

# OFDM for Optical Communications

William Shieh  
Ivan Djordjevic



# OFDM for Optical Communications

William Shieh

*Department of Electrical and Electronic Engineering  
The University of Melbourne*

Ivan Djordjevic

*Department of Electrical and Computer Engineering  
The University of Arizona*



AMSTERDAM • BOSTON • HEIDELBERG • LONDON  
NEW YORK • OXFORD • PARIS • SAN DIEGO  
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Academic Press is an imprint of Elsevier



Academic Press is an imprint of Elsevier  
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA  
525 B Street, Suite 1900, San Diego, California 92101-4495, USA  
84 Theobald's Road, London WC1X 8RR, UK

© 2010 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

### Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors assume any liability for any injury and/or damage to persons or property as a matter of product liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

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

Application submitted.

### British Library Cataloguing-in-Publication Data

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

ISBN: 978-0-12-374879-9

For information on all Academic Press publications  
visit our Web site at [www.elsevierdirect.com](http://www.elsevierdirect.com)

Printed in the United States of America.

09 10 9 8 7 6 5 4 3 2 1

Working together to grow  
libraries in developing countries

[www.elsevier.com](http://www.elsevier.com) | [www.bookaid.org](http://www.bookaid.org) | [www.sabre.org](http://www.sabre.org)

ELSEVIER

BOOK AID  
International

Sabre Foundation

# **OFDM for Optical Communications**

*To my wife, Jennifer, my lovely kids Heather and Edmund,  
and my parents Zhengfa and Chaorong.  
—William Shieh*

*To my parents Blagoje and Verica, brother Slavisa,  
and to Milena.  
—Ivan Djordjevic*

# *Preface*

We have recently witnessed a dramatic surge of interest in orthogonal frequency-division multiplexing (OFDM) from the optical communications community. This is evidenced by an increase in the number of publications, and many eye-catching “hero” experimental demonstrations of OFDM technology in a wide spectrum of applications. One of the main drivers behind the emergence of OFDM technology in optical communications is the rapid advance of silicon signal processing capability underpinned by Moore’s Law. The introduction of sophisticated electronic digital signal processing (DSP) and coding could fundamentally alter optical networks as we see them today. On the other hand, although OFDM has emerged as the leading physical interface in wireless communications over the past two decades, it is still regarded as alien by many optical engineers. The most frequently asked question is whether OFDM can provide a solution to the major problems of today’s “fragile” and “rigid” optical networks.

This book intends to give a coherent and comprehensive introduction to the fundamentals of OFDM signal processing and coding, with a distinctive focus on its broad range of applications. It is designed for two diverse groups of researchers: (1) optical communication engineers who are proficient in optical science and interested in applying OFDM technology, but who are intimidated by sophisticated OFDM terminologies, and (2) wireless communication engineers who are content with their DSP skill set, but are disoriented by a perceived huge gap between the optical and radio-frequency (RF) communications worlds. We have attempted to make the individual chapters self-contained while maintaining the flow and connectivity between them.

The book is organized into twelve chapters, and describes various topics related to optical OFDM, starting from basic mathematical formulation through OFDM signal processing and coding for OFDM, to various applications, such as single-mode fiber transmission, multimode fiber transmission, free space-optical systems, and optical access networks. The book also provides fundamental concepts of optical communication, basic channel impairments and noise sources, and optical system engineering process. The book presents interesting research problems in the emerging field of optical OFDM and touches the intriguing issue of standardization of optical OFDM technology.

The authors would like to thank their colleagues, in particular, R. S. Tucker, G. Pendock, R. Evans, B. Krongold, H. Bao, W. Chen, X. Yi, Y. Tang, Y. Ma, Q. Yang, S. Chen, B. Vasic, L. Xu, and T. Wang, whose collaboration on the subject of optical OFDM has contributed directly and indirectly to the completion of the book. We also express our sincere gratitude to C. Xie at Bell Labs, X. Yi at University of California, Davis, K. Hinton, R. S. Tucker, and Y. Tang at the University of Melbourne, and Hussam G. Batshon at the University of Arizona for their careful proofreading of the book chapters. The authors would like to acknowledge the ARC Special Research Centre for Ultra-Broadband Information Networks (CUBIN), National ICT Australia (NICTA), and the National Science Foundation (NSF) for their support of OFDM related research activities.

Finally, special thanks are extended to Tim Pitts, Melanie Benson, and Sarah Binns of Elsevier for their tremendous effort in organizing the logistics of the book, including the editing and promotion that allowed this book to happen.

## ***Author Biography***

William Shieh is an associate professor and reader in the Electrical and Electronic Engineering Department at the University of Melbourne, Melbourne, Australia. He received his M.S. in electrical engineering and Ph.D. in physics from the University of Southern California, Los Angeles, in 1994 and 1996, respectively. From 1996 to 1998 he worked as a member of Technical Staff in the Jet Propulsion Laboratory, Pasadena, CA. From 1998 to 2000 he worked as a member of Technical Staff in Bell Labs, Lucent Technologies, Holmdel, NJ. From 2000 to 2003 he worked as a technical manager in Dorsal Networks, Columbia, MD. Since 2004 he has been with the Electrical and Electronic Engineering Department at the University of Melbourne, Melbourne, Australia.

Ivan Djordjevic is an assistant professor of Electrical and Computer Engineering (ECE) at the University of Arizona, Tucson. Prior to this appointment in August 2006 he was with University of Arizona, Tucson, as a research assistant professor; University of the West of England, Bristol, UK; University of Bristol, Bristol, UK; Tyco Telecommunications, Eatontown, USA; and National Technical University of Athens, Athens, Greece. His current research interests include optical networks, error control coding, constrained coding, coded modulation, turbo equalization, OFDM applications, and quantum error correction. He currently directs the Optical Communications Systems Laboratory (OCSL) within the Electrical and Computer Engineering Department at the University of Arizona. Dr. Djordjevic serves as an associate editor for *Research Letters in Optics* and as an associate editor for *International Journal of Optics*. Dr. Djordjevic is an author of about 100 journal publications and over 80 conference papers.



# Contents

<b>Chapter 1: Introduction .....</b>	<b>1</b>
1.1 Historical Perspective of Optical Communications .....	3
1.2 Trends in Optical Communications .....	4
1.2.1 Evolution toward 100 Gb/s Ethernet .....	5
1.2.2 Emergence of Dynamically Reconfiguration Networks .....	6
1.2.3 Software-Defined Optical Transmission.....	7
1.3 Moore's Law and Its Effect on Digital Signal Processing.....	8
1.3.1 Moore's Law Scaling .....	9
1.3.2 Progress in Electronic Digital Signal Processing for Optical Communication.....	11
1.4 Single-Carrier or Multicarrier Transmission: An Optical Debate .....	12
1.5 The Difference between RF OFDM and Optical OFDM Systems .....	16
1.6 What Does OFDM Bring to the "Game"? .....	19
1.6.1 Scalability to the High-Speed Transmission .....	19
1.6.2 Compatibility to the Future Reconfigurable Optical Networks.....	20
1.7 Channel Coding and OFDM .....	23
1.8 Overview of the Book.....	23
<b>Chapter 2: OFDM Principles .....</b>	<b>31</b>
2.1 Introduction.....	31
2.2 Historical Perspective of OFDM .....	31
2.3 OFDM Basics .....	32
2.3.1 Mathematical Formulation of an OFDM Signal .....	32
2.3.2 Discrete Fourier Transform Implementation of OFDM.....	34
2.3.3 Cyclic Prefix for OFDM .....	36
2.3.4 Spectral Efficiency for Optical OFDM .....	38
2.3.5 Cross-Channel OFDM: Multiplexing without Guard Band.....	39
2.3.6 Complex and Real Representations of an OFDM Signal.....	40
2.4 Peak-to-Average Power Ratio of OFDM Signals .....	41
2.5 Frequency Offset and Phase Noise Sensitivity .....	44
2.5.1 Frequency Offset Effect .....	46
2.5.2 Phase Noise Effect .....	48

<b>Chapter 3: Optical Communication Fundamentals .....</b>	<b>53</b>
3.1 Introduction.....	53
3.2 Key Optical Components .....	54
3.2.1 Optical Transmitters .....	58
3.2.2 Optical Receivers.....	64
3.2.3 Optical Fibers .....	66
3.2.4 Optical Amplifiers.....	74
3.2.5 Other Optical Components.....	79
3.3 Noise Sources .....	83
3.3.1 Mode Partition Noise .....	84
3.3.2 Reflection-Induced Noise.....	84
3.3.3 Relative Intensity Noise and Laser Phase Noise .....	84
3.3.4 Modal Noise .....	86
3.3.5 Quantum Shot Noise .....	87
3.3.6 Dark Current Noise .....	87
3.3.7 Thermal Noise .....	88
3.3.8 Spontaneous Emission Noise .....	88
3.3.9 Noise Beat Components.....	89
3.3.10 Crosstalk Components.....	89
3.4 Channel Impairments.....	91
3.4.1 Fiber Attenuation.....	91
3.4.2 Insertion Losses .....	92
3.4.3 Chromatic Dispersion.....	92
3.4.4 Polarization Mode Dispersion.....	95
3.4.5 Fiber Nonlinearities.....	97
3.5 Transmission System Performance Assessment and System Design.....	107
3.5.1 Quantum Limit for Photodetection.....	109
3.5.2 Shot Noise and Thermal Noise Limit.....	110
3.5.3 Receiver Sensitivity for Receivers with an Optical Preamplifier .....	111
3.5.4 Optical Signal-to-Noise Ratio .....	111
3.5.5 Power Penalty Due to Extinction Ratio .....	111
3.5.6 Power Penalty Due to Intensity Noise .....	112
3.5.7 Power Penalty Due to Timing Jitter.....	112
3.5.8 Power Penalty Due to GVD.....	113
3.5.9 Power Penalty Due to Signal Crosstalk .....	113
3.5.10 Accumulation Effects .....	114
3.5.11 Systems Design.....	115
3.5.12 Optical Performance Monitoring .....	116
3.6 Summary .....	117
<b>Chapter 4: Signal Processing for Optical OFDM.....</b>	<b>119</b>
4.1 Introduction.....	119
4.2 End-to-End OFDM Signal Processing.....	119
4.3 DFT Window Synchronization .....	122

4.4	Frequency Offset Synchronization.....	125
4.4.1	Frequency Acquisition.....	125
4.4.2	Frequency Tracking.....	126
4.5	Subcarrier Recovery: Channel Estimation and Phase Estimation.....	127
4.6	Channel Estimation.....	128
4.6.1	Why Is Channel Estimation Needed?.....	128
4.6.2	Channel Estimation Algorithms.....	130
4.7	ADC/DAC Impact.....	138
4.8	MIMO-OFDM Perspective.....	141
4.8.1	MIMO Fundamentals.....	142
<b>Chapter 5: Polarization Effects in Optical Fiber.....</b>		<b>149</b>
5.1	Introduction.....	149
5.2	Polarization Dispersion Effect in Optical Fiber.....	150
5.2.1	The Origin of Polarization Dispersion Effect.....	150
5.2.2	Jones Vector and Jones Matrix Representation.....	151
5.2.3	Principal State of Polarization and Differential Group Delay.....	152
5.2.4	Stokes Representation of PMD and Its Statistical Properties.....	153
5.2.5	Autocorrelation Function of the Channel Transfer Function and Coherence Bandwidth of an Optical Fiber.....	155
5.2.6	Why PMD Has Been Considered the Fundamental Barrier.....	156
5.3	Polarization-Dependent Loss.....	159
5.4	Theoretical Model for Coherent Optical MIMO-OFDM Signals in the Presence of Polarization Effects.....	160
5.5	Simulation and Experimental Study of MIMO-OFDM Systems.....	164
5.5.1	Polarization Mode Dispersion: Detriment or Benefit?.....	165
5.5.2	$1 \times 2$ SIMO-OFDM Experiment: Polarization Diversity Detection.....	166
5.5.3	$2 \times 1$ MISO-OFDM Experiment: Polarization Time Coding for Optical Broadcast Networks.....	169
5.5.4	$2 \times 2$ MIMO-OFDM in Polarization Domain.....	173
5.6	Nonlinear Polarization Effects.....	175
5.6.1	Nonlinear Polarization Effects in a Birefringence Fiber.....	175
5.6.2	Nonlinear Polarization Effects in Randomly Varying Birefringence Fiber.....	177
<b>Chapter 6: Coding for Optical OFDM Systems.....</b>		<b>183</b>
6.1	Standard FEC Schemes.....	185
6.1.1	Linear Block Codes.....	190
6.1.2	Cyclic Codes.....	194
6.1.3	Bose–Chaudhuri–Hocquenghem Codes.....	196
6.1.4	Reed–Solomon Codes, Concatenated Codes, and Product Codes.....	199
6.2	Codes on Graphs.....	202
6.2.1	Turbo Codes.....	202
6.2.2	Turbo Product Codes.....	204
6.2.3	LDPC Codes.....	205

6.2.4 Generalized LDPC Codes .....	211
6.2.5 FPGA Implementation of Large-Girth LDPC Codes.....	216
6.2.6 Nonbinary Quasi-Cyclic LDPC Codes .....	219
6.3 $M$ -ary QAM and $M$ -ary PSK .....	222
6.4 Coded Modulation .....	223
6.5 Coded OFDM in Fiber-Optics Communication Systems with Direct Detection...	229
6.5.1 Performance Assessment of LDPC-Coded OFDM Fiber-Optics Communications .....	232
6.5.2 Simultaneous Chromatic Dispersion and PMD Compensation via LDPC-Coded OFDM.....	237
6.6 Coded OFDM in Fiber-Optics Communication Systems with Coherent Detection....	242
6.6.1 Description of PMD Channel Model.....	245
6.6.2 PMD Compensation by Coded OFDM in Fiber-Optics Communication Systems with Coherent Detection.....	246
6.7 Summary .....	255
<b>Chapter 7: Various Types of Optical OFDM .....</b>	<b>263</b>
7.1 Introduction.....	263
7.2 Coherent Optical OFDM.....	264
7.2.1 Principle of CO-OFDM.....	264
7.2.2 Optical Transmitter Design for CO-OFDM .....	265
7.2.3 Up-/Down-Conversion Design Options for CO-OFDM Systems.....	265
7.2.4 Optical I/Q Modulator for Linear RF-to-Optical up Conversion .....	266
7.2.5 Discussion of the Null Bias Point for CO-OFDM Systems .....	268
7.2.6 Coherent Detection for Linear Down-Conversion and Noise Suppression....	269
7.2.7 Receiver Sensitivity for CO-OFDM .....	271
7.3 Direct Detection Optical OFDM.....	272
7.3.1 Linearly Mapped DDO-OFDM.....	272
7.3.2 Nonlinearly Mapped DDO-OFDM .....	280
<b>Chapter 8: Spectrally Efficient High-Speed Coherent OFDM System.....</b>	<b>295</b>
8.1 Introduction.....	295
8.2 Orthogonal Band Multiplexed OFDM.....	296
8.2.1 Principle of OBM-OFDM .....	297
8.2.2 Implementation of OBM-OFDM .....	298
8.2.3 Experimental Setup and Description .....	300
8.2.4 Measurement and Discussion.....	305
8.3 111 Gb/s No-Guard Interval CO-OFDM Transmission.....	307
8.3.1 Experimental Configuration for 111 Gb/s NGI-CO-OFDM Transmission..	307
8.3.2 The NGI-CO-OFDM Transmission Experimental Results .....	309
8.4 Simulation of 100 Gb/s CO-OFDM Transmission .....	310
8.4.1 Comparison between Uniform Filling and Random Filling for 100 Gb/s OBM-OFDM.....	310
8.4.2 Dispersion Map Influence on 100 Gb/s CO-OFDM Transmission.....	313

8.4.3 100 Gb/s CO-OFDM Transmission with Cascaded ROADMs .....	315
8.5 High Spectral Efficiency CO-OFDM Systems.....	318
<b>Chapter 9: OFDM for Multimode Fiber Systems .....</b>	<b>325</b>
9.1 Multimode Fibers .....	325
9.2 Optical OFDM in MMF Links .....	329
9.2.1 Power-Efficient OFDM .....	335
9.3 The Use of Optical OFDM in MMF Links for beyond Short-Reach Applications .....	337
9.4 Optical OFDM in Broadcast MIMO Signaling over MMF Links .....	339
9.5 Summary .....	349
<b>Chapter 10: OFDM in Free-Space Optical Communication Systems.....</b>	<b>353</b>
10.1 Introduction.....	353
10.2 FSO-OFDM Transmission System .....	356
10.2.1 Aggregation of RF/Microwave Channels Using OFDM .....	362
10.3 Atmospheric Turbulence Channel Modeling.....	363
10.3.1 Zero Inner Scale .....	364
10.3.2 Nonzero Inner Scale .....	364
10.3.3 Temporal Correlation FSO Channel Model .....	365
10.4 Soft Iterative Decoding .....	368
10.5 Performance Assessment of Coded FSO-OFDM Systems with Direct Detection.....	369
10.6 OFDM in Hybrid Optical Networks.....	372
10.6.1 Hybrid Optical Networks .....	373
10.6.2 Description of Receiver and Transmission Diversity Scheme .....	376
10.6.3 Performance Evaluation of Hybrid Optical Networks .....	378
10.7 Summary .....	381
<b>Chapter 11: OFDM Applications in Access Optical Networks .....</b>	<b>385</b>
11.1 OFDM in Radio-over-Fiber Systems.....	385
11.2 OFDM in Passive Optical Networks .....	389
11.3 Ultra Wideband Signals and Optical OFDM .....	393
11.4 Coded-OFDM over Plastic Optical Fibers .....	399
11.4.1 Performance Analysis of LDPC-Coded OFDM over POFs .....	403
11.5 Indoor Optical Wireless Communications and OFDM.....	405
11.5.1 Infrared Optical Wireless Communications .....	405
11.5.2 Visible Light Communications .....	408
11.6 Summary .....	409
<b>Chapter 12: Future Research Directions.....</b>	<b>413</b>
12.1 Introduction.....	413
12.2 Optical OFDM for 1 Tb/s Ethernet Transport.....	414
12.3 Multimode Fiber for High Spectral Efficiency Long-Haul Transmission .....	417
12.4 Optoelectronic Integrated Circuits for Optical OFDM .....	420

12.5 Adaptive Coding in Optical OFDM .....	422
12.6 Optical OFDM-Based Access Networks .....	426
12.7 Standardization Aspects of Optical OFDM.....	428
12.8 Conclusions.....	429
<b>Index.....</b>	<b>433</b>

# *Introduction*

In the virtually infinite broad electromagnetic spectrum, there are only two windows that have been largely used for modern-day broadband communications. The first window spans from the long-wave radio to millimeter wave, or from 100 kHz to 300 GHz in frequency, whereas the second window lies in the infrared lightwave region, or from 30 THz to 300 THz in frequency. The first window provides the applications that we use in our daily lives, including broadcast radio and TV, wireless local area networks (LANs), and mobile phones. These applications offer the first meter or first mile access of the information networks to the end user with broadband connectivity or the mobility in the case of the wireless systems. Nevertheless, most of the data rates are capped below gigabit per second (Gb/s) primarily due to the lack of the available spectrum in the RF microwave range. In contrast, due to the enormous bandwidth over several terahertz (THz) in the second window, the lightwave systems can provide a staggering capacity of 100 Tb/s and beyond. In fact, the optical communication systems, or fiber-optic systems in particular, have become indispensable as the backbone of the modern-day information infrastructure. There has been a worldwide campaign in the past decade to push the fiber ever closer to the home. Despite the fact that the Internet “bubble” fizzled out in the early 2000s, Internet traffic has been increasing at an astounding rate of 75% per year.<sup>1,2</sup> The new emerging video-centric applications such as IPTV will continue to put pressure on the underlying information infrastructure.

Digital modulation techniques can be generally classified into two categories. The first is single-carrier modulation, in which the data are carried on a single main carrier. This is the “conventional” modulation format that has been the workhorse in optical communications for more than three decades. Single-carrier modulation has in fact experienced rapid advancement in recent years, and many variants to the conventional non-return-to-zero (NRZ) format have been actively explored, including return-to-zero (RZ),<sup>3,4</sup> duobinary,<sup>5,6</sup> differential phase-shift keying (DPSK),<sup>7,8,9</sup> and coherent quaternary phase-shift keying (QPSK).<sup>10–12</sup> The second category of modulation technique is multicarrier transmission, in which the data are carried through many closely spaced subcarriers. Orthogonal frequency-division multiplexing (OFDM) is a special class of MCM system that has only recently gained attention in the optical communication community, especially after being proposed as the attractive long-haul transmission format in coherent detection<sup>13</sup> and direct detection.<sup>14,15</sup>

Experiments on coherent optical OFDM (CO-OFDM) transmission at 100 Gb/s by various groups<sup>16–18</sup> have put the optical OFDM in the race for the next generation of 100 Gb/s Ethernet transport.

OFDM has emerged as the leading modulation technique in the RF domain, and it has evolved into a fast-progressing and vibrant field. It has been triumphant in almost every major communication standard, including wireless LAN (IEEE 802.11 a/g, also known as Wi-Fi), digital video and audio standards (DAV/DAB), and digital subscriber loop (DSL). It is not surprising that the two competing fourth-generation (4G) mobile network standards, Worldwide Interoperability for Microwave Access (WiMAX, or IEEE 802.16) from the computing community and Long-Term Evolution (LTE) from the telecommunication community, both have adopted OFDM as the core of their physical interface. Although the arrival of optical OFDM has been quite recent, it does inherit the major controversy that has lingered more than a decade in the wireless community—the debate about the supremacy of single-carrier or multicarrier transmission.<sup>19,20</sup> It has been claimed that OFDM is advantageous with regard to computation efficiency due to the use of fast Fourier transform (FFT), but the single carrier that incorporates cyclic prefix based on blocked transmission can achieve the same purpose.<sup>19,20</sup> Perhaps the advantage of the OFDM has to do with the two unique features that are intrinsic to multicarrier modulation. The first is scalable spectrum partitioning from individual subcarriers to a sub-band and the entire OFDM spectrum, which provides tremendous flexibility in either device-, or subsystem-, or system-level design compared to single-carrier transmission. The second is the adaptation of pilot subcarriers simultaneously with the data carriers enabling rapid and convenient ways for channel and phase estimation. In this book, we do not intend to resolve the debate on the superiority between single-carrier and multicarrier transmission. Instead, we focus on multicarrier modulation related to its principle, design, transmission, and application. Readers who are interested in advanced modulation formats for single-carrier transmission are referred to other excellent reading material that summarizes progress in single-carrier transmission.<sup>21,22</sup>

Optical OFDM bears both similarities to and differences from the RF counterpart. On the one hand, optical OFDM suffers from two well-known problems, namely high peak-to-average power ratio (PAPR) and sensitivity to phase/frequency noise. On the other hand, the optical channel has its own unique set of problems. One of the prominent differences is the existence of fiber channel nonlinearity and its intricate interaction with fiber dispersion, which is nonexistent in the RF systems. Furthermore, in the RF systems, the main nonlinearity occurs in the RF power amplifier, where a bandpass filter cannot be used to cut off the out-of-band leakage due to unacceptable filter loss. However, in optical OFDM systems, the erbium-doped fiber amplifier (EDFA; by far the most prevalent optical amplifier) is perfectly linear regardless of the level of saturation, and it is usually accompanied by a wavelength multiplexor that can remove the out-of-band spectral leakage.



In summary, after reading this book, we expect that readers—whether from an RF or an optical background—will grasp the unique promises and challenges of the optical OFDM systems.

## 1.1 Historical Perspective of Optical Communications

The use of light as a means of communication is natural and can be traced back to early ages of many civilizations. For instance, along the Great Wall of China is a relatively sophisticated ancient communication system composed of countless beacon towers that in many ways resembles modern-day optical communication systems. Using the color of smoke or the number of lanterns to inform the size of an invading enemy is a crude method of “multilevel” signaling. Analogous to today’s repeated communication systems, the beacon towers are positioned at regular intervals along the Great Wall, and guards in each tower, upon seeing a signal from the previous one, would send the same pattern of signal to the next tower. A message could be relayed from one end of the Great Wall to the other, more than 7300 km, in slightly more than 1 hour.

Optical communication systems took a back seat for quite awhile after the advent of telegraphy, telephone, and radio networks in the first half of the 20th century. However, in the late 20th century, such electrical-based systems had reached a point of saturation in terms of capacity and reach. A typical coaxial transport system operated at a rate of 200 Mb/s needs to regenerate every 1 km, which is costly to operate. The natural trend was to study the lightwave communication systems, in which the data rate can be increased dramatically. This was boosted after the invention and the realization of a laser that gives a coherent source for the transmitter.<sup>23</sup> The remaining obstacle is to find an appropriate lightwave transmission medium. In 1966, Kao and Hockman proposed the idea of using the optical fiber as the lightwave transmission medium despite the fact that optical fiber at the time suffered unacceptable loss.<sup>24</sup> They argued that the attenuation in fibers available at the time was caused by impurities, which could be removed, rather than by any fundamental physical effects such as Rayleigh scattering. Their prophetic prediction of 20 dB/km for telecom-grade optical fiber was realized 5 years later by researchers from Corning, and currently a loss of 0.2 dB/km is the routine specification for single-mode fiber.

Despite their extremely low loss compared to that of the RF counterpart, optical systems still need regeneration for spans commonly less than 100 km. In the late 1980s and early 1990s, coherent detection communication systems were introduced to enhance the transmission distance.<sup>25–27</sup> However, this effort faded after the invention of the optical amplifier in the 1990s. The advent of the optical amplifier heralded a new era of optical communications in which a massive number of wavelength-division multiplexing (WDM) signals can be conveyed over thousands of kilometers.<sup>28</sup>