Optical Fiber Telecommunications VIA

Components and Subsystems

Ivan P. Kaminow
Tingye Li
Alan E. Willner

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SIXTH EDITION

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Dedication

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)

致以深切的怀念!

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Dedication 2

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

Preface—Overview of OFT VI A & B

Optical Fiber Telecommunications VI (*OFT VI*) is the sixth installment of the *OFT* series. Now 3 years old, the series is a compilation by the research and development community of progress in th field of optical fiber communications. Each edition reflects the current state of the art at the time. A editors, we started with a clean slate and selected chapters and authors to elucidate topics that hav 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 natur 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 networkin 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-t 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. Subtitle 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 topic 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 rela to older topics. Typically, certain devices may have adequately solved transmission problems for th systems of that era. However, as systems become more complex, critical device technologies th might have been considered a “solved problem” would now have new requirements placed upon the and need a fresh technical treatment. For this reason, each edition has grown in sheer size, i.e. addi the new and, if necessary, re-examining the old.

~~An example of this circular feedback mechanism relates to the fiber itself. At first, systems simp~~ required low-loss fiber. However, long-distance transmission enabled by EDFAs drove research o low-dispersion fiber. Further, advances in WDM and the problems of nonlinear effects necessitate development of non-zero-dispersion fiber. Cost and performance considerations today drive researc in plastic fibers, highly bendable fibers, few-mode fibers, and multicore fibers. We believe that thes 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 unprecedente upheaval circa 2000, at which time worldwide telecom traffic ceased being dominated by the slov growing voice traffic and was overtaken by the rapidly growing Internet traffic. The *irration* investment exuberance and subsequent depression-like period of oversupply (i.e. the “bubble-an bust”) wreaked havoc on our field. We are happy to say that, by nearly all accounts, the field continu to gain strength again and appears to have entered a stage of *rational* growth. Demand for bandwid continues to grow at a very healthy rate. Capacity needs are real, and are expected to continue in th future.

We note that optical fiber communications is firmly entrenched as part of the global informatic infrastructure. For example: (i) there would be no Internet as we know it if not for optics, (ii) mode data centers may have as many as 1,000,000 lasers to help interconnect boards and machines, and (ii 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 communications, e.g. wireless, access and on-premises networks, Interconnections, satellites, etc. Th odds are that, indeed, optics will continue to play a significant role in assisting all types of futu communications. This is in stark contrast to the voice-based future seen by *OFT*, published in 197 which occurred before the first commercial intercontinental or transatlantic cable systems deployed the 1980s. We now have Tbit/s systems for metro and long-haul networks. It is interesting an exciting to contemplate what topics, concerns, and innovations might be contained in the next editic of the series, *OFT VII*.

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

We wish sincerely to thank Tim Pitts, Charlie Kent, Susan Li, Jason Mitchell of Elsevier and Ha Huang of USC for their gracious and invaluable support throughout the publishing process. We ar also deeply grateful to all the authors for their laudable efforts in submitting their scholarly works distinction. Finally, we wish to thank the many people whose insightful suggestions were of gre 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 cavi designs and configurations and considers their impact on the laser performance. Special emphasis given to the fiber parameters that define the power scalability and stability, the polarizatio performance, as well as the linewidth and phase-noise characteristics. The wavelength coverage ar tunability mechanisms are also discussed. The chapter finally reviews the use of fiber DFB lasers non-telecom applications, such as advanced optical fiber sensors, and concludes with an outlook of th 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 acces metro, long-haul, and undersea telecommunication networks. Although there are many variants implementing optical integration, the focus is on monolithic integration where multip semiconductor devices, up to many hundreds in some cases, are integrated onto the same substrat Monolithic integration poses the greatest technical challenge and the biggest opportunity f bandwidth and size scaling. The PICs discussed here are based on the two most popular semiconduct material systems: Groups III–V indium phosphide-based devices and Group IV silicon-based device The chapter also covers the historical evolution of the technology from the decades-old origin 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 *Optic Fiber Telecommunications V*. The quests for higher-speed p-i-n detectors and lower-noise avalanc photodiodes (APDs) with high gain-bandwidth product remain.

To a great extent, high-speed structures have coalesced to evanescently coupled waveguide device bandwidths exceeding 140 GHz have been reported. A primary APD breakthrough has been th development of Ge on Si separate-absorption-and-multiplication devices that achieve long-waveleng response with the low-noise behavior of Si. For III–V compound APDs, ultra-low noise has bee achieved by strategic use of complex multilayer multiplication regions that provide a mo deterministic impact ionization. However, much of the excitement and innovation have focused o 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 fo the manipulation of photons and have made substantial progresses in recent years. This chapter fir introduces research activities that are geared toward realizing the ultimate nanolaser using th photonic bandgap effect. Important aspects of this effort are in the achievement of spontaneou emission suppression and strong optical confinement using a photonic nanocavity. During the proce of implementation of this goal, interesting phenomena, which can be classified as Quantum Anti-Zen effect, have been observed. The rest of the chapter focuses on the current state of research in the fie of broad-area coherent photonic crystal lasers using the band-edge effect, which occupies a positio opposite to that of nanolasers discussed above. The main characteristics of these lasers will b discussed, including their high-power operation, the generation of tailored beam patterns, the surfac 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 Core Pilgrim

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

6A Nanophotonics For Low-Power Switches

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

Switches and modulators are key devices in ubiquitous applications of photonics: telecom measurement equipment, sensor, and the emerging field of optical interconnects in high-performanc 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 properti of low-power dissipation in operation and nanostructured photonics. It first summarizes some of th most important existing and emerging materials for nanophotonics lowpower switches, and describ their physical mechanisms, operation mode, and characteristics. The chapter then focuses on bas operation and power dissipation issues of electronically controlled switches, which in many importa cases by using a simple model are operated by charging and discharging capacitors and thus changin absorption and/or refraction properties of the medium between the capacitor plates. All optic 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-waveleng VCSELs for short-distance applications. Standards are in place for 100 Gbit/s applications based on 1 Gbit/s optics and are being developed for ∼25 Gbit/s optics. Then it briefly introduces the theory light propagation in multimode fibers. The actual performance of an MMF link (the bit error rate an inter-symbol interference) depends on both the fiber and the laser. Effective model bandwidth, whic includes both fiber and laser effects, will be discussed, and the method of characterizing fiber with th differential-mode-delay measurement and the laser with the encircled flux measurement will b summarized as well. Bend-insensitive multimode fiber is then presented, explaining how the new fib achieves high bandwidth with low bend loss. New fibers for short-distance consumer applications an home networking are discussed. Finally, fibers designed for high-performance computing a 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) f space-division-multiplexed transmission. The design criteria are outlined, along with performan limitations of the traditional step-profile and graded-index profiles. The trade-offs between number usable optical modes (related to total channel capacity), differential group delay, differential mod attenuation, mode coupling, and the impact on multiple-input and multiple-output (MIMO) receiv complexity are outlined. Improved fiber designs are analyzed which maximize channel capacity wi 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 anticipated as a problem in the near future, and therefore various types of optical fibers an multiplexing methods have been intensively researched in recent years. This chapter introduces th multi-core fibers for spatial division multiplexed transmission. It describes various characteristi specific to the multi-core fibers, which have been elucidated theoretically and experimentally recent years. Though there are many important factors, many pages are devoted especially to th description of inter-core crosstalk, which is crucial when signals are transmitted over each co independently. The chapter also describes other characteristics related to the improvement of co 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 fibe (POFs) become promising candidates for optical interconnects as well as optical networking in loc area networks. This chapter presents an overview of the evolution of POF, reviewing the technic achievements of both fiber design and system architectures that today allow using POF for Gb/s da links. In particular, the chapter presents the different POF materials such as polymethyl methacryla (PMMA), perfluorinated polymers, types such as step-index POF and graded-index POF, as well as th POF production process, describing the resulting optical characteristics in terms of attenuatio dispersion, and bandwidth. The main applications of POF in industrial automation, home networkin and local area networks are also discussed.

11A Integrated And Hybrid Photonics For High-Performance

Interconnects

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

Optical interconnection technologies are increasingly deployed in high-performance electron systems to address challenges in connectivity, size, bandwidth, latency, and cost. Projecte performance requirements lead to formidable cost and energy efficiency challenges. Hybrid ar 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 importa challenges that photonics currently face, identifies the various optical technologies that are bein considered for use at the different interconnection levels, and presents examples of demonstrate state-of-the-art optical interconnection systems. Finally, the prospects and potential of thes 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, ar capacity of the external memory system. One of the most significant challenges is how to effective connect on-chip processors to off-chip memories. This chapter introduces optical interconnects as possible solution to the emerging performance wall in high-density supercomputer application arising from limited bandwidth and density of on-chip interconnects and chip-to-chip (processor-t memory) electrical interfaces. The chapter focuses on the translation of system- and link-lev performance metrics to photonic component requirements. The topics to be developed incluc 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 materi that is in close optical contact. In this structure, the optical confinement can be easily transferred fro one material to the other and intermediate modes exist for which the light is contained in bo materials simultaneously. In hybrid silicon lasers, the optical gain is provided by the electrical pumped III–V material and the optical cavity is ultimately formed by the silicon waveguide. This typ of laser can be heterogeneously integrated with silicon components that have superior performan compared to III–V components. These lasers can be fabricated in high volumes as components complex photonic integrated circuits, largely with CMOS-compatible processes. These traits a expected to allow for highly complex, non-traditional photonic integrated circuits with very hig yields and relatively low manufacturing costs. This chapter discusses the theory of hybrid silic lasers, wafer-bonding techniques, examples of experimental results, examples of syste 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 lov power dissipation and low-cost manufacturability. This chapter reviews the foundations for th technology, as well as the device and module design challenges of extending the data rate beyond th current level. The chapter begins with a review of data communications from the business perspectiv and continues with a brief discussion of the current and future standards. This is followed by a surve of recent advances in VCSELs, including data links operating at 28 Gbit/s. Recent efforts on ultra-fa data links are reviewed and the advantages of the different approaches are discussed. The chapter als examines key design aspects of optical transceiver modules and focuses on novel applications in hig performance computing using both multi-mode and single-mode fiber optics. The importance of th device/component-level and system-level modeling is highlighted, and some modeling examples a 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 edg 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 th integrated circuits (ICs) that process the received signals or condition the transmit signals. Th chapter discusses implementation aspects of these ICs and their main building blocks, as da converters, baseband signal processing, forward error correction, and interfacing. This chapter als highlights selected implementation details for some baseband signal processing blocks of a cohere receiver. The latest generation of coherent ICs also supports advanced forward error correctio techniques based on soft decisions. The circuits for encoding and decoding low-density parity chec (LDPC) codes are introduced and evaluation of different forward error correction schemes based on 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 Richardso

This chapter reviews the general principles and approaches used to regenerate phase-encode signals of differing levels of coding complexity. It first reviews different approaches and nonline processes that may be used to perform the regeneration of phase-encoded signals. The primary focu is on parametric effects, which as explained previously can operate directly on the optical phase. Th chapter then proceeds to review progress on regenerating the simplest of phase modulation format namely DPSK/BPSK- and for which the greatest progress has been made to date. In the following, th progress in regenerating more complex modulation format signals—in particular (D)QPSK and oth M-PSK signals—is discussed. The chapter also reviews the choice of nonlinear components availab to construct phase regenerators. Finally, it reviews the prospects for regenerating even more comple 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 J 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-calle ~~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 netwo functionalities are available today using a plethora of available materials, so now it is time to look new network scenarios that take advantage of the serial nature of the data, e.g. try to come up wi 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 teleco systems since the late 1990s. More recently, the adoption of liquid crystals in Wavelength Selectiv Switches—with the control of light on a pixel-by-pixel basis—has been enabled by developments Liquid Crystal on Silicon (LCoS) backplane technologies derived from projection displays. Th chapter presents the principles of operation of liquid crystals, focusing in particular on how the operate within an LCoS chip. It then explains in detail the design and operation of an LCoS-base wavelength selective switch (WSS), with particular emphasis on the key optical parameters th determine performance in an optical communications network. In the final section, the chapter brief describes the broad scope of new opportunities that arise from the intrinsic performance ar 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 capacit discusses fundamentals of nonlinear capacity of single-mode fibers, and indicates that improvemen in the properties of single-mode fibers only moderately increase the nonlinear fiber capacity. Th leads to the conclusion that fiber capacity can be most effectively grown by increasing the number spatial modes. This chapter also discusses nonlinear propagation in multimode fiber, a complex fie still largely unexplored. It gives a basic nonlinear propagation equation derived from the Max-we equation, along with simplified propagation equations in the weak- and strong-coupli approximations, referred to as generalized Manakov equations. Finally, the chapter presen experimental observations of two inter-modal nonlinear effects, inter-modal cross-phase modulatio and inter-modal four-wave mixing, over a few-km-long few-mode fiber. Important differenc 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 ar product commercialization of 100-Gbit/s for optical transport networks. Optical channel capacity h been growing over the past four decades to address traffic demand growth and will continue this tren for the foreseeable future to meet ever-increasing bandwidth requirements. In this chapter, optic channels are reclassified into three basic design types. Commercial 100-Gbit/s channel developme experienced all three types of channel designs before eventually settling on the single-carri polarization-multiplexed quadrature-phase-shift keying (PM-QPSK) format using coherent detectio which appears to be the optimal design in the industry. A series of 100-Gbit/s channel related fiel trials was performed in service providers' networks to validate the technical merits and busine advantages of this new capacity standard before its deployment. Introduction of the 100-Gbit channel brings new opportunities to boost fiber capacity, accommodates increases in client interfa speed rates, lowers transmission latency, simplifies network management, and speeds up th 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 create a channel of desired capacity, has recently attracted much research and development in a effort to increase the capacity and cost-effectiveness of wavelength-division multiplexing (WDM systems. Using superchannels avoids the electronic bottleneck via optical parallelism and provid high per-channel data rates and better spectral utilization, especially in transparent mesh optic networks. This chapter reviews recent advances in the generation, detection, and transmission optical superchannels with channel data rates on the order of Tbit/s. Multiplexing schemes such optical orthogonal-frequency-division-multiplexing (O-OFDM) and Nyquist-WDM are described, conjunction with modulation schemes such as OFDM and Nyquist-filtered single-carrier modulatio Superchannel transmission performance is discussed. Finally, networking implications brought by th 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 rad frequency or microwave technologies, current state-of-the-art satellite communications (Satcom) a often constrained by hardware and spectrum allocation limitations. Such limitations are expected worsen due to the use of more sophisticated data-intensive sensors in future interplanetary, dee space, and manned missions, an increased demand for information, and the demand for a bigger retu on space-exploration investment. This chapter presents the recent advances in optical satelli communications technologies. Lasercom link budgets, the first step in designing a lasercom syste are discussed. The chapter then reviews the major challenges facing laser beam propagation throu the atmosphere, including atmo-spheric attenuation, scattering, radiance, and turbulence. It als discusses mitigation approaches. The rest of the chapter focuses on optical transceiver technologi for satellite communications systems. Finally, space and ground terminals in optical satelli communications are discussed.

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

Optical Communication Systems

Polina Bayvel, Carsten Behrens, and David S. Millar

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

6B Advanced Coding For Optical Communications

Ivan B. Djordjevic

This chapter represents an overview of advanced coding techniques for optical communicatio Topics include the following: codes on graphs, coded modulation, rate adaptive coded modulation, an turbo equalization. The main objectives of this chapter are as follows: (i) to describe different class of codes on graphs of interest for optical communications, (ii) to describe how to combine multilev modulation and channel coding, (iii) to describe how to perform equalization and soft-decodi jointly, and (iv) to demonstrate efficiency of joint demodulation, decoding, and equalization dealing with various channel impairments simultaneously. The chapter describes both binary an nonbinary LDPC codes, their design, and decoding algorithms. A field-programmable gate arra (FPGA) implementation of decoders for binary LDPC codes is discussed. In addition, this chapt demonstrates that an LDPC-coded turbo equalizer is an excellent candidate to simultaneously mitiga chromatic dispersion, polarization mode dispersion, fiber nonlinearities, and I/Q-imbalance. In th end, the information capacity study of optical channels with memory is provided for completeness 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) an orthogonal frequency-division multiplexing (OFDM) transmission with higher-order multiplicit which is aiming at ultra-high spectral efficiency approaching the Shannon limit. Key technologies a the coherent detection with a frequency-stabilized fiber laser and an optical PLL circuit. Single-carri 1024 QAM and 256 QAM-OFDM transmissions are successfully achieved, demonstrating a spectr efficiency exceeding 10 bit/s/Hz. Such an ultra-high spectrally efficient transmission system wou also play a very important role in increasing the total capacity of WDM systems and improving th tolerance to chromatic dispersion and polarization mode dispersion as well as in reducing pow consumption. The chapter also describes a novel high-speed, spectrally efficient transmission schen that combines the OTDM and QAM techniques, in which a pulsed local oscillator (LO) sign obtained with an optical phase-lock loop (OPLL) enables precise demultiplexing and demodulatio simultaneously. An optimum OTDM and QAM combination would provide the possibility fo realizing long-haul Tbit/s/channel transmission with a simple configuration, large flexibility, and lov 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 optic communication. Starting with an introduction to historical perspectives in the development of optic multicarrier technologies, the chapter presents different variants of optical multicarrier transmissio including electronic and optical fast Fourier transform (FFT)-based realizations. In the next sectio several problems of fiber nonlinearity in optical multicarrier transmission systems are highlighted ar an analysis of fiber capacity under nonlinear impairments is presented. The applications multicarrier techniques to long-haul systems, access networks, and free-space optical communicatio systems are also discussed. Finally, this chapter summarizes several possible directions for researc 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 efficiencie This chapter introduces the general theory of orthogonal pulse shaping followed by a discussion th places more emphasis on the orthogonal frequency division multiplexing (OFDM) and Nyqui frequency-division multiplexing schemes. Subsequently, the chapter shows that the rectangula shaped pulses used for OFDM can mathematically be treated by the Fourier transform. This leads the theory of the time-discrete Fourier transform (DFT) and to a discussion of practic implementations of the DFT and its inverse in the optical domain. The chapter concludes wi exemplary implementations of OFDM transceivers that either rely on direct pulse shaping or use th 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* h been identified as the only known physical dimension yet unexploited for optical modulation ar multiplexing. Space-division multiplexing (SDM) may use uncoupled or coupled cores of multi-co fiber, or individual modes of multimode waveguides. If crosstalk rises to levels where it cannot b treated as a transmission impairment any more, multiple-input multiple-output (MIMO) digital sign processing (DSP) techniques have to be used to manage crosstalk in highly integrated SDM system This chapter reviews the fundamentals and practical experimental aspects of MIMO-SDM. First, 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