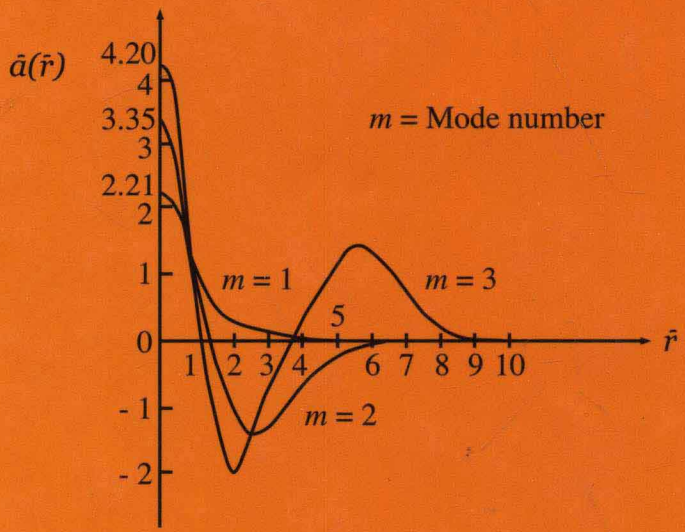
Nonlinear Optics

Theory, Numerical Modeling, and Applications



Partha P. Banerjee

Nonlinear Optics

Theory, Numerical Modeling, and Applications

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Preface

Nonlinear Optics: Theory, Numerical Modeling, and Applications is a self-explanatory book in a rather new and changing area, and is geared toward advanced senior or first-year graduate students in electrical engineering and physics. It is assumed that the students taking the course have had exposure to Fourier optics and electro-optics. This book is the culmination of a course on nonlinear optics that I have taught several times at the graduate level over the last ten years, and has also introduced some of the topics of senior-level classes on laser systems. It is also based on my research in the area over the last 20 years.

The unique features of the book are as follows. Students are first reacquainted with pertinent topics from linear optics that are useful in understanding some of the concepts used later on in the book. Thereafter, rigorous treatment of nonlinear optics is developed alongside a heuristic treatment to enable the reader to understand the underlying essential physics, instead of being overwhelmed with extensive tensor calculus. Recent topics of interests, applications, and measurement and calculation techniques are discussed. While the plane wave approach to harmonic generation is first explained, more recent developments such as the effect of beam profile on second harmonic generation, second generation during guided wave propagation, and the combined role of quadratic and cubic nonlinearities are also examined. Cubic nonlinearities are discussed at length along with their effects such as self-focusing and defocusing, self-bending of beams, and spatial solitons. The role of cascaded second-order nonlinearities is also examined. The z-scan technique and its modification are described in detail as a means of character-

ization of optical nonlinearities. We also discuss other cubic nonlinearity effects such as soliton propagation through nonlinear fibers, with some attention to the recent development of dispersion management in nonlinear optical fibers. Optical bistability and switching in a nonlinear ring cavity as well as during optical propagation across a linear/nonlinear interface are treated at length. Traditional topics such as stimulated Brillouin and Raman scattering are summarized. Also, phase conjugation in a cubically nonlinear material and dynamic holography are introduced. A simple k-space picture is used to explain phase conjugation of beams and pulses. Thereafter, the nonlinear optics of photorefractive materials is discussed in detail, including applications to dynamic holography, two-wave mixing, phase conjugation, and image processing. Photorefractive crystals as well as organic thin-film photorefractive materials are discussed. Examples of image processing such as edge enhancement using these materials are introduced. The nonlinear optics of liquid crystals is discussed at length, including the effects of applied electric and optical fields (including beams) on the nonlinearity. The effective nonlinearity of liquid crystals is determined from a careful evaluation of the position-dependent nonlinearity in the material. Self-organization plays a vital role in human behavioral system, in the brain, in fluid mechanics, in chemical reactions, etc.—in any system that has nonlinearity and feedback. It is therefore not unnatural to expect self-organization in optical systems as well. In this book, we therefore discuss spatiotemporal effects in nonlinear optical materials, leading to self-organization and spatial pattern formation, using photorefractives as a representative nonlinear medium. Innovative potential applications of self-organization are also presented. Finally, we treat photonic crystals or photonic bandgap structures that can be engineered to yield specific stop-bands for propagating waves, and demonstrate their application in optical bistability and hysteresis, soliton formation, and phase matching during second harmonic generation. Pertinent numerical methods, often used to analyze beam and pulse propagation in nonlinear materials, such as the split-step beam propagation method and the fully adaptive wavelet transform technique, are presented in the Appendices. Also, illustrative problems at the end of each of chapter are intended to aid the student in grasping the fundamentals and applying them to other interesting problems in nonlinear optics. In short, the book extends the concepts of nonlinear optics to areas of recent interest and, in a sense, brings contemporary and ongoing research areas not usually covered in many nonlinear optics books to the attention of readers.

The emphasis of this book is on the understanding of physical principles and potential applications. Students interested in further in-depth coverage of basics are referred to more comprehensive treatments such as the *Handbook of Nonlinear Optics* (Richard L. Sutherland, ed., Marcel Dekker, 2003).

I would like to thank Ms. Cheryl McKay from the University of Alabama in Huntsville for typing parts of the manuscript, my graduate student Ms. Jia Zhang for assistance with most of the figures, all of my graduate students whose work appears in the text who have worked with me through the years, and several students who took the course during the preparation of the manuscript for their helpful comments. Finally, I would like to thank my family and friends for their moral support.

Partha P. Banerjee

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1
Optical Propagation in Linear Media

In this chapter, we will review some of the properties of optical waves propagating through an unbounded linear medium. We believe that this review will serve as an adequate foundation for the topics in nonlinear optics, to which the entire book is devoted. To this end, we enunciate Maxwell's equations and derive the wave equation in a linear homogeneous isotropic medium. We define intrinsic impedance, the Poynting vector and irradiance, as well as introduce the concept of polarization. We then expose readers to concepts of plane-wave propagation through anisotropic media, introduce the index ellipsoid, and show an application of electro-optic materials. We also summarize concepts of Fresnel and Fraunhofer diffraction, starting from the paraxial wave equation, and examine the linear propagation of a Gaussian beam. Finally, we expose readers to the important topic of dispersion, which governs the spreading of pulses during propagation in a medium. More importantly, we show how by knowing the dispersion relation, one can deduce the underlying partial differential equation that needs to be solved to find the pulse shapes during propagation. We hope this chapter presents readers with most of the background material required for starting on the rigors of nonlinear optics, which will be formally introduced in Chap. 2. For further reading on related topics, the reader is referred to Cheng (1983), Banerjee and Poon (1991), Goodman (1996), Yariv (1997), and Poon and Banerjee (2001).

1 MAXWELL'S EQUATIONS

In the study of optics, we are concerned with four vector quantities called electromagnetic fields: the electric field strength **E** (V/m); the electric flux density **D** (C/m^2); the magnetic field strength **H** (A/m); and the magnetic flux

density $\mathbf{B}$ (Wb/m^2). The fundamental theory of electromagnetic fields is based on Maxwell's equations. In differential form, these are expressed as

$$\nabla \cdot \mathbf{D} = \rho, \tag{1-1}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{1-2}$$

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}, \tag{1-3}$$

$$\nabla \times \mathbf{H} = \mathbf{J} = \mathbf{J}_C + \frac{\partial \mathbf{D}}{\partial t}, \tag{1-4}$$

where $\mathbf{J}$ is the current density (A/m^2) and ρ denotes the electric charge density (C/m^3). $\mathbf{J}_C$ and ρ are the sources generating the electromagnetic fields.

We can summarize the physical interpretation of Maxwell's equations as follows: Equation (1-1) is the differential representation of *Gauss' law for electric fields*. To convert this to an integral form, which is more physically transparent, we integrate Eq. (1-1) over a volume V bounded by a surface S and use the *divergence theorem* (or *Gauss' theorem*),

$$\int_V \nabla \cdot \mathbf{D} \mathrm{d}V = \oint_S \mathbf{D} \cdot \mathrm{d}\mathbf{S} \tag{1-5}$$

to obtain

$$\oint_S \mathbf{D} \cdot \mathrm{d}\mathbf{S} = \int_V \rho \mathrm{d}V. \tag{1-6}$$

This states that the electric flux $\oint_S \mathbf{D} \cdot \mathrm{d}\mathbf{S}$ flowing out of a surface S enclosing V equals the total charge enclosed in the volume.

Equation (1-2) is the magnetic analog of Eq. (1-1) and can be converted to an integral form similar to Eq. (1-6) by using the divergence theorem once again:

$$\oint_S \mathbf{B} \cdot \mathrm{d}\mathbf{S} = 0. \tag{1-7}$$

The right-hand sides (RHSs) of Eqs. (1-2) and (1-7) are zero because, in the classical sense, magnetic monopoles do not exist. Thus the magnetic flux is always conserved.

Equation (1-3) enunciates *Faraday's law of induction*. To convert this to an integral form, we integrate over an open surface S bounded by a line C and use Stokes' theorem,

$$\int_S (\nabla \times \mathbf{E}) \cdot \mathrm{d}\mathbf{S} = \int_C \mathbf{E} \cdot \mathrm{d}\ell, \tag{1-8}$$

to obtain

$$\int_C \mathbf{E} \cdot \mathrm{d}\ell = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot \mathrm{d}\mathbf{S}. \tag{1-9}$$

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