JAMES E. TONEY

LITHIUM NIOBATE PHOTONICS

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James E. Toney

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turn to the back of this book.

To Michele

Preface

This is a book that would have helped me immensely 15 years ago, when the focus of my work changed from semiconductors and nuclear radiation detectors to electro-optic switching devices. There was no single book that covered the basic concepts, principles of device operation, and practical design considerations for real electro-optic devices and systems. That is the void that *Lithium Niobate Photonics* aims to fill.

The objective of the book is to bridge from the theory of guided wave and crystal optics, which is nicely covered in several textbooks, to the practice of lithium niobate device design and application, for which one typically has to refer to the literature. While formalism is used where appropriate, the emphasis is on practical analysis using modern modeling and simulation tools.

The book has three major sections: materials, devices, and applications. The first section (Chapters 2 and 3) explains the fundamental physics that gives rise to the electro-optic effect, classes of electro-optic materials, electro-optic properties of lithium niobate, and the process of ferroelectric domain inversion. The differences among the available types of lithium niobate crystals (congruent versus stoichiometric, magnesium-doped) are discussed, and the production of electro-optic thin films by crystal ion slicing is introduced.

Chapters 4 through 8 explain the principles of operation, performance measures, and design considerations for the most basic types of electro-optic devices: beam deflectors, waveguides, intensity, and phase modulators, including quasi-phased matched devices. A chapter on the potential and challenges of electro-optic photonic crystals is also included.

Chapters 9 through 12 deal with the most important applications of lithium niobate electro-optic devices in microwave photonics, sensing, signal processing, and data transmission. The final chapter introduces the burgeoning area of optical and quantum frequency conversion using periodically poled lithium niobate.

A reader who has completed the first three years of an undergraduate electrical engineering or physics program should have adequate background to follow everything in the book. The only essential prerequisite is the equivalent of Calculus-Based Physics II (Physics 1251 in the Ohio State system), but a prior applied optics course would be helpful. A concise review of the essential concepts of optics and fiber optics can be found in Appendices A and B of [1].

I wish to express my gratitude to my mentors and colleagues without whom this work could not exist: Dr. Sri Sriram and Dr. Vincent Stenger of SRICO, Inc.; Dr. T. E. (Ed) Schlesinger of Johns Hopkins University; and Dr. Dan Stancil of North Carolina State University. I acknowledge the contributions of my current and past co-workers at SRICO: Andrea Pollick, Peter Pontius, Jason Retz, Joe Reich, Jon Scholl, Mike Shnider, Dr. Neil Smith, Jim Busch, and Dr. Stuart Kingsley.

My deepest thanks go to my wife, Michele, who tolerated my disappearing into my own world virtually every night and weekend for nine months. I could not have written this book without her patient support and encouragement.

References

[1] Lefevre, H. C., *The Fiber-Optic Gyroscope*, Second Edition, Norwood, MA: Artech House, 2014.

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1

Introduction

Every day terabytes of data traverse the Internet, and most of it travels—for at least part of the path between web servers and our computers, tablets, and smart phones—over optical fiber. But at this writing, those electronic portals and servers still rely on electrons, not photons, to store and process information. That means that before data can be transmitted over a fiber optic cable, it must be converted from electronic to optical form. In high-speed, long-haul transmission, the device that accomplishes that conversion is an electro-optic (EO) modulator.

This book explains the basic physics that makes that device possible, the essential procedures for designing it, and analysis of the key performance parameters of a fiber optic link employing an EO modulator. In addition it presents the fundamental concepts of a variety of other applications of the electro-optic effect, including beam steering, electric field sensing, photonic analog-to-digital conversion and radio frequency (RF)/microwave transmission and filtering. The final chapter covers the fundamental issues in the design of devices for optical frequency conversion, which has recently found a new field of application in quantum frequency conversion for secure communication systems [1].

1.1 Uses of the Electro-Optic Effect

A general book (or course) on photonics typically covers four major topics: (1) generation of light, as in a laser or light emitting diode; (2) transmission of light, as in an optical fiber or planar waveguide; (3) detection of light, as in a photodiode or photomultiplier tube; and (4) manipulation of light, as in a modulator, filter, or frequency converter. The devices covered in this book fall entirely within the fourth topic and are based, with one exception, on the linear electro-optic effect. (The final chapter deals with the closely related second-order nonlinear optical effect.) The focus is on lithium niobate ($LiNbO_3$) as the electro-optic/nonlinear optical material of choice, although most of the analysis is directly applicable to other EO materials as well.

The operation of an electro-optic device is illustrated in Figure 1.1. It is comparable to modulation of an RF wave by an audio frequency signal in a radio communication system, in that the modulating signal is impressed as an envelope onto a carrier. The key difference is that the carrier is an optical-frequency wave (*optical* being broadly defined to encompass visible to mid-IR wavelengths) rather than an RF wave. The time scale in the figure should not be interpreted literally—the modulating signal may lie anywhere in the electromagnetic spectrum, from DC to terahertz, so a pulse in the modulated carrier could contain hundreds to trillions of optical cycles. While the figure illustrates amplitude modulation (Chapter 6), the quantity being modulated

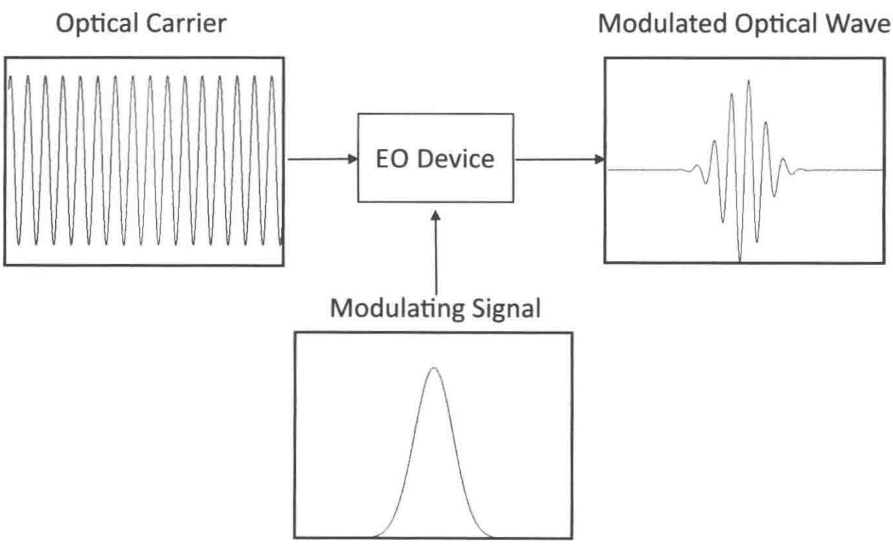

Figure 1.1 Operation of an electro-optic device.