LIGHT PROPAGATION IN GAIN MEDIA

Over the past two decades, optical amplifiers have become of key importance in modern communications. In addition to this, the technology has applications in cutting-edge research such as biophotonics and lab-on-a-chip devices. This book provides a comprehensive treatment of the fundamental concepts, theory, and analytical techniques behind modern optical amplifier technology.

The book covers all major optical amplification schemes in conventional materials, including the Raman and parametric gain processes. The final chapter is devoted to optical gain in metamaterials, a topic that has been attracting considerable attention in recent years. The authors emphasize analytical insights to give a deeper, more intuitive understanding of various amplification schemes. The book assumes background knowledge of electrical engineering or applied physics, including exposure to electrodynamics and wave motion, and is ideal for graduate students and researchers in physics, optics, bio-optics, and communications.

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Optical Amplifiers

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For Anne, Sipra, Caroline, and Claire
–Govind P. Agrawal

For Erosha, Gehan, and Sayumi
–Malin Premaratne

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Preface

Everything should be made as simple as possible, but not simpler.
–Albert Einstein

An optical fiber amplifier is a key component for enabling efficient transmission of wavelength-division multiplexed (WDM) signals over long distances. Even though many alternative technologies were available, erbium-doped fiber amplifiers won the race during the early 1990s and became a standard component for long-haul optical telecommunications systems. However, owing to the recent success in producing low-cost, high-power, semiconductor lasers operating near 1450 nm, the Raman amplifier technology has also gained prominence in the deployment of modern lightwave systems. Moreover, because of the push for integrated optoelectronic circuits, semiconductor optical amplifiers, rare-earth-doped planar waveguide amplifiers, and silicon optical amplifiers are also gaining much interest these days.

Interestingly, even though completely unrelated to the conventional optical communications technology, optical amplifiers are also finding applications in biomedical technology either as power boosters or signal-processing elements. Light is increasingly used as a tool for stretching, rotating, moving, or imaging cells in biological media. The so-called lab-on-chip devices are likely to integrate elements that are both acoustically and optically active, or use optical excitation for sensing and calibrating tasks. Most importantly, these new chips will have optical elements that can be broadly used for processing different forms of signals.

There are many excellent books that cover selective aspects of active optical devices including optical amplifiers. This book is not intended to replace these books but to complement them. The book grew out of the realization that there is a need for coherent presentation of the theory behind various optical amplifiers from a common conceptual standpoint, while highlighting the capabilities of established methods and the limitations of current approaches.

Most of the existing literature on amplifiers covers the advances in amplifier technology related to their fabrication and operation. While it is important to be aware of these developments, this awareness is being achieved at the cost of skipping the fundamentals and the material related to the important physical concepts and underlying mathematical representation. We try to bridge this gap by providing a theoretical framework within which the amplifier theory and device concepts are presented. Our objective is to provide a comprehensive account of light propagation in active media and employ it for describing the signal amplification in different optical amplifier structures. Whenever possible, we obtain approximate analytical results to estimate the operational characteristics of amplifiers, thus enabling the reader to build a detailed intuitive picture about the device operation. We provide sufficient details for numerical implementation of the key algorithms, but we emphasize throughout this text the value and utility of having approximate solutions of different amplification processes. Such an approach not only provides a thorough understanding of the underlying key process of light interaction with matter but also enables one to build a mental picture of the overall operation of the device, without being cluttered with details. However, we have intentionally not included the analysis of noise in amplifiers because a rigorous treatment of noise processes requires sophisticated mathematical machinery beyond the scope of this book. Interested readers may find a thorough discussion of amplifier noise in the book by E. Desurvire, *Erbium-Doped Fiber Amplifiers: Principles and Applications* (Wiley, 1994).

Our presentation style is multi-folded in the sense that we use different descriptions of light, as rays, scalar waves, or vector electromagnetic waves, depending on the sophistication needed to carry out the intended analysis. Our intention is to equip the reader with such sophistication and understanding that he or she gradually develops adequate insight to use a combination of these different descriptions of light to describe the operation of modern optical amplifiers. More specifically, we show that the optical gain of an amplifying medium either can be derived from the first principles using the material susceptibility based on a quantum-mechanical approach or it can be deduced from empirical phenomenological models based on experimental observations. Most importantly, our approach is not to pick a specific model but to show diverse models and techniques to the reader so that reader can make the best possible choice of the method based on the circumstances and the domain of applicability.

In this book, state-of-the-art methods and algorithms suitable for understanding the underlying governing principles and analyzing optical amplifiers are presented in a manner suited to graduate research students and professionals alike. The material in this book may be suitable for scientists and engineers working in the fields of telecommunications, biophotonics, metamaterials, etc., and for those interested in learning and advancing the technology behind modern optical amplifiers. This book is also suitable for individuals opting for self-study as a way for continuing professional development and for professional consultants evaluating technology for industry and government agencies. The readers are assumed to have background in electrical engineering or applied modern physics, including some exposure to electrodynamics and wave motion. Knowledge of quantum mechanics, high-level programming languages such as C++ or Matlab, and numerical software methods is helpful but not essential. We recognize the importance of computer modeling in understanding, analyzing, and designing optical amplifiers. By emphasizing the mathematical and computational issues and illustrating various concepts and techniques with representative examples of modern optical amplifiers, we try to make this book appeal to a wider audience. While any programming language in conjunction with a suitable visualization tool could, in principle, be employed, we feel that reader is best served by learning C++ or a Matlab-type high-level programming language for numerical work associated with this book. We occasionally describe algorithms in this text, but we attempt to avoid programming-specific details.

Our intent has been to provide a self-contained account of the modern theory of optical amplifiers, without dwelling too much on the specific details of each amplifier technology. The book should, therefore, not be considered as a compendium that encompasses applications and design optimizations applicable to a specific amplifying system. Brief derivations of many basic concepts are included to make this book self-contained, to refresh memory of readers who had some prior exposure, or to assist the readers with little or no prior exposure to similar material. The order of the presentation and the level of rigor have been chosen to make the concepts clear and suitable for computer implementation while avoid unnecessary mathematical formalism or abstraction. The mathematical derivations are presented with intermediate steps shown in as much detail as is reasonably possible, without cluttering the presentation or understanding. Recognizing the different degrees of mathematical sophistication of the intended readership, we have provided extensive references to widely available literature and web links to related numerical concepts at the book's website, www.malinp.com.

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