

Acousto-Optic Devices

Principles, Design, and Applications

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Preface

Several excellent books on acousto-optic (AO) theory and AO signal processing have been published, however, with regard to AO device design and specification little is available. Indeed, acousto-optic theory in the available texts is often treated in a conceptual manner and therefore is not comprehensive enough to solve practical problems. One can argue that a theory is never truly understood until it can be used to calculate a real physical value, and this is perhaps the most important motivating factor behind this book. The book naturally falls into two parts. In the first part, Chapters 1–5, a comprehensive theory is systematically developed from first principles for all aspects of acousto-optic devices. The most important formulas are derived on a step-by-step basis and subsequently rendered in a form most suitable for quantitative calculation and design purposes. Full use of abbreviated subscript formalism has been adopted, thereby reducing the tensor operations to simple matrix-vector or matrix-matrix multiplications. Problems designed to lead the reader through the theory necessary to deal with practical design issues are included in each of the first five chapters of the book. Many of these problems are helpful in designing specific state-of-the-art AO devices. The idea has been to keep the exposition of the fundamental theory as clear and concise as possible. The first five chapters of the book have been written for use as a textbook. The material has been taught many times to students of Applied Physics and Electrical Engineering in both the U.S. and China at a graduate level. The first part of this book may also be used as a training reference for device designers. In the second part of the book, Chapters 6–10, AO device design and applications are covered. Performance parameters are specified and the design ideas and optimal design procedures are thoroughly discussed for all types of AO devices. The figures and tables provided with this discussion illustrate the design procedures and

optimal results for various AO devices. For AO device applications, emphasis is placed on explaining the basic structure and concepts behind the important acousto-optic systems. The discussion is based on a complex transmittance representation of the AO device to better fit into the general framework of optical signal processing. These features make this part of the book best suited for use as a reference manual by designers and other workers in the field.

Chapters 1–5 make up the principal part of this book, and of these, Chapters 1–3 are the most fundamental. The first chapter provides a concise explanation of crystal optics and crystal acoustics, while Chapter 2 deals with AO interaction theory. A unified coupled-wave theory capable of treating both isotropic and birefringent AO interaction is established based on parametric interaction concepts. Chapter 3 discusses piezoelectric transducer theory. The presentation includes detailed calculations on all of the single mode cut lithium niobate (LN) transducers, and a general theoretical approach for calculating the transducer bandwidth of piezoelectric transducers used in AO devices. Chapter 4 discusses the theory behind thin-film AO devices including the guided optical wave (GOW) in a slab waveguide, the surface acoustic wave (SAW), thin-film AO interaction, and interdigital transducers. This is an area fully deserving of a book in its own right, and the material in this chapter is meant to serve more as an introduction, with these topics directly paralleling the theory presented in Chapters 1–3. Finally, in Chapter 5, multifrequency AO interaction is discussed. This provides the basis for many of the most sophisticated AO device applications. Due to the limited success of the coupled-wave equation, this chapter considers a new approach to AO interaction theory based on Feynman diagrams and state space representation. A complete perturbation solution for any number of applied frequencies is obtained based on this method.

Chapters 6–8 form the design part of this book. Chapter 6 is devoted to the design of bulk wave deflectors and Bragg cells. The primary task in designing these AO devices involves solving the contradictory requirements imposed by a high diffraction efficiency and a large Bragg bandwidth. Two of the principal methods are discussed in much detail, beam steering for both isotropic and birefringent devices and birefringent devices with the tangential condition satisfied. Chapter 7 deals with the design of other bulk wave devices including modulators, tunable filters, multifunction, and multifrequency devices. In addition, lateral diffraction loss of the acoustic wave is considered, together with

the design of multichannel AO devices. Chapter 8 discusses the design of piezoelectric transducers and thin-film AO devices. Two typical combinations of transducer material and AO medium are considered and a detailed calculation of the transducer bandwidth performed. Since the manufacture of AO devices is so dependent on the transducers, key manufacturing technology and quality control measurements for the transducer are briefly discussed. For the thin-film AO device, the primary design task remains bandwidth enhancement while maintaining a high diffraction efficiency. Toward this end, two of the main approaches, multiple tilting interdigital transducers and beam steering, are discussed and the related calculations detailed. Chapters 9 and 10 form the application part of the book. Chapter 10 presents an introductory overview of AO signal processing, while Chapter 9 discusses other applications of AO devices.

There are a total of 13 appendices supplementing the 10 chapters in this book. Appendices A and B provide a background essential for a clear understanding of the material in Chapters 1–5. Appendices C through E explain the point group restrictions on the various coefficient matrices and provide numerical values for some important AO materials. This material is essential to understanding the basic theoretical calculations and solving the problems at the end of the first five chapters. Appendices F through J outline some supplementary proofs useful in understanding certain points in the text. Appendices K through M are comprised of numerical data for design purposes.

There are no special preliminary requirements needed for reading this book, although a knowledge of tensor analysis and linear algebra is useful. Even then, readers not familiar with these areas can find the necessary background in Appendix A.

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Chapter 1

Crystal Optics and Acoustics

All acousto-optic (AO) devices are based upon the interaction of acoustic and optical waves within a medium. Therefore, in any study of the subject, it is essential to first understand the propagation laws of both acoustic and optical waves in media. This is particularly true for anisotropic media, since nearly all high-quality AO devices are made of crystalline materials. This chapter will cover the important aspects of crystal optics and crystal acoustics with an emphasis on AO device design. It will also review the optical and acoustic characteristics of two of the more important AO materials in the visible and near infrared wavelength range, lead molybdate (PbMoO_4 , or simply PM) and paratellurite (TeO_2).

An analysis of wave propagation within a medium involves two fundamentally different types of relationships. The first type of relationship concerns the universal laws. These are given by Maxwell's equations for optical waves and Newton's second law for acoustic waves. Equations that fall under this heading are independent of the material properties of the medium. The second type of relationship describes the material properties of the medium. For optical waves, the dielectric constitutive equation connects the electric displacement \mathbf{D} with the electric field \mathbf{E} . For acoustic waves, Hooke's law connects the stress \mathbf{T} and strain \mathbf{S} . The equations in this category are very much dependent on the intrinsic properties of the medium, and as a consequence are usually expressed in tensor form for anisotropic materials. From these two types of equations, we can derive the fundamental equations governing wave propagation within anisotropic crystalline media along

with the corresponding eigenvalues and eigenmodes.

For readers not familiar with tensor analysis and linear algebra (in particular, the solution of linear homogeneous equations and eigenvalue problems), we suggest a review of Appendix A first.

1.1 Fundamental Equations of Crystal Optics [1–4]

Our discussion on the propagation properties of the optical wave must be predicated on several assumptions. First, we assume that no free charge or current exists within the material in which the optical wave travels. Furthermore, as is usually the case for optically transparent materials, we take this material to be nonferromagnetic, such that $\mathbf{B} = \mu_0 \mathbf{H}$. Under these conditions, Maxwell's equations can be written as

$$\dot{\mathbf{D}} = \nabla \times \mathbf{H}, \quad \dot{\mathbf{H}} = -\frac{1}{\mu_0} \nabla \times \mathbf{E}, \quad (1.1a)$$

$$\nabla \cdot \mathbf{D} = 0, \quad \nabla \cdot \mathbf{H} = 0. \quad (1.1b)$$

All of the electromagnetic quantities introduced in this book are based on the MKS system of units, and in our notation, the upper dot represents a time derivative. For time-varying electromagnetic fields, Eqs. (1.1a) represent the more important relationships. Taking the second derivative of the electric displacement with respect to time, we have

$$\ddot{\mathbf{D}} = -\frac{1}{\mu_0} \nabla \times (\nabla \times \mathbf{E}). \quad (1.2)$$

For bulk optical waves propagating within a medium, it will be sufficient to consider only the plane wave solution for a single angular frequency. In this case, the field quantities assume a space and time dependence given by

$$\exp\{j(\omega t - \mathbf{k} \cdot \mathbf{r})\} = \exp\{j\omega(t - \frac{\mathbf{n} \cdot \mathbf{r}}{c})\}. \quad (1.3)$$

The index vector is defined as $\mathbf{n} \equiv \mathbf{k}/k_f$, where k_f is the freespace wave vector modulus given by

$$k_f = \frac{\omega}{c} = \frac{2\pi}{\lambda_0} \quad (1.4)$$

and λ_0 is the freespace wavelength. The direction of \mathbf{n} is colinear with that of \mathbf{k} , and its modulus is given by the refractive index $n = c/v$.

For anisotropic material, the index n (or phase velocity v) changes with propagation direction and polarization state of the electromagnetic wave. Its value is determined by solving the previously mentioned eigenvalue problem. From Eq. (1.3), we get the following transformations:

$$\frac{\partial}{\partial t} \longleftrightarrow j\omega, \quad (1.5)$$

$$\nabla \times \longleftrightarrow -j\mathbf{k} \times \quad \text{or} \quad -j\frac{\omega}{c}\mathbf{n} \times .$$

Thus, Eqs. (1.1a) and (1.2) become

$$\mathbf{D} = -\frac{1}{c}\mathbf{n} \times \mathbf{H}, \quad \mathbf{H} = \frac{1}{\mu_0 c}\mathbf{n} \times \mathbf{E}, \quad (1.6)$$

$$\frac{1}{\epsilon_0}\mathbf{D} = -\mathbf{n} \times (\mathbf{n} \times \mathbf{E}) = n^2\mathbf{E} - (\mathbf{n} \cdot \mathbf{E})\mathbf{n}, \quad (1.7)$$

where $c^2 = 1/\epsilon_0\mu_0$. From Eq. (1.6), we see that \mathbf{D} , \mathbf{H} , and \mathbf{n} are mutually perpendicular and that \mathbf{H} is perpendicular to \mathbf{E} . The directions of \mathbf{D} and \mathbf{E} are generally different, however, in an anisotropic medium. The direction of energy propagation is determined by Poynting's vector

$$\mathbf{S} \equiv \mathbf{E} \times \mathbf{H}. \quad (1.8)$$

Figure 1.1 shows the directions of all of these quantities, and in particular, how \mathbf{D} , \mathbf{E} , \mathbf{k} , and \mathbf{S} are all perpendicular to \mathbf{H} . Note that \mathbf{D} is always perpendicular to the propagation direction \mathbf{k} , while \mathbf{E} is generally not. This is demonstrated by substituting the plane wave solution of Eq. (1.3) into Eq. (1.1b), resulting in $\mathbf{k} \cdot \mathbf{D} = 0$ or $\mathbf{D} \perp \mathbf{k}$. Thus, the polarization direction of an electromagnetic wave in anisotropic media always refers to the direction of the displacement vector \mathbf{D} .

The dielectric constitutive equation is given by

$$\frac{1}{\epsilon_0}\mathbf{D} = [\epsilon]\mathbf{E}, \quad (1.9)$$

where $[\epsilon]$ is the relative permittivity of the medium. For anisotropic materials, $[\epsilon]$ is a rank 2 symmetric tensor regardless of the coordinate system orientation. Substituting Eq. (1.9) into Eq. (1.7), we get an equation for \mathbf{E} ,

$$[\epsilon]\mathbf{E} = n^2\mathbf{E} - (\mathbf{n} \cdot \mathbf{E})\mathbf{n}. \quad (1.10)$$