops the appropriate theory.
(ii) Those currently active in the very broad arena, who wish a compact yet comprehensive overview of the field as well as of those works that would be complementary to their own. ... This book should prove to be of real value in expanding the scope of their individual researches.
(iii) Graduate students. ... The authors should be commended for expressing their visions as to what remains to *be done*, what is important, and the possible modes of attack. This book should prove to be an excellent source of thesis problems as well as a *map* to achieve the desired solution.

As one who has been in all three of these groups (in reverse order), I found this book to be a treasure trove. . . . I trust you will too.

In an old Pennsylvania Dutch saying, I sign myself as one who is

Old too soon, smart too late.

Preface

"So, what is a complex medium?" Had you asked me this question in 1990, I would not have been able to give you a coherent answer. Although by then I had studied electromagnetic fields in materials with complicated response properties for about seven years, my understanding of electromagnetics lacked the necessary breadth. Furthermore, electromagnetics researchers studying diverse types of response properties were just beginning to interact with each other.

A decade later, the subdiscipline of complex-mediums electromagnetics (CME) has taken shape. At least two series of conferences on CME are held regularly, and many scientific and technical meetings have special sessions devoted to CME. Among other complex mediums, carbon nanotubes, metamaterials, materials in which light bends "differently," and materials in which light "rotates" are commonly written about in science magazines (such as *Nature*, *Science* and *Materials Today*), as well as in monthly organs of learned societies (such as *OE Magazine*, *Optics and Photonics News* and *IEEE Antennas and Propagation Magazine*).

In 2003, I can give two answers to your question: a short answer, and a long one. The short answer is that a *positive* definition of complex mediums still remains elusive. The consensus among CME researchers is that a complex medium is not a simple medium; and that the response properties of any complex medium must be different from linear, isotropic dielectric. The long answer? Well, read on . . . .

Giant strides were made during much of the 20th century in understanding and commercially exploiting the electromagnetic properties of our atmosphere and virtually matter-free space. Yet materials research for the most part remained confined to simplified (preferably dielectric) response properties. The situation began to change during the 1980s. Scientific and technological progress came to be dominated by the conceptualization, characterization, fabrication, and application of many different classes of materials. Although some of these materials are found in nature, laboratory processing is often needed for efficient use. Others are entirely synthetic, created by chemical and physical processes. Certain materials are multiphase composites designed for certain desirable response properties otherwise unavailable. Multifunctional materials as well as functional gradient materials are needed for special purposes. Nanoengineering is often used to make material samples with the same chemical composition but different response characteristics. Thus, novel fabrication techniques and a multifarious understanding of the relationship between the macroscopic properties and the microstructural morphology of materials led to rapid progress in research on the interaction of the electromagnetic field and matter.

Electromagnetics is a science of the microscopic, though, perhaps reasonably, undergraduate textbooks rarely mention that subtlety. Many graduate textbooks also do not sufficiently emphasize that foundation. Since the 1890s, however, the Lorentz–Heaviside visualization has prevailed over earlier, even Maxwell's, understanding of electromagnetism. All matter is an ensemble of discrete charges dispersed in free space or vacuum; but an exact treatment of that kind is virtually impossible, even today, when the charge-bearing entities exceed a few million in number. Fortunately, when electromagnetic wavelengths considerably exceed molecular dimensions, matter can be treated as a continuum for a host of technological purposes.

A simple medium—most easily exemplified by a linear, isotropic dielectric material—affects the progress of electromagnetic signals in two ways:

- a delay is created with respect to propagation in vacuum, and
- absorption of electromagnetic energy takes place.

Both effects evince dependencies on frequency, but not on spatial direction. Calculations can be made and measurements can be interpreted on the per unit amplitude/intensity basis. An isotropic dielectric medium is thus equivalent to an isotropic contraction of space with absorption overlaid.

In complex mediums, the progress of electromagnetic signals is additionally affected in one or more of several ways:

- *anisotropy*: the direction-dependent contraction of space and absorption;
- *chirality*: the twisting of space;
- *nonhomogeneity*: the dispersal of energy into different directions by either interfaces between uniform mediums or continuous gradients in material dispersal; and
- *nonlinearity*: the emission of absorbed energy at (generally) some other frequency.

In consequence, CME research has several characteristics different from research on simple mediums.

First, CME formulations are best couched in terms of the fundamental entity in modern electromagnetics: the *electromagnetic field.* It happens to have two parts, named the electric field **E** and the magnetic field **B**, and identified separately for historical reasons as well as convenience. The two parts cannot be separated from the other, except after making some approximation or the other. Take a piece of a material that you think is linear, isotropic and dielectric; and make it move at a constant velocity with respect to you. You will find that it displays bianisotropic properties upon motion. A Lorentz-covariant description is therefore the only proper description of electromagnetic response properties.

Second, causality must be incorporated in CME research. Every material responds after a delay. The instantaneous part of its response properties cannot be different from that of free space; otherwise, the material would possess foreknowledge, a prospect best left for sci-fi authors to exploit. The development of femtosecond-pulse optics and the generation of attosecond pulses suggest that it is better not to cast time aside by the artifice of the Fourier transform. Even in the frequency domain, causality takes the form of dissipation and dispersion, which are the two sides of the same coin.

Third, although matter is nonhomogeneous at microscopic length scales, piecewise homogeneity is commonplace at macroscopic length scales. Statistical techniques provide a bridge between the two length scales. Complicated macroscopic response properties should not be assumed casually. For instance, if a homogeneous piece of a medium with a certain set of response properties cannot be found, the existence of continuously nonhomogeneous analogs of that set at macroscopic length scales is a dubious proposition. The development of homogenization techniques for complex mediums is a major challenge today, despite very recent successes for linear bianisotropic materials.

Fourth, nonlinearity is an essential attribute of wave-material interaction. Nonlinearity introduces dependency on amplitude or strength, and is responsible for the occurrence of multiwavelength processes. It also accounts for the electromagnetic exposure histories of materials. We all know from high-school textbooks that matter modifies electromagnetic waves; but waves also modify matter. Observe how a newspaper yellows after lying in the sun for a few days. Electromagnetic waves emitted by the sun (i.e., sunlight) effect that change.

The complexity of actual materials cannot yet be handled in its entirety. Complexity is like Gulliver, while CME researchers are like the Lilliputians. Although an individual CME researcher takes only one or two meaningful steps towards the taming of complexity, different steps are taken by different CME researchers. CME commands the attentions of scientists from a wide spectrum of disciplines: from physics and optics to electrical and electronic engineering, from chemistry to materials science, to applied mathematics and even biophysics. Thus, CME is presently a multidisciplinary research area spanning basic theoretical and experimental research at universities to the industrial production of a diverse array of electrical, microwave, infrared and optical materials and devices. A recent impetus for multidisciplinarity is the unrelenting progress of nanotechnology, which is now beginning to engender mesoscopic approaches in CME.

This book is a collection of essays to explain complex mediums for optical and electromagnetic applications. The genesis of this book lies in a series of conferences organized at the successive Annual Meetings of SPIE from 1999 to 2002. The scope of Conference 3790, *Engineered Nanostructural Thin Films and Materials,* was not fully explained by its title. Subsequently, Conference 4097 was entitled *Complex Mediums*. Further explication being needed, Conference 4467 was named *Complex Mediums II: Beyond Linear Isotropic Dielectrics* and was followed by Conference 4806 *Complex Mediums III: Beyond Linear Isotropic Dielectrics*. All four were organized by me, very ably assisted by Werner S. Weiglhofer, Russell F. Messier, Ian J. Hodgkinson, Martin W. McCall, and Graeme Dewar. A multitude of CME researchers participated wholeheartedly.

Werner S. Weiglhofer, my co-editor, was involved in all four conferences. He and I felt that the optics community at large should benefit from a relatively broad introduction to complex mediums. Many speakers who had delivered *Key Lectures* and *Critical Review Lectures* at the conferences agreed, as also did Rick Hermann and Sharon Streams of SPIE Press. We therefore invited the presenters to update and expand their initial lectures. Other prominent researchers were invited to contribute essays on CME topics that were deemed important but had not been covered in the four conferences. The essays were edited, reviewed, revised and compiled into this book.

All contributors were requested to write with two aims: first, to educate on phenomenology and terminology; second, to provide a state-of-the-art review of a particular topic. The vast scope of CME exemplified by the actual materials covered in the essays should provide a plethora of opportunities to the novice and the initiated alike. Graduate students in the broad disciplines of electrical engineering, materials science, and physics are likely to find inspiration from one essay or another to pursue CME research; and our fondest hope is that this book would serve the next decade or so as a goldmine for dissertation topics. Experienced researchers desirous of either switching research areas or synthesizing new types of material responses may profit from this book as well. R&D engineers in industry may be able to conceptualize and actualize new types of devices, after reading certain parts of this book.

I must add here that, although Werner and I had agreed to divide editorial responsibilities equally, he was the Managing Editor. To this position, he brought his considerable organizational acumen. He interacted with all contributors and reviewers, as well as with Sharon Streams at SPIE. All contributors were supplied progress reports at suitable intervals; e-mails were promptly answered by him with unfailing courtesy; and so on. When on January 5, 2003, he asked me to initiate the writing of a preface, I replied that the end of March was far away. A week later, he was killed by an avalanche on the slopes of Bispen, a Norwegian mountain that he had ascended 29 times. I had to assume his mantle; I had to write this preface solo. This book is now a memorial to my friend Werner S. Weiglhofer, as you will notice from the inclusion of a section entitled *In Memoriam*.

A linguistic note: You will notice the absence in this book of Latin and Greek plurals of words from those languages commonly used in English. This was a deliberate editorial decision. During some 14 years of collaboration, both Werner and I were appalled at the widespread misuse of plurals—such as *criteria*, *media* and *spectra*—as singulars in scientific literature. Such pluralization is artificial to the native robustness of English. At best, it is an affectation. No wonder so many native and non-native speakers of this language make those mistakes! Taking a leaf from George Bernard Shaw's introductions to his plays that English spelling needs reform, in 1996 we decided in favor of the normal English pluralization of Latin and Greek singulars. Although uncommon, this practice is not new. Most journals accept it. So do the Royal Society (of London), John Wiley & Sons, and SPIE.

The cooperation that Werner and I received from all contributors and reviewers was nothing short of splendid. Ms. Sharon Streams and others at SPIE have provided unstinted support. Professors David R. Fearn and Edward Spence graciously contributed their memories of Werner; and they also assisted in the transfer of editorial correspondence from Werner's computer to me. In the latter task, they were joined by Mr. David Thom (University of Glasgow) and Professor Joseph P. Cusumano (Pennsylvania State University). I am grateful to everyone involved in this project.

Complex Mediums IV: Beyond Linear Isotropic Dielectrics was convened in early August 2003, by Graeme Dewar and Martin W. McCall. I shall be delighted if a companion volume were published after another two or three editions of this conference. So would Werner, I am sure.

Akhlesh Lakhtakia
August 2003

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