Theory and Design of Terabit Optical Fiber Transmission Systems

This comprehensive, modular treatment of the challenging issues involved in very high-speed optical transmission systems contains all the theory and practical design criteria required to optimize transmission system design.

Each chapter covers the theoretical modeling of a given system, well supported by real-world worked examples, and accompanied by receiver design examples and online MATLAB resources. Critical analysis and comparison of engineering solutions are presented, to make clear the principles underlying system performance optimization, and a broad range of transmission systems is discussed, including the status and performance demands of the terabit systems now entering the next-generation market.

Blending theoretical and practical considerations for high-speed fiber optic systems design, this is an indispensible reference for all forward-looking professionals and researchers in optical communications.

Stefano Bottacchi leads the Advanced Optical Transmission System Group at TriQuint Semiconductor, Dallas, TX, having previously worked with u^{2}t Photonics AG Siemens/ Infineon Technologies AG, and CISCO. He has over 25 years' experience of optical component and system design, and is the author of several books in the field of optical communications.

"The book provides a very broad theoretical background of general topics which are relevant for any engineer working in the field of optical fiber transmission systems. Topics include the description of signals, basics of higher order modulation formats, basics of polarized light propagation including light amplification and interferometric devices, with special emphasis on Mach Zehnder modulators, as well as a discussion of coherent receivers. All these topics are dealt with in great detail with a very thorough analysis. The book thus helps to get a deep understanding of important aspects of high capacity optical fiber communication systems, and it will thus be very helpful for any reader with interest in these aspects."

Klaus Petermann
Technische Universität Berlin

Theory and Design of Terabit Optical Fiber Transmission Systems

STEFANO BOTTACCHI
TriQuint Semiconductor, Dallas

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521192699

First published 2014

Printed in the United Kingdom by Bell and Bain Ltd

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-19269-9 Hardback

Additional resources for this publication at www.cambridge.org/bottacchi

To my wife Laura
and my charming daughters
Francesca and Alessandra

Contents

Preface

This book is addressed to engineering professionals, researchers and R&D designers, as well as to electrical engineering graduate and PhD students, as a compendium of topics concerning advanced optical fiber transmission systems and components relying on coherent optical technologies. It has been written using original material. From the very beginning, my principal aim has been to provide an engineering reference, with numerous applications and simulations, to the state of the art in terabit optical fiber transmission.

The subject is vast and cannot be covered in a single book. I have attempted to include the most important topics, spanning optical signal theory, complex modulation formats, non-linear optics, light amplification, optical modulation and detection, and the integrated intradyne coherent optical photoreceiver for detection of high-order optical modulation formats relying on orthogonal polarizations. I assume that the reader is familiar with the background principles of optical signals, light amplification and noise, but I have added and reviewed many arguments concerning these fundamental physical quantities.

As the reader will observe, considering the book's coverage I have used few references. This is justified by the original content used to approach most of the arguments. However, I have added many simulations and examples expressly written in Matlab® R2013a, in keeping with the operative approach of the book. The book deals with complex optical signals and noise and makes great use of the mathematical formalism. As a guideline, I have attempted to introduce each argument first at a conceptual level, then developing the mathematical formalism to approach the operative model used for design purposes.

The extraordinary achievements in coherent optical systems are almost equally shared between integrated optical technology and powerful digital signal processing. None of these results could have been achieved without synergy between these two different engineering disciplines. This is a clear example of the interdisciplinary skills required to develop the next generation of optical fiber communication systems. The digital signal processing enabling coherent optical communication systems is beyond the scope of this book, but will be part of a future book.

This book is organized into four parts and 13 chapters. Part I, consisting of three chapters, approaches the theory of optical signals, spectral efficiency and complex optical modulations. Part II, in four chapters, is devoted to non-linear optics, light polarization, light amplification and noise generated by optical amplifiers. All these concepts are presented with the mathematical formalism appropriate to design and simulation.

Part III includes five chapters, dealing with the theory and application of the Mach–Zehnder modulator (MZM). This device plays a fundamental role in optical fiber transmission and is one of the enabling factors for successful coherent optical transmission systems. Today, every high-order optical modulation requires multiple MZMs, providing orthogonal polarizations and quadrature optical phase modulation on a single optical carrier. Chapter 8 presents the coupled-mode theory of the single-mode optical coupler, the basic building block for more complex interferometric structures, and in particular the Mach–Zehnder interferometer (MZI). Chapter 9 introduces the theory of the MZI, with several applications in optical communications. The interferometric optical responses of the MZI as a six-pole device are formulated in Chapter 10. The functional parameters of the MZM are illustrated in Chapter 11, where the theory of the chirp function is derived and illustrated with computer simulations. Chapter 12 approaches the theory and modeling of the quadrature MZM as the most suitable device for generating quadrature optical modulated signals used in coherent optical communication. The chapter contains original contributions on characterization of the extinction ratio of the quadrature MZM by the field inversion method, and on the theory of the compound chirp function at the output of the quadrature MZM. A very interesting feature of the quadrature MZM is its ability to generate the simplest quadrature phase shift keying (DP-QPSK) and higher-order optical modulation formats such as DP-16QAM and the recently proposed dual-polarization quadrature duobinary (DP-QDB) format, providing appropriate phase bias and driving signal amplitudes.

Part IV consists of a single chapter, the last of the book. The theory and modeling of the coherent optical photoreceiver, based on the 90° optical hybrid and dual-polarization intradyne detection, is presented in detail and accompanied by simulations and working examples. The unique feature of this coherent detection scheme, paired with appropriate digital signal processing, is its ability to detect the simple DP-QPSK as well as higher-order optical modulation formats such as DP-16QAM, with no change in device hardware.

The simultaneous ability of the dual-polarization quadrature MZM and the dual-polarization 90°hybrid intradyne photoreceiver to manage any high-order quadrature optical modulation based on two orthogonal polarizations is an astonishing occurrence in optical fiber communications, leading to the extraordinary success of optical coherent technology in achieving terabit transmission capacity in small-footprint devices.

Chapter 1

System complexity and transmission impairments grow with increasing transmission speed, and sophisticated optical modulation formats have been investigated since 1998 to mitigate transmission bandwidth and optical fiber impairments. Conventional on–off keying (OOK) optical modulation has been progressively replaced by more complex but efficient formats, especially in long-haul and high-density metro transmission systems. Higher-order modulation formats not only encompass simple binary light intensity modulation using multilevel coding, but include phase and vector modulation formats, in which both amplitude and phase carry information content simultaneously on the same optical carrier. The simple baseband square-pulse model no longer adequately supports the complex signals generated by higher-order modulations, and more general models of signals and spectra are required. This chapter reviews basic concepts in signal theory and presents selected topics on conjugated domain pulses. Most of the conclusions of this chapter find application in modeling the signals at the output of higher-order optical demodulators.

Chapter 2

Optical modulation, indeed any signal modulation, is a process of up-converting the energy of information content to the required spectral domain for transmission. Unfortunately, real baseband signals require an optically modulated spectrum to satisfy the conjugate symmetry condition, leading to double spectral occupancy relative to a single-sideband spectrum. Is there a way to bring the baseband equivalent of the single-sideband (SSB) spectrum up to the level of the modulated optical spectrum? The answer to this question is well known in communication engineering and deals with analytic signals and Hilbert transforms. The aim of this chapter is to provide mathematical insight into the relationships between Fourier transforms and Hilbert transforms of real signals and to combine those properties in a SSB modulation useful in high-spectral-efficiency optical communications. The achievement of SSB modulation depends on the modulation format. Specifically, single-carrier amplitude shift keying (ASK) modulation can easily be converted to SSB-ASK by doubling the spectral efficiency. Unfortunately, quadrature amplitude modulations like QPSK and more generally *m*QAM are not easily converted to the SSB format, making SSB less suited for the high-order modulation formats under development in optical fiber communications. However, SSB-QPSK represents an interesting application for the Hilbert transform and merits further exploration.

Chapter 3

Optical communication has in recent years dramatically changed system architecture and network design. Most engineering solutions and enabling technologies for terabit transmission rely on high-order optical modulation and increased spectral efficiency to relax electronic speed requirements and achieve higher information capacity. The OOK optical modulation that has dominated since the 1980s has exhausted its role as a long-haul modulation format, replaced by more efficient and dispersion-tolerant high-order formats. Fundamental optical amplitude and phase modulations play a fundamental role in the photodetection process and form the background to ever more complex optical modulation formats.

Chapter 4

Nowadays, optimum transmission performance in optical communications requires a profound understanding of several engineering disciplines. Among these, the basic concepts of non-linear optics and light polarization must be mastered by every engineer in this fascinating field. They are essential to an understanding of the interactions between electric fields and matter, in particular the dielectric materials in glass-based optical fibers and, more generally, dielectric waveguides. The non-linear threshold for high-order effects is highly variable among materials such as semiconductors, crystals and optical polymers, but their behaviors are predictable using the same mathematical models. Polarization has a profound impact on light–matter interactions – no longer considered a mere perturbation but more often than ever carrying information, thus increasing the dimensionality of the optical field and allowing higher information capacity.

Chapter 5

Light amplification serves optical communication as electrical amplification enables radio communication. This seems obvious, but we wouldn't have successful optical networks nowadays without large-scale deployment of optical amplifiers. Light amplification is based on the fundamental process of stimulated emission when an electromagnetic field interacts with matter: an excited electron interacting with a photon of suitable energy decays, emitting a photon with the same wave vector as the incoming photon. The stimulated photon is a clone of the incoming photon, with the same spatial direction and wavelength (color). The result is elementary light amplification, doubling the number of photons. Thus, ideal light amplification follows a quadratically growing curve as a function of the number of stimulated emissions. Of course, nothing is achieved for nothing: the electron must be excited from the ground state, meaning we must somehow transfer (pump) energy to it. Unfortunately, the incoming photon has an alternative destiny: it could get lost, absorbed by the electron instead of stimulating another photon, and unfortunately the chances of these complementary processes are exactly equal. Analogously to electrical amplification, we must supply a suitable form of energy to the optical amplifier to be converted into optical energy once the stimulation takes place. Light amplification is demanded in every application of optical communication, in long-haul transport as well as high-density networks.

Chapter 6

Optical amplifiers are the enabling components of terabit long-haul optical transmission systems, and their characterization and modeling is fundamental to optimizing system performance. Optical gain levels out when the optical power density approaches saturation, limited by the medium's properties and by pumping mechanisms. Thus, optical gain is a non-linear function of the input signal power, and this requires the solution of non-linear gain equations. Moreover, the gain depends on the spectral content of the input signal, and this leads to spectral-gain modeling of optical amplification. The model is presented with the erbium-doped fiber amplifier in mind, but most of the mathematical assumptions and related equations are general and applicable to various optical amplification mechanisms.

Chapter 7

Light amplification enables long-haul optical transmission in direct as well as coherent detection, but it adds unavoidable optical noise. But what is optical noise? Light consists of elementary energy packets called photons, so why are some noisy while others are called signal photons? It is a matter of coherence: coherent light particles are eligible to be signal quanta, whereas incoherent, randomly generated ones become the noisy elements, impairing the clarity and order of the signal. Every amplification process is affected by some random particle generation, whether it is thermal electrons in electrical amplification or spontaneously emitted photons in optical amplification. Moreover, each spontaneously emitted photon is subject to the same amplification process as a "signal" photon. There is no difference between them as they undergo amplification. Thus in any optical amplifier we must deal with amplified spontaneous emission (ASE) noise as the original cause of optically induced electrical noise. During photodetection, by either direct or coherent processes, fluctuations of the optical electric field are converted to noise photocurrents and can strongly impair recognition of the signal photocurrent.

Chapter 8

This chapter will present the theory and mathematical modeling of the single-mode optical coupler, according to coupled-mode theory. The optical coupler has had a fundamental role in every optical fiber communication system since the first transmission experiments in the 1970s. The bibliography is very large, with thousands of papers, conference proceedings and many chapters in dedicated books on optical fibers and technologies. The simplest but largest application of the optical coupler is as a power divider, but it has gained special attention since 2000 as a fundamental building block in many applications of the optical MZI. The detection of optical DPSK and DQPSK modulated signals using the self-homodyne MZI is among the most interesting applications in state-of-the-art optical transmission systems operating at 43 Gb/s and 100 Gb/s. The optical interleaver and the 90° hybrid are other interesting applications of the single-mode optical coupler, used as building blocks in many complex interferometric devices.

Chapter 9

This chapter provides the theory and mathematical modeling of the continuous wave (CW) operation of the MZI, realized using optical fiber couplers, planar lightwave circuitry (PLC) or, more recently, nanophotonic technology. (The theory of the optical frequency response of the MZI is presented in Chapter 10, using the general Fourier transform technique.) The MZI has gained great relevance in all applications of optical fiber communication. It is a versatile structure, well suited to numerous applications, including traditional intensity and phase modulation of input CW optical fields, through to wavelength division multiplexing and optical wavelength interleaving.

The MZI is the basic building block in optical coherent receivers using balanced photodetection. The detection of optical DPSK and DQPSK modulated signals using the self-homodyne MZI will be presented in Chapters 12 and 13, as a relevant application to state-of-the-art optical fiber communication.

Chapter 10

This chapter deals with the theory, modeling and simulation of the optical coupler and its applications, as composite coupling structures and in particular the MZI as an optical–optical linear device. The MZI represents an important application of the coupled-mode field theory developed in Chapters 8 and 9. The aim of this chapter is to find mathematical equations governing the behavior of these four-port optical–optical devices in terms of their optical matrices. The matrix description allows simple and complete device modeling in both time and frequency domains for the detection of specific optical modulations or multiple-component problems. The compact matrix representation of the MZI is a useful toolbox for the design and optimization of many applications.

Chapter 11

Optical communication today is engaged in a great search for higher transmission rates and larger capacity through high-order optical modulation formats and optical super-channels. Almost all optical modulators consist of MZIs, optimized for high transmission rates and large extinction ratios. Among the most critical design tasks is the achievement of a symmetric layout optimized to bring the modulator into a balanced operating condition with respect to both electro-optic waveguides and interferometric sections. The performance of the MZM, as of any interferometric structure, is based on the layout symmetry. Symmetric design of input and output optical couplers as well as the waveguide structures is mandatory for achieving large extinction ratios and zero chirp at the output ports. “Chirp” refers to residual modulation of the optical phase during optical intensity transients, at the output ports of the MZM. Chirp leads to additional spectral broadening and to detrimental effects on optical transmission performance when combined with a dispersive medium. It arises from asymmetries in the optical and electrical operation of the MZM, as well as from refractive index variations in the electro-optic waveguides during optical intensity transients. This chapter will neglect material-induced chirp and focus on chirp induced by optical and electrical imbalances of the MZM structure.

Chapter 12

Coherent optical technology has radically changed the architecture of optical communication systems and has significantly increased their capacity and reach. Optical transmission based on coherent optical technology uses amplitude and phase information, as well as the state of polarization of the optical field, allowing polarization-multiplexed, high-order complex optical modulation formats, with large gain factors between the bit rate and the symbol rate. This opens the door to transmission speeds well beyond the terabit range while still requiring only a few tens of GHz bandwidth from optoelectronic devices, and achieving spectral efficiencies in excess of 12 for DP-64QAM with Nyquist spectral shaping.

Part of the price to pay for such huge increases in transmission capacity is increased complexity of the optical transmitter. Currently, the most advanced architecture for optical modulators allows transmission of two orthogonal polarizations with quadrature phase tributaries, each with about 40 GHz bandwidth. At the lowest complexity level, dual-polarization quadrature optical modulation allows transmission of the DP-QPSK format, with a spectral efficiency of 4 with Nyquist spectral shaping. Increasing the level of the modulation format, DP-16QAM doubles the spectral efficiency. None of these achievements would be conceivable without the single-quadrature optical modulator (SQMO). This chapter is devoted to the theory and mathematical modeling of this complex device, exploring the relationships between intrinsic design parameters and optical performance.

Chapter 13

Growing bandwidth demands a reasonable match with the emerging yet consolidated optical intradyne coherent technology, enhanced by orthogonal polarization multiplexing. Complex *m*QAM optical modulation formats are demodulated using coherent photoreceiver architecture based on the optical 90° hybrid building block. This device couples the input optical signal with two quadrature phases of the local oscillator, allowing the coherent photocurrents to be proportional to each quadrature component of the input signal and recognized by appropriate digital signal processing. The unique feature of the intradyne coherent photoreceiver is its ability to work with any order of quadrature amplitude modulation, as well as with other formats like binary phase shift keying (BPSK), ASK and quadrature optical duobinary (QDB). Complete knowledge of the intradyne coherent photoreceiver can be partitioned into the optical coherent subsystem and the digital signal processing of the resulting photocurrent. This chapter will present the theory of the optical coherent photoreceiver based on the 90° hybrid with dual-polarization configuration, assuming homodyne detection and polarization alignment. Recognition of the polarization diversity by intradyne detection is performed by digital signal processing and is outside the scope of this book.

Acknowledgments

I wrote this book to satisfy my interest in finding a systematic approach to the interdisciplinary application of optical fiber communications and coherent optical technologies to multi-terabit communication capacity. I am indebted to u^{2}t Photonics AG for its stimulating work environment, a vital premise for all successful engineering achievements. I am grateful to Cambridge University Press, and in particular to Dr Julie Lancashire, Ms Caroline Mowatt and Ms Elizabeth Horne, for the time, expertise and encouraging patience they continuously offered me during the long preparation of this manuscript. A special acknowledgment to Mr John King for the competence and the patience he devoted to the accurate review of the manuscript. Finally, I thank my family and my parents, Wanda and Franco, for their unlimited trust, patience and motivation during the book's development.