

Preface

It was in April 1976 that I published my first book entitled *Fundamentals of Laser Diode Amplifiers*. Since then we have witnessed rapid and dramatic advances in optical fiber communication technology. To provide a comprehensive and up-to-date account of laser diodes and laser diode amplifiers I decided to publish this new book, which in fact is an extensive extension to my above book. The main objective of this new book is also to serve both as a textbook and as a reference monograph. As a result, each chapter is designed to cover both physical understanding and engineering aspects of laser diodes and amplifiers.

With the rapid growth and sophistication of digital technology and computers, communication systems have become more versatile and powerful. This has given a modern communication engineer two key problems to solve: (i) how to handle the ever-increasing demand for capacity and speed in communication systems and (ii) how to tackle the need to integrate a wide range of computers and data sources, so as to form a highly integrated communication network with global coverage.

The foundations of communication theory show that by increasing the frequency of the carrier used in the system, both the speed and capacity of the system can be enhanced. This is especially true for modern digital communication systems. As the speeds of computers have increased dramatically over recent years, digital communication systems operating at a speed which can match these computers have become increasingly important. Rather than the electronic circuitry, it is now apparent that the upper bound on the speed of a communication system is limited by the transmission medium. An example which illustrates fast development in recent communication is that today's PC generally uses PCI bus as the electrical interconnect, which can provide data transfer rate up to 8.8 Gb/s. However, the speed of the modem normally connected to such a PC has just recently reached 8 Mb/s over copper lines using ADSL technology in commercial broadband access networks. This is at least 1100 times slower than

the current electrical interconnect in the PC. One of the reasons for such mismatch is that modems use telephone lines (which are typically twisted-pair transmission lines) and these cannot operate at very high frequencies. To improve the speed and hence capacity of the system, one does not only need to switch to a carrier with a higher frequency, but to switch to an alternative transmission medium.

Given the preceding argument, one will not be surprised by the rapid development of optical communications during the past 30 years. Ever since Kao and his co-workers discovered the possibility of transmitting signals using light in circular dielectric waveguides, research in optical communication systems has developed at an unprecedented pace and scale. Optical communications offer two distinct advantages over conventional cable or wireless systems. Firstly, because the carrier frequency of light is in the region of THz (i.e. 10^{14} Hz), it is possible to carry many more channels than radio wave or even microwave systems. Secondly, the former advantage can be realised because of the development of a matching transmission medium, namely optical waveguides (including fibres and planar structures). Optical waveguides not only provide the necessary frequency bandwidth to accommodate a potentially large number of channels (and hence a huge capacity), but also offer an immunity from the electromagnetic interference from which the traditional transmission medium often suffers.

In addition to optical waveguides, another key area of technological development which plays a crucial role in the success of optical communication systems is optical devices. The rapid growth of semiconductor laser diodes has allowed optical transmitters to be miniaturised and become more powerful and efficient. Both the fabrication and theoretical research in semiconductor lasers have given rise to a wide range of components for optical communication systems. For example, from conventional buried heterostructure laser diodes to the recent development of multiple quantum-well lasers and from simple Fabry-Perot structures to (i) distributed feedback (DFB) structures, (ii) single cavity laser diodes and (iii) multiple cavity laser diodes. Laser diodes are not only important in compact disc players, but they also provide coherent light sources which are crucial in enhancing the speed and range of transmission of optical communication systems.

The technological forces which gave us optical waveguides and semiconductor laser diodes have recently explored theoretical research and manufacturing technology to develop further innovative devices that are crucial in optical communications, for example, optical amplifiers, optical

switches and optical modulators. Previously *optical/electronic* conversion devices had to be used for performing these functions, but the bandwidth of these was limited. The integration of semiconductor laser diodes with optical waveguide technology allows such components to be developed specifically for optical communications. This force of integration does not stop here. The advent of photonic integrated circuits (PIC), which are ICs built entirely with optical components, such as laser diodes, waveguides and modulators, will further enhance the power and future prospects of optical communication networks.

In view of the increasing pace of development and growing importance of optical communication technology, I believe students, researchers and practicing engineers should be well equipped with the necessary theoretical foundations for this technology, as well as acquiring the necessary skills in applying this basic theory to a wide range of applications in optical communications. There are of course many good books about optical communication systems, but they seldom direct their readers to concentrate on the two key aspects behind the success in optical communications which we have discussed above. I am attempting to fill this gap with this book. I will be concentrating on the basic theory of optical waveguides and semiconductor laser technology, and I will illustrate how these two aspects are closely related to each other. In particular, I will examine how semiconductor laser amplifiers have been developed based on applications of the basic theory of these two areas.

Throughout this book, it is intended that the reader gains both a basic understanding of optical amplification and a factual knowledge of the subject based on device analysis and application examples. I hope that this book will be beneficial to students aiming to study optical amplification, and to the active researchers at the cutting edge of this technology. This book is organised as follows:

Chapter 1 explores the state of the art of optical fibre communication systems in this rapidly evolving field. A short introduction includes the historical development, the principles and applications of semiconductor laser amplifiers in optical fibre communications, the general optical system and the major advantages provided by this technology. In Chapter 2, the fundamentals and important performance characteristics of optical amplifiers will be outlined. Chapter 3 gives an introduction to optical amplification in semiconductor laser diodes. Chapters 4 to 6 deal with the analysis of semiconductor laser amplifiers (SLAs). In these chapters the waveguiding properties and the basic performance characteristics of SLAs

(i.e. amplifier gain, gain saturation and noise) will be studied. Also a new technique, which is based on an equivalent circuit model, will be introduced for the analysis of SLAs. Implications of SLAs on optical fibre communication system performance will also be discussed. In Chapter 7 the accuracy and limitations of the equivalent circuit model will be investigated by comparing both theoretical and experimental results for actual devices. In Chapter 8 we introduce a new semiconductor laser diode amplifier structure. Chapter 9 deals with amplification characteristics of pico-second Gaussian pulses in various amplifier structures. Chapter 10 studies the sub-pico-second gain dynamic in a highly index-guided tapered-waveguide laser diode amplifier. In Chapter 11 we introduce a novel approximate analytical expression for saturation intensity of tapered travelling-wave semiconductor laser amplifier structures. Wavelength conversion using cross-gain modulation in linear tapered-waveguide semiconductor laser amplifiers is studied in Chapter 12.

The main theme of the work presented in Chapters 13 to 17 is microwave circuit principles applied to semiconductor laser modelling. The advantages and additional insight provided by circuit models that have been used for *analytical* analysis of laser diodes have long been acknowledged. In these chapters, we concentrate on the derivation, implementation, and application of *numerical* circuit-based models of semiconductor laser devices.

Design automation tools are playing an increasingly important role in today's advanced photonic systems and networks. A good photonic computer aided design (PCAD) package must include a model of the semiconductor laser, one of the key optoelectronic devices in fibre-optic communications. In this part of the book, the feasibility and advantages of applying microwave circuit techniques to semiconductor laser modelling for PCAD packages are investigated.

Microwave circuit models allow us to explore fundamental properties of electromagnetic waves without the need to invoke rigorous mathematical formulations. These equivalent circuit models are easy to visualise, providing a simple and clear physical understanding of the device. Two types of circuit models for semiconductor laser devices have been investigated: (i) lumped-element model, and (ii) distributed-element model based on transmission-line laser modelling (TLLM). The main differences between the lumped circuit and distributed circuit models have been compared in this book.

Most other dynamic models of laser diodes have failed to consider the high-frequency parasitics effect and impedance matching. These microwave

aspects of the laser diode can be conveniently included in microwave circuit models. The matching network has been, for the first time, included in the integrated TLLM model, based on monolithically integrated lumped elements. The parasitics effect and matching considerations have been included in both small-signal and large-signal RF modulation of the laser transmitter module. The carrier dependence of the laser impedance within the TLM network has also been investigated.

Computational intensive two-dimensional (2-D) models of tapered laser devices are unattractive for PCAD packages. An efficient 1-D dynamic model of tapered structure semiconductor lasers has been developed based on TLLM, in which a semi-analytical approach was introduced to further enhance the computational efficiency. The tapered structure transmission-line laser model (TS-TLLM) includes inhomogeneous effects in both lateral and longitudinal directions, and is used to study picosecond pulse amplification. Previous models of tapered semiconductor amplifier structures failed to consider residual reflectivity but in TS-TLLM, reflections have been taken into account. Furthermore, the stochastic nature of TS-TLLM allows the influence of noise to be studied.

The TS-TLLM developed in this book has been combined with other existing TLLM models to form a multisegment mode-locked laser incorporating distributed Bragg reflectors, and a tapered semiconductor amplifier. This novel design can be used to generate high-power mode-locked optical pulses for various applications in fibre-optic systems. Important design considerations and optimum operating conditions of the novel device have been identified in conjunction with the RF detuning characteristics. A new parameter to define stable active mode-locking, or locking range, is discovered. Microwave circuit models of semiconductor laser devices provide a useful aid for microwave engineers, who wish to embark on the emerging research area of microwave photonics, and bring on a fresh new perspective for those already in the field of optoelectronics.

In Chapter 13, first, a short historical background and the relevant physics behind the semiconductor laser will be given. Chapter 14 introduces the transmission-line matrix (TLM) method that provides the basic microwave circuit concepts used to construct the time-domain semiconductor laser model known as the transmission-line laser model (TLLM). We then proceed to compare two categories of equivalent circuit models, i.e. lumped-element and distributed-element, of the semiconductor laser in Chapter 15. In the same chapter, a comprehensive laser diode transmitter model is developed for microwave optoelectronic simulation. The microwave

optoelectronic model is based on the transmission-line modelling technique, which allows propagation of optical waves, as well as lumped electrical circuit elements, to be simulated. In Chapter 16, the transmission-line modelling technique is applied to a new time-domain model of the tapered waveguide semiconductor laser amplifier, useful for investigating short pulse generation and amplification when finite internal reflectivity is present. The new dynamic model is based on the strongly index-guided laser structure, and quasi-adiabatic propagation is assumed. Chapter 17 demonstrates the usefulness of the microwave circuit modelling techniques that have been presented in this thesis through a design study of a novel mode-locked laser device. The novel device is a multisegment monolithically integrated laser employing distributed Bragg gratings and a tapered waveguide amplifier for high power ultrashort pulse generation. Finally, Chapter 18 is devoted to some concluding remarks and comments. The book is referenced throughout by extensive end-of-chapter references which provide a guide for further reading and indicate a source for those equations and/or expressions which have been quoted without derivation.

The principal readers of this book are expected to be undergraduate and postgraduate students who would like to consolidate their knowledge in lightwave technology, and also researchers and practicing engineers who need to equip themselves with the foundations for understanding and using the continuing innovations in optical communication technologies. Readers are expected to be equipped with a basic knowledge of communication theory, electromagnetism and semiconductor physics.

Finally, I must emphasize that optical communication is still a rapidly growing technology with very active research. After reading the book, I hope that the reader will be equipped with the necessary skills to apply the most up-to-date technology in optical communications.

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