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BOOK REVIEWS

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Nonlinear Optics: A Student's Perspective—With Python Problems and Examples. Mark G. Kuzyk. 352 pp. Create Space Independent Publishing Platform, North Charleston, SC, 2017. Price: $12.95 (paper). ISBN 978-1523334636. (Elsa Garmire, Reviewer.)

This textbook offers nonlinear optics as a fun subject for physics students and practitioners with a theoretical bent. If the derivations are followed closely, the subject is straightforward to understand, even though it can be complex to calculate carefully and explicitly. These complexities give students a chance to practice with tensors, Fourier transforms, polarized electromagnetic waves, quantum mechanics and, most importantly, with nonlinear relations between light's electric field and molecular polarizability. They will feel the power that this knowledge gives them. Those with a good background in undergraduate physics will find this book an excellent opportunity for cementing basic concepts in nonlinear optics that will last a lifetime. It is less helpful as a practical resource for working physicists.

When the ruby laser was invented in 1960, its intense coherent light could induce a molecular polarizability in transparent materials that was no longer linear with light's electric field. Electric fields of intense laser beams were large enough to distort molecular dimensions, creating a nonlinear polarizability. Nonlinear optics became a field of physics in its own right, typically explored by expanding susceptibilities in Taylor series in the electric field and looking for new phenomena. Light traveling through materials that had initially been non-absorbing causes dramatic effects that could be made useful.

Nonlinear optics was first demonstrated in 1962 by the conversion of red ruby laser light into ultraviolet light at twice the frequency. Second harmonic generation (frequency doubling) has arguably become the most important application for nonlinear optics because the luminous efficiency of human vision peaks in the green and there are no really efficient green lasers. Instead, second harmonic generation of infrared laser light in suitable crystals creates coherent green beams. For example, the "green laser" pointer used for lectures is not actually a green laser but rather a diode-pumped infrared laser converted by second harmonic generation into a green beam. Only red (diode) laser pointers are really red lasers. Green pointers are used in surveying and offer one of the few opportunities to observe nonlinear optics applications in daily life, usually hidden within a large variety of sophisticated systems.

High-power lasers are no longer required for nonlinear optics. It soon was discovered that long optical fibers exhibited large nonlinear effects. Because laser light is coherent, small nonlinearities can build up over long distances, even at relatively low powers. Large bandwidth telecommunication signals will be distorted by nonlinearity while traveling large distances along fibers unless special precautions are taken. But nonlinearity within fibers, when properly controlled, has enabled a range of new devices with numerous applications.

Ultra-short pulses are created from multi-mode lasers by using nonlinearity to create trains of pulses lasting anywhere from sub-femtoseconds to tens of picoseconds. Pulses less than 100 femtoseconds long (10^{-13} s) produce very high peak powers from modest average power lasers. These ultra-intense pulses can easily create large optical nonlinearities in materials that act back on the light, introducing distortions in temporal, frequency, or spatial propagation, which must be considered when such light is used.

In recent years, technological developments have led to commercially available nonlinear devices and systems, such as optical parametric oscillators and amplifiers, driven by intense ultra-short laser pulses. These systems use nonlinearity to break up the photons of the initial laser pump wave into two waves with frequencies that sum to the input frequency. The parametric oscillator is the first practical source of widely tunable coherent light, used by spectroscopists and quantum physicists, since the two output waves are phase-correlated. These systems use guided wave optics on a single chip (called "integrated optics" or "photonics"). Light confined in very small waveguides over reasonable lengths can produce nonlinear effects at modest power levels. All these applications, and many others, are exciting to today's engineering and applied physics students.

Arguably nonlinear optics largest impact has been on science. Not only physics, but materials science (materials processing), biology (nonlinear microscopy), chemistry (nonlinear spectroscopy), medicine, astronomy, etc., have all been advanced in ways unfathomable without nonlinear optics. At least eight Nobel prizes would not have happened without it. The breadth of science and engineering applications is now so wide that a variety of courses and textbooks are becoming available for graduate students and researchers.

Kuzyk has provided an excellent textbook for physics graduate students, focused almost entirely on theory. This does not mean the book is unreadable by others, but it will be particularly appreciated by those who enjoy Dirac notation, Feynman-like diagrams, density matrices, etc. The quantum theory is well-written and includes all steps in proofs. The optical wave is treated as a classical electromagnetic wave, especially focused on the nonlinear wave equation and its implications. I enjoyed reading the book, as it reminded me of my days as a graduate student, and I rarely was stopped in my understanding as I went through each step.

Kuzyk first introduces nonlinear optics without quantum mechanics by invoking classical models of nonlinear polarization. As the book proceeds, nonlinearities are fully described using the quantum picture of the atom or molecule. Nonlinearities cause quantum states of a molecule to interfere, creating a virtual state that acts back on the light (which is treated classically), causing distortions that can be measured. Thankfully he does not quantize the light as well, which would have added considerable more complexity to describe the fully quantum nonlinear system.

My daughter studied "the new physics" in high school. After her first day, this confused young woman asked me "Is light made of particles or waves?" I gave her my standard answer: "Light is what it is. The role of physics is to provide us poor humans with models that make sense to our limited minds. In the classical limit we model light as a wave, while the quantum limit is necessary to understand light that is very weak." This conundrum of how to view light affects all classes in lasers and nonlinear optics and has fascinated me since I began teaching. I'd love to teach it all classically, but it seems impossible to avoid quantum mechanics to explain the interaction of light with matter, particularly when dealing with the complex nonlinear phenomena. Kuzyk has handled this challenge by first describing the classical nonlinear oscillator (not optical) in some detail, grounding students in the ideas of nonlinearity before he sails on to more complex nonlinear optics in all its glory. His descriptions are simple and clear.

Unfortunately Kuzyk uses Gaussian units (statvolts, $\varepsilon = 1 + 4\pi\chi$, etc.) throughout the text. Although traditional in nonlinear optics (which originated before SI units became the norm), most modern texts now use them. Fortunately Gaussian units are explained for susceptibility (first, second, and third order nonlinearities), also for force and the electric field (statvolts/cm). SI units are more appropriate today because most of us do not use stat-volts/cm every day (and SI units don't need an explanation of why 4π is in the wave equation). In this book, however, Gaussian units are not a problem because no physical numbers are put anywhere near the derivations. Formulas for conversion to SI are found in the last chapter, the only place where a few physical numbers are given.

Nonlinear optics relies on lasers, which can vary in emission from single photons (10^{-25} J) to peak irradiance levels of $10^{24}\,\mathrm{W/m^2}$. This means that nonlinear effects may be very small or very large, depending on materials, response times, and interaction lengths. Only a few materials are highly nonlinear with response times anywhere from minutes to 10^{-11} s.

The length over which coherent interactions take place can vary from 100 nm to 100 km. The effects depend on the size of the nonlinearity. Because of the wide range of these parameters, students need practice using the equations they derive to estimate orders of magnitude, learning what kinds of experiments would be nonlinear and which won't be. For classes, this book should be augmented by notes that offer worked physical examples and explanations about the size of the phenomena.

Kuzyk teaches his students to use Python to model nonlinear optical phenomena and includes an example calculating transmission through a spatially nonuniform absorber. Trying to carry out the assigned problem, I got stopped by the statement that the "loss" was $\alpha(z) = \alpha_o + \sin z$, with α earlier defined in units of inverse length. Since the two terms have different units, the equation makes no physical sense. Of course Python would give me a numerical result if I ignore units, but the result would be meaningless in the real world. I hope that even first-year students would pick up such an error.

Throughout his Python "numerical modeling," he makes no attempt to define units within his computer code; no physical numbers are given. Thus students may learn the "shape" of how nonlinear behaviors depend on various parameters, but they'll have no "practical" understanding of nonlinear optics when they're done. As a postdoc at Caltech, I heard underground gossip that a theoretical physicist failed his final Ph.D. defense in nuclear physics because he did not know the size of a *barn*. I don't want students to go through such an experience. Physicists, no matter what their stripe, theoretical or experimental, should always have a feeling for the size of the quantities they deal with.

A chapter is devoted to understanding the properties of the third-order nonlinear index in liquids. Kuzyk's technical interests include optical nonlinearities in organic molecules, and his understanding of and interest in analytic quantum mechanical analyses is demonstrated both in his technical publications and in the clear presentations of quantum mechanical modeling of optical nonlinearities, both second and third order.

Kuzyk chose not to include some nonlinearities that are important in practice, which narrows the focus of the book, but simplifies his self-consistent quantum mechanical explanation of the most basic set of optical nonlinearities. Missing are optical nonlinearities that result from real transitions induced by high intensity light in atoms, molecules or materials that would be transparent to low intensity light. Such phenomena include two photon and multiphoton absorption as well as scattering processes such as stimulated Raman, Brillouin, and four-photon scattering. These stimulated scattering processes have turned out to be important in many practical applications.

Kuzyk uses an interesting and clever approach to ensure that students will understand his book, which could provide a model for other books. He keeps the book focused on what learning students want to emphasize. This textbook grew out of a previous "Lecture Notes in Nonlinear Optics: A Student's Perspective" that was put together in 2010. The preface describes compiling these notes:

"This book grew out of lecture notes from a graduate course.… Each student took notes for about the equivalent of two book sections, then prepared an electronic version using Latex. Each section was criticized by two students who acted as devil's advocates with particular attention to clarity of presentation and accuracy. After making edits, each student presented me with a draft, which I edited and in some cases rewrote. I contributed a chapter, merged all the sections together, and added bridge material when necessary. This book is the result of a process with started on Day 1 of class, and spilled over into the summer."

He has made these notes freely available at http://www.nlosource.com/LectureNotesBook.pdf.

The resultant textbook has extraordinary clarity and beauty in its explanation of complex concepts to those graduate students with a strong grounding in classical and quantum physics. Review sections remind students of important basic concepts. The textbook is true to Kuzyk's professed intention of providing help to physics graduate students who are learning the formalities of nonlinear optics. The text is nicely coherent (like my pun?) as the material presented grows smoothly in complexity from simple classical physics to density matrices.

I repeat my complaint that nowhere does the book provide actual values for known nonlinear optical materials. On page 20 the orders of magnitude for various nonlinear susceptibilities are given, but students never learn how to plug these values into equations. Will they realize how short phase-matching lengths are in condensed matter? Will they realize how much of nonlinear optics is materials-limited, rather than theory-limited? Experimentalists need physical numbers to be able to use what they are learning. A table of physical properties for the most important materials would have been useful and could be provided as supplementary material. Also, a table defining symbols and terminology would have been nice. It is easy to forget these definitions or where to look for them in the text. An example is "hyperpolarizability," used many times but defined only in Chapter 1 and not listed in the index. Providing units for derived equations would have made it easier to evaluate experiments, especially since the book expresses the equations in the unfamiliar Gaussian units. Boxes around these final, derived equations would help researchers and students use the book as a reference source. Even more valuable would be providing numerical examples for these equations.

A few somewhat arcane cases are introduced: describing stimulated emission as negative temperature to demonstrate amplification, and not defining "gain," although used later without definition; presenting the Manly-Rowe relations without mentioning conservation of energy; including optical nonlinearities in magnetic materials, as well as monopoles, even though they don't exist; nonlinear optics of single atoms using the quantum mechanical solution for atomic hydrogen, which most students may never encounter.

This textbook gives full attention to transparent media, with somewhat less emphasis on nonlinear optics near atomic or molecular resonances. Completely omitted are the stimulated scattering processes of Raman, Brillouin, and four-photon scattering. Nonlinearities arising from interaction of light with phonons or plasmons, or from nonlinear absorption in semiconductors, are likewise omitted. Also missing is nonlinear optics at surfaces and in quantum confined structures. Those interested in these important processes will have to look elsewhere.

If I imagine myself a beginning student, I would be fascinated by the theory presented in this book and pleased that I could follow it step-by-step. But I would have no idea how to use it in the real world. Nonetheless, I thought the beauty of the underlying physics was apparent from the presentations in the textbook and will be enjoyed by graduate students. Kuzck states that the book is "amenable to self-study," and I agree that a conscientious physicist interested in entering the field of nonlinear optics will find this an excellent place to begin understanding its basic principles.

Elsa Garmire is retired from 20 years as Sydney E. Junkins professor and Dean in the Thayer School of Engineering, Dartmouth College. Previously she had spent 20 years at University of Southern California and 9 years at Caltech. She was a pioneer in nonlinear optics in the 1960s, in integrated Optics in the 1970s, optical bistability in the 1980s and then nonlinear optics and photorefractivity in semiconductors. At present she is writing a book on nonlinear optical technology.

BOOKS RECEIVED

The Great Silence: The Science and Philosophy of Fermi's Paradox. Milan M. Čirović 422 pp. Oxford U.P., New York, 2018. Price: $32.95 (hardcover) ISBN 978-0-19-964630-2.

The Man Who Saw Tomorrow: The Life and Inventions of Stanford Ovshinsky. Lilian Hoddeson and Peter Garrett. 392 pp. MIT Press, Cambridge, MA, 2018. Price: $29.95 (hardcover) ISBN 9780262037532.

Finding Einstein's Brain. Frederick E. Lepore. 329 pp. Rutgers U.P., New Brunswick, NJ, 2018. Price: $27.95 (hardcover) ISBN 978-0-8135-8039-5.

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