

# Optical Fiber Telecommunications

## VIA

Components and Subsystems



Ivan P. Kaminow  
Tingye Li  
Alan E. Willner



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# Optical Fiber Telecommunications VIA

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## Components and Subsystems

SIXTH EDITION

Ivan P. Kaminow

Tingye Li

Alan E. Willner



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# Dedication

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*To the memory of Dr. Tingye Li*

*(July 7, 1931 – December 27, 2012)*

*A pioneer, luminary, friend, mentor, and champion of our field.*

*We will miss him dearly.*

*From the optical communications community*

## 题词

光通信领域的同仁们:

请向我们的先驱、引路人、朋友、导师、倡导者和勇士,

厉鼎毅博士

(1931年7月7日 - 2012年12月27日)

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致以深切的怀念!

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The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK  
225 Wyman Street, Waltham, MA 02451, USA

Sixth edition 2013

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## **Library of Congress Cataloging-in-Publication Data**

A catalog record for this book is available from the Library of Congress

## **British Library Cataloguing in Publication Data**

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

For information on all Academic Press publications visit our web site at  
[books.elsevier.com](http://books.elsevier.com)

Printed and bound in the US

13 14 15 16 17 10 9 8 7 6 5 4 3 2 1



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# Dedication 2

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*For Florence, Paula, Leonard, and Ellen with love – IPK*

*For Edith, Debbie, and Kathy with love – TL*

*For Michelle, Moshe, Asher, Ari and Yaakov with love – AEW*

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# Preface—Overview of OFT VI A & B

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*Optical Fiber Telecommunications VI (OFT VI)* is the sixth installment of the *OFT* series. Now 50 years old, the series is a compilation by the research and development community of progress in the field of optical fiber communications. Each edition reflects the current state of the art at the time. As editors, we started with a clean slate and selected chapters and authors to elucidate topics that have evolved since *OFT V* or that have now emerged as promising areas of research and development.

## Six Editions

Installments of the series have been published roughly every 5–8 years and chronicle the natural evolution of the field:

- In the late 1970s, the original *OFT* (Chenoweth and Miller, 1979) was concerned with enabling a simple optical link, in which reliable fibers, connectors, lasers, and detectors played the major roles.
- In the late 1980s, *OFT II* (Miller and Kaminow, 1988) was published after the first field trials and deployments of simple optical links. By this time, the advantages of multi-user optical networking had captured the imagination of the community and were highlighted in the book.
- *OFT III* (Kaminow and Koch, 1997) explored the explosion in transmission capacity in the early-to-mid-1990s, made possible by the erbium-doped fiber amplifier (EDFA), wavelength-division-multiplexing (WDM), and dispersion management.
- By 2002, *OFT IV* (Kaminow and Li, 2002) dealt with extending the distance and capacity envelope of transmission systems. Subtle nonlinear and dispersive effects, requiring mitigation or compensation in the optical and electrical domains, were explored.
- *OFT V* (Kaminow, Li, and Willner, 2008) moved the series into the realm of network management and services, as well as employing optical communications for ever-shorter distances. Using the high-bandwidth capacity in a cost-effective manner for customer applications started to take center stage.
- The present edition, *OFT VI* (Kaminow, Li, and Willner, 2013), continues the trend of photonic integrated circuits, higher-capacity transmission systems, and flexible network architectures. Topics that have gained much interest in increasing performance include coherent technologies, higher-order modulation formats, and space-division-multiplexing. In addition, many of the topics from earlier volumes are brought up to date and new areas of research which show promise of impact are featured.

Although each edition has added new topics, it is also true that new challenges emerge as they relate to older topics. Typically, certain devices may have adequately solved transmission problems for the systems of that era. However, as systems become more complex, critical device technologies that might have been considered a “solved problem” would now have new requirements placed upon them and need a fresh technical treatment. For this reason, each edition has grown in sheer size, i.e. adding

the new and, if necessary, re-examining the old.

An example of this circular feedback mechanism relates to the fiber itself. At first, systems simply required low-loss fiber. However, long-distance transmission enabled by EDFAs drove research on low-dispersion fiber. Further, advances in WDM and the problems of nonlinear effects necessitated development of non-zero-dispersion fiber. Cost and performance considerations today drive research in plastic fibers, highly bendable fibers, few-mode fibers, and multicore fibers. We believe that these cycles will continue.

## Perspective Of The Past 5 Years

*OFT V* was published in 2008. At that point, our field was still emerging from the unprecedented upheaval circa 2000, at which time worldwide telecom traffic ceased being dominated by the slowly growing voice traffic and was overtaken by the rapidly growing Internet traffic. The irrational investment exuberance and subsequent depression-like period of oversupply (i.e. the “bubble-and-bust”) wreaked havoc on our field. We are happy to say that, by nearly all accounts, the field continued to gain strength again and appears to have entered a stage of *rational* growth. Demand for bandwidth continues to grow at a very healthy rate. Capacity needs are real, and are expected to continue in the future.

We note that optical fiber communications is firmly entrenched as part of the global information infrastructure. For example: (i) there would be no Internet as we know it if not for optics, (ii) modern data centers may have as many as 1,000,000 lasers to help interconnect boards and machines, and (iii) Smartphones would not be so smart without the optical fiber backbone.

A remaining question is how deeply will optical fiber penetrate and complement other forms of communications, e.g. wireless, access and on-premises networks, Interconnections, satellites, etc. The odds are that, indeed, optics will continue to play a significant role in assisting all types of future communications. This is in stark contrast to the voice-based future seen by *OFT*, published in 1977, which occurred before the first commercial intercontinental or transatlantic cable systems deployed in the 1980s. We now have Tbit/s systems for metro and long-haul networks. It is interesting and exciting to contemplate what topics, concerns, and innovations might be contained in the next edition of the series, *OFT VII*.

In this edition, *OFT VI*, we have tried to capture the rich and varied technical advances that have occurred in our field. Innovations continue to abound! We hope our readers learn and enjoy from all the chapters.

We wish sincerely to thank Tim Pitts, Charlie Kent, Susan Li, Jason Mitchell of Elsevier and Haoyang Huang of USC for their gracious and invaluable support throughout the publishing process. We are also deeply grateful to all the authors for their laudable efforts in submitting their scholarly works for distinction. Finally, we wish to thank the many people whose insightful suggestions were of great assistance.

Below are brief highlights of the different chapters in the two volumes.

## OFT VI Volume A: Components and Subsystems

### 1A Advances In Fiber Distributed-Feedback Lasers

*Michalis N. Zervas*

This chapter covers advances in fiber distributed-feedback (DFB) lasers and their potential use

modern coherent optical telecommunication systems. In particular, it describes novel DFB cavity designs and configurations and considers their impact on the laser performance. Special emphasis is given to the fiber parameters that define the power scalability and stability, the polarization performance, as well as the linewidth and phase-noise characteristics. The wavelength coverage and tunability mechanisms are also discussed. The chapter finally reviews the use of fiber DFB lasers in non-telecom applications, such as advanced optical fiber sensors, and concludes with an outlook of the fiber laser technologies and their future prospects.

## 2A Semiconductor Photonic Integrated Circuit Transmitters And Receivers

***Radhakrishnan Nagarajan, Christopher Doerr, and Fred Kish***

This chapter covers the field of semiconductor photonic integrated circuits (PIC) used in access metro, long-haul, and undersea telecommunication networks. Although there are many variants of implementing optical integration, the focus is on monolithic integration where multiple semiconductor devices, up to many hundreds in some cases, are integrated onto the same substrate. Monolithic integration poses the greatest technical challenge and the biggest opportunity for bandwidth and size scaling. The PICs discussed here are based on the two most popular semiconductor material systems: Groups III–V indium phosphide-based devices and Group IV silicon-based devices. The chapter also covers the historical evolution of the technology from the decades-old original proposal to the current-day Tbit/s class, coherent PICs.

## 3A Advances In Photodetectors And Optical Receivers

***Andreas Beling and Joe C. Campbell***

This chapter reviews the significant advances in photodetectors that have occurred since *Optical Fiber Telecommunications V*. The quests for higher-speed p-i-n detectors and lower-noise avalanche photodiodes (APDs) with high gain-bandwidth product remain.

To a great extent, high-speed structures have coalesced to evanescently coupled waveguide devices with bandwidths exceeding 140 GHz have been reported. A primary APD breakthrough has been the development of Ge on Si separate-absorption-and-multiplication devices that achieve long-wavelength response with the low-noise behavior of Si. For III–V compound APDs, ultra-low noise has been achieved by strategic use of complex multilayer multiplication regions that provide a more deterministic impact ionization. However, much of the excitement and innovation have focused on photodiodes that can be incorporated into InP-based integrated circuits and photodetectors for photonics.

## 4A Fundamentals Of Photonic Crystals For Telecom Applications— Photonic Crystal Lasers

***Susumu Noda***

Photonic crystals, in which the refractive index changes periodically, provide an exciting tool for the manipulation of photons and have made substantial progresses in recent years. This chapter first introduces research activities that are geared toward realizing the ultimate nanolaser using the photonic bandgap effect. Important aspects of this effort are in the achievement of spontaneous

emission suppression and strong optical confinement using a photonic nanocavity. During the process of implementation of this goal, interesting phenomena, which can be classified as Quantum Anti-Zeno effect, have been observed. The rest of the chapter focuses on the current state of research in the field of broad-area coherent photonic crystal lasers using the band-edge effect, which occupies a position opposite to that of nanolasers discussed above. The main characteristics of these lasers will be discussed, including their high-power operation, the generation of tailored beam patterns, the surface-emitting laser operation in the blue-violet region, and even the beam-steering functionality.

## 5A High-Speed Polymer Optical Modulators

*Raluca Dinu, Eric Miller, Guomin Yu, Baoquan Chen, Annabelle Scarpaci, Hui Chen, and Corentin Pilgrim*

Recent advances in thin-film-polymer-on-silicon (TFPS) technology have provided the foundation to support commercial devices manufactured at production levels. A fundamental understanding of the material systems and fabrication techniques has been demonstrated, and will provide a stable platform for future developments to support next-generation applications. The chapter focuses on high-speed polymer-based optical modulators and on the molecular engineering of chromophores. The design of electron donor, bridge, electron acceptor, and isolating groups are discussed. Finally, the current commercial technologies are presented.

## 6A Nanophotonics For Low-Power Switches

*Lars Thylen, Petter Holmström, Lech Wosinski, Bozena Jaskorzynska, Makoto Naruse, Tadashi Kawazoe, Motoichi Ohtsu, Min Yan, Marco Fiorentino, and Urban Westergren*

Switches and modulators are key devices in ubiquitous applications of photonics: telecommunication measurement equipment, sensor, and the emerging field of optical interconnects in high-performance computing systems. The latter could accomplish a breakthrough in offering a mass market for the switches. This chapter deals with photonic switches and the quest for the partly interlinked properties of low-power dissipation in operation and nanostructured photonics. It first summarizes some of the most important existing and emerging materials for nanophotonics lowpower switches, and describes their physical mechanisms, operation mode, and characteristics. The chapter then focuses on basic operation and power dissipation issues of electronically controlled switches, which in many important cases by using a simple model are operated by charging and discharging capacitors and thus changing absorption and/or refraction properties of the medium between the capacitor plates. All optical switches are also discussed and some present devices are presented.

## 7A Fibers For Short-Distance Applications

*John Abbott, Scott Bickham, Paulo Dainese, and Ming-Jun Li*

This chapter first reviews the current use of multimode fibers (MMF) with short-wavelength VCSELs for short-distance applications. Standards are in place for 100 Gbit/s applications based on 10 Gbit/s optics and are being developed for  $\sim 25$  Gbit/s optics. Then it briefly introduces the theory of light propagation in multimode fibers. The actual performance of an MMF link (the bit error rate and inter-symbol interference) depends on both the fiber and the laser. Effective model bandwidth, which includes both fiber and laser effects, will be discussed, and the method of characterizing fiber with the

differential-mode-delay measurement and the laser with the encircled flux measurement will be summarized as well. Bend-insensitive multimode fiber is then presented, explaining how the new fiber achieves high bandwidth with low bend loss. New fibers for short-distance consumer applications and home networking are discussed. Finally, fibers designed for high-performance computing are reviewed, including multicore fibers for optical interconnects.

## 8A Few-Mode Fiber Technology For Spatial Multiplexing

*David W. Peckham, Yi Sun, Alan McCurdy, and Robert Lingle Jr.*

This chapter gives an overview of design and optimization of few-mode optical fibers (FMF) for space-division-multiplexed transmission. The design criteria are outlined, along with performance limitations of the traditional step-profile and graded-index profiles. The trade-offs between number of usable optical modes (related to total channel capacity), differential group delay, differential mode attenuation, mode coupling, and the impact on multiple-input and multiple-output (MIMO) receiver complexity are outlined. Improved fiber designs are analyzed which maximize channel capacity with foreseeable next-generation receiver technology. FMF measurement technology is overviewed.

## 9A Multi-Core Optical Fibers

*Tetsuya Hayashi*

Spatial division multiplexing attracts lots of attention for tackling the “capacity crunch,” which is anticipated as a problem in the near future, and therefore various types of optical fibers and multiplexing methods have been intensively researched in recent years. This chapter introduces the multi-core fibers for spatial division multiplexed transmission. It describes various characteristics specific to the multi-core fibers, which have been elucidated theoretically and experimentally in recent years. Though there are many important factors, many pages are devoted especially to the description of inter-core crosstalk, which is crucial when signals are transmitted over each core independently. The chapter also describes other characteristics related to the improvement of core density.

## 10A Plastic Optical Fibers And Gb/S Data Links

*Yasuhiro Koike and Roberto Gaudino*

As high-speed data processing and communication systems are required, plastic optical fibers (POFs) become promising candidates for optical interconnects as well as optical networking in local area networks. This chapter presents an overview of the evolution of POF, reviewing the technical achievements of both fiber design and system architectures that today allow using POF for Gb/s data links. In particular, the chapter presents the different POF materials such as polymethyl methacrylate (PMMA), perfluorinated polymers, types such as step-index POF and graded-index POF, as well as the POF production process, describing the resulting optical characteristics in terms of attenuation, dispersion, and bandwidth. The main applications of POF in industrial automation, home networking, and local area networks are also discussed.

## 11A Integrated And Hybrid Photonics For High-Performance

# Interconnects

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***Nikos Bamiedakis, Kevin A. Williams, Richard V. Penty, and Ian H. White***

Optical interconnection technologies are increasingly deployed in high-performance electronic systems to address challenges in connectivity, size, bandwidth, latency, and cost. Project performance requirements lead to formidable cost and energy efficiency challenges. Hybrid and integrated photonic technologies are currently being developed to reduce assembly complexity and reduce the number of individually packaged parts. This chapter provides an overview of the important challenges that photonics currently face, identifies the various optical technologies that are being considered for use at the different interconnection levels, and presents examples of demonstrated state-of-the-art optical interconnection systems. Finally, the prospects and potential of these technologies in the near future are discussed.

## 12A CMOS Photonics For High-Performance Interconnects

***Jason Orcutt, Rajeev Ram, and Vladimir Stojanović***

For many applications, multicore chips are primarily constrained by the latency, bandwidth, and capacity of the external memory system. One of the most significant challenges is how to effectively connect on-chip processors to off-chip memories. This chapter introduces optical interconnects as a possible solution to the emerging performance wall in high-density supercomputer applications arising from limited bandwidth and density of on-chip interconnects and chip-to-chip (processor-to-memory) electrical interfaces. The chapter focuses on the translation of system- and link-level performance metrics to photonic component requirements. The topics to be developed include network topology, photonic link components, circuit and system design for photonic links.

## 13A Hybrid Silicon Lasers

***Brian R. Koch, Sudharsanan Srinivasan, and John E. Bowers***

The term “hybrid silicon laser” refers to a laser that has a silicon waveguide and a III–V material that is in close optical contact. In this structure, the optical confinement can be easily transferred from one material to the other and intermediate modes exist for which the light is contained in both materials simultaneously. In hybrid silicon lasers, the optical gain is provided by the electrically pumped III–V material and the optical cavity is ultimately formed by the silicon waveguide. This type of laser can be heterogeneously integrated with silicon components that have superior performance compared to III–V components. These lasers can be fabricated in high volumes as components of complex photonic integrated circuits, largely with CMOS-compatible processes. These traits are expected to allow for highly complex, non-traditional photonic integrated circuits with very high yields and relatively low manufacturing costs. This chapter discusses the theory of hybrid silicon lasers, wafer-bonding techniques, examples of experimental results, examples of system demonstrations based on hybrid silicon lasers, and prospects for future devices.

## 14A VCSEL-Based Data Links

***Julie Sheridan Eng and Chris Kocot***

Vertical cavity surface emitting laser (VCSEL)-based data links are attractive due to their low power dissipation and low-cost manufacturability. This chapter reviews the foundations for the

technology, as well as the device and module design challenges of extending the data rate beyond the current level. The chapter begins with a review of data communications from the business perspective and continues with a brief discussion of the current and future standards. This is followed by a survey of recent advances in VCSELs, including data links operating at 28 Gbit/s. Recent efforts on ultra-fast data links are reviewed and the advantages of the different approaches are discussed. The chapter also examines key design aspects of optical transceiver modules and focuses on novel applications in high-performance computing using both multi-mode and single-mode fiber optics. The importance of the device/component-level and system-level modeling is highlighted, and some modeling examples are shown with comparison to measured data. The chapter concludes with a comparison of the VCSEL-based data links with other competing technologies, including silicon photonics and short-cavity edge-emitting lasers.

## 15A Implementation Aspects Of Coherent Transmit And Receive Functions In Application-Specific Integrated Circuits

*Andreas Leven and Laurent Schmalen*

One of the most challenging components of an optical coherent communication system is the application-specific integrated circuits (ICs) that process the received signals or condition the transmit signals. This chapter discusses implementation aspects of these ICs and their main building blocks, as data converters, baseband signal processing, forward error correction, and interfacing. This chapter also highlights selected implementation details for some baseband signal processing blocks of a coherent receiver. The latest generation of coherent ICs also supports advanced forward error correction techniques based on soft decisions. The circuits for encoding and decoding low-density parity check (LDPC) codes are introduced and evaluation of different forward error correction schemes based on a set of recorded measurement data is presented in this chapter.

## 16A All-Optical Regeneration Of Phase-Encoded Signals

*Joseph Kakande, Radan Slavík, Francesca Parmigiani, Periklis Petropoulos, and David Richardson*

This chapter reviews the general principles and approaches used to regenerate phase-encoded signals of differing levels of coding complexity. It first reviews different approaches and nonlinear processes that may be used to perform the regeneration of phase-encoded signals. The primary focus is on parametric effects, which as explained previously can operate directly on the optical phase. This chapter then proceeds to review progress on regenerating the simplest of phase modulation formats, namely DPSK/BPSK, and for which the greatest progress has been made to date. In the following, the progress in regenerating more complex modulation format signals—in particular (D)QPSK and other M-PSK signals—is discussed. The chapter also reviews the choice of nonlinear components available to construct phase regenerators. Finally, it reviews the prospects for regenerating even more complex signals including QAM and mixed phase-amplitude coding variants.

## 17A Ultra-High-Speed Optical Time Division Multiplexing

*Leif Katsuo Oxenløwe, Anders Clausen, Michael Galili, Hans Christian Hansen Mulvad, Hua Jiang, Hao Hu, and Evarist Palushani*

The attraction of optical time division multiplexing (OTDM) technology is the promise

achieving higher bit rates per channel than electronics could provide, thus alleviating the so-called electronic speed bottleneck. In this chapter, the state-of-the-art OTDM systems are presented, with focus on experimental demonstrations. This chapter especially highlights demonstrations at 640–128 Gbaud per polarization based on a variety of materials and functionalities. Many essential network functionalities are available today using a plethora of available materials, so now it is time to look at new network scenarios that take advantage of the serial nature of the data, e.g. try to come up with practical schemes for ultra-high bit rate optical data packets in supercomputers or within data centers.

## 18A Technology And Applications Of Liquid Crystal On Silicon (LCoS) In Telecommunications

*Stephen Frisken, Ian Clarke, and Simon Poole*

Liquid crystal is now the dominant technology for flat-screen displays and has been used in telecommunication systems since the late 1990s. More recently, the adoption of liquid crystals in Wavelength Selective Switches—with the control of light on a pixel-by-pixel basis—has been enabled by developments in Liquid Crystal on Silicon (LCoS) backplane technologies derived from projection displays. This chapter presents the principles of operation of liquid crystals, focusing in particular on how they operate within an LCoS chip. It then explains in detail the design and operation of an LCoS-based wavelength selective switch (WSS), with particular emphasis on the key optical parameters that determine performance in an optical communications network. In the final section, the chapter briefly describes the broad scope of new opportunities that arise from the intrinsic performance and flexibility of LCoS as a switching medium.

## OFT VI Volume B: Systems and Networks

### 1B Fiber Nonlinearity And Capacity: Single-Mode And Multimode Fibers

*René-Jean Essiambre, Robert W. Tkach, and Roland Ryf*

This chapter presents the trends in optical network traffic and commercial system capacity, discusses fundamentals of nonlinear capacity of single-mode fibers, and indicates that improvements in the properties of single-mode fibers only moderately increase the nonlinear fiber capacity. This leads to the conclusion that fiber capacity can be most effectively grown by increasing the number of spatial modes. This chapter also discusses nonlinear propagation in multimode fiber, a complex field still largely unexplored. It gives a basic nonlinear propagation equation derived from the Maxwell equation, along with simplified propagation equations in the weak- and strong-coupling approximations, referred to as generalized Manakov equations. Finally, the chapter presents experimental observations of two inter-modal nonlinear effects, inter-modal cross-phase modulation and inter-modal four-wave mixing, over a few-km-long few-mode fiber. Important differences between intra-modal and inter-modal nonlinear effects are also discussed.

### 2B Commercial 100-Gbit/S Coherent Transmission Systems

*Tiejun J. Xia and Glenn A. Wellbrock*

This chapter provides a global network service provider's view on technology development and

product commercialization of 100-Gbit/s for optical transport networks. Optical channel capacity has been growing over the past four decades to address traffic demand growth and will continue this trend for the foreseeable future to meet ever-increasing bandwidth requirements. In this chapter, optical channels are reclassified into three basic design types. Commercial 100-Gbit/s channel development has experienced all three types of channel designs before eventually settling on the single-carrier polarization-multiplexed quadrature-phase-shift keying (PM-QPSK) format using coherent detection, which appears to be the optimal design in the industry. A series of 100-Gbit/s channel related field trials was performed in service providers' networks to validate the technical merits and business advantages of this new capacity standard before its deployment. Introduction of the 100-Gbit/s channel brings new opportunities to boost fiber capacity, accommodates increases in client interface speed rates, lowers transmission latency, simplifies network management, and speeds up the realization of next-generation optical add/drop functions.

## 3B Advances In Tb/S Superchannels

*S. Chandrasekhar and Xiang Liu*

Optical superchannel transmission, which refers to the use of several optical carriers combined to create a channel of desired capacity, has recently attracted much research and development in an effort to increase the capacity and cost-effectiveness of wavelength-division multiplexing (WDM) systems. Using superchannels avoids the electronic bottleneck via optical parallelism and provides high per-channel data rates and better spectral utilization, especially in transparent mesh optical networks. This chapter reviews recent advances in the generation, detection, and transmission of optical superchannels with channel data rates on the order of Tbit/s. Multiplexing schemes such as optical orthogonal-frequency-division-multiplexing (O-OFDM) and Nyquist-WDM are described, in conjunction with modulation schemes such as OFDM and Nyquist-filtered single-carrier modulation. Superchannel transmission performance is discussed. Finally, networking implications brought by the use of superchannels, such as flexible-grid WDM, are also discussed.

## 4B Optical Satellite Communications

*Hamid Hemmati and David Caplan*

Current satellite-based communication systems are increasingly capacity-limited. Based on radio frequency or microwave technologies, current state-of-the-art satellite communications (Satcom) are often constrained by hardware and spectrum allocation limitations. Such limitations are expected to worsen due to the use of more sophisticated data-intensive sensors in future interplanetary, deep space, and manned missions, an increased demand for information, and the demand for a bigger return on space-exploration investment. This chapter presents the recent advances in optical satellite communications technologies. Lasercom link budgets, the first step in designing a lasercom system, are discussed. The chapter then reviews the major challenges facing laser beam propagation through the atmosphere, including atmospheric attenuation, scattering, radiance, and turbulence. It also discusses mitigation approaches. The rest of the chapter focuses on optical transceiver technologies for satellite communications systems. Finally, space and ground terminals in optical satellite communications are discussed.

## 5B Digital Signal Processing (DSP) And Its Application In

# Optical Communication Systems

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*Polina Bayvel, Carsten Behrens, and David S. Millar*

The key questions in current optical communications research are how to maximize both capacity and transmission distance in future optical transmission networks by using spectrally efficient modulation formats with coherent detection and how digital signal processing can aid in this quest. There is a clear trade-off between spectral efficiency and transmission distance, since the most spectrally efficient modulation formats are more susceptible to optical fiber nonlinearities. This chapter illustrates the application of nonlinear back-propagation to mitigate both linear and nonlinear transmission impairments in a range of modulation formats at varying symbol rates, wavelength spacing, and signal bandwidth. The basics of coherent receiver structure and digital signal processing (DSP) algorithms for chromatic dispersion compensation, equalization, and phase recovery for different modulation formats employing amplitude, phase, and polarization are reviewed and the effectiveness of the nonlinearity compensating DSP based on digital back-propagation is explored. This chapter includes a comprehensive literature review of the key experimental demonstrations of nonlinearity compensating DSP.

## 6B Advanced Coding For Optical Communications

*Ivan B. Djordjevic*

This chapter represents an overview of advanced coding techniques for optical communications. Topics include the following: codes on graphs, coded modulation, rate adaptive coded modulation, and turbo equalization. The main objectives of this chapter are as follows: (i) to describe different classes of codes on graphs of interest for optical communications, (ii) to describe how to combine multilevel modulation and channel coding, (iii) to describe how to perform equalization and soft-decoding jointly, and (iv) to demonstrate efficiency of joint demodulation, decoding, and equalization in dealing with various channel impairments simultaneously. The chapter describes both binary and nonbinary LDPC codes, their design, and decoding algorithms. A field-programmable gate array (FPGA) implementation of decoders for binary LDPC codes is discussed. In addition, this chapter demonstrates that an LDPC-coded turbo equalizer is an excellent candidate to simultaneously mitigate chromatic dispersion, polarization mode dispersion, fiber nonlinearities, and I/Q-imbalance. In the end, the information capacity study of optical channels with memory is provided for completeness of presentation.

## 7B Extremely Higher-Order Modulation Formats

*Masataka Nakazawa, Toshihiko Hirooka, Masato Yoshida, and Keisuke Kasai*

This chapter reviews recent progress on coherent quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM) transmission with higher-order multiplicity, which is aiming at ultra-high spectral efficiency approaching the Shannon limit. Key technologies are the coherent detection with a frequency-stabilized fiber laser and an optical PLL circuit. Single-carrier 1024 QAM and 256 QAM-OFDM transmissions are successfully achieved, demonstrating a spectral efficiency exceeding 10 bit/s/Hz. Such an ultra-high spectrally efficient transmission system would also play a very important role in increasing the total capacity of WDM systems and improving the tolerance to chromatic dispersion and polarization mode dispersion as well as in reducing power consumption. The chapter also describes a novel high-speed, spectrally efficient transmission scheme.

that combines the OTDM and QAM techniques, in which a pulsed local oscillator (LO) signal obtained with an optical phase-lock loop (OPLL) enables precise demultiplexing and demodulation simultaneously. An optimum OTDM and QAM combination would provide the possibility for realizing long-haul Tbit/s/channel transmission with a simple configuration, large flexibility, and low power consumption.

## 8B Multicarrier Optical Transmission

*Xi Chen, Abdullah Al Amin, An Li, and William Shieh*

This chapter is an overview of multicarrier transmission and its application to optical communication. Starting with an introduction to historical perspectives in the development of optical multicarrier technologies, the chapter presents different variants of optical multicarrier transmission including electronic and optical fast Fourier transform (FFT)-based realizations. In the next section several problems of fiber nonlinearity in optical multicarrier transmission systems are highlighted and an analysis of fiber capacity under nonlinear impairments is presented. The applications of multicarrier techniques to long-haul systems, access networks, and free-space optical communication systems are also discussed. Finally, this chapter summarizes several possible directions for research into the implementation of multicarrier technologies in optical transmission.

## 9B Optical OFDM And Nyquist Multiplexing

*Juerg Leuthold and Wolfgang Freude*

New pulse shaping techniques allow for optical multiplexing with the highest spectral efficiency. This chapter introduces the general theory of orthogonal pulse shaping followed by a discussion that places more emphasis on the orthogonal frequency division multiplexing (OFDM) and Nyquist frequency-division multiplexing schemes. Subsequently, the chapter shows that the rectangular shaped pulses used for OFDM can mathematically be treated by the Fourier transform. This leads to the theory of the time-discrete Fourier transform (DFT) and to a discussion of practical implementations of the DFT and its inverse in the optical domain. The chapter concludes with exemplary implementations of OFDM transceivers that either rely on direct pulse shaping or use the DFT approaches.

## 10B Spatial Multiplexing Using Multiple-Input Multiple-Output Signal Processing

*Peter J. Winzer, Roland Ryf, and Sebastian Randel*

In order to further scale network capacities and to avoid a looming “capacity crunch,” *space* has been identified as the only known physical dimension yet unexploited for optical modulation and multiplexing. Space-division multiplexing (SDM) may use uncoupled or coupled cores of multi-core fiber, or individual modes of multimode waveguides. If crosstalk rises to levels where it cannot be treated as a transmission impairment any more, multiple-input multiple-output (MIMO) digital signal processing (DSP) techniques have to be used to manage crosstalk in highly integrated SDM systems. This chapter reviews the fundamentals and practical experimental aspects of MIMO-SDM. First, it discusses the importance of selectively addressing all modes of a coupled-mode SDM channel transmitter and receiver in order to achieve reliable capacity gains. It shows that reasonable levels

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