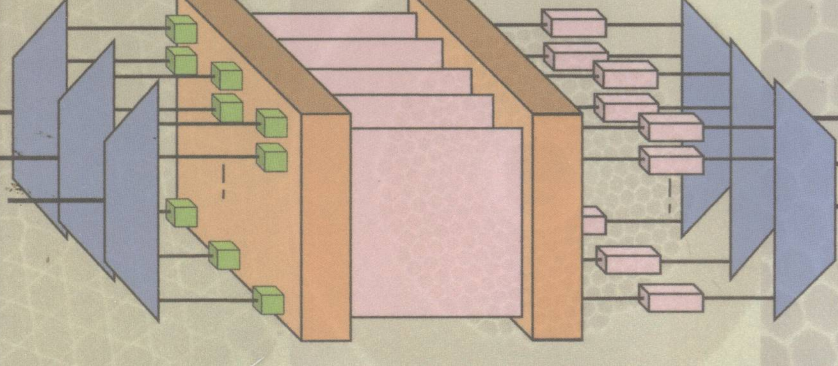
Optical Fiber Telecommunications

V

B: Systems and Networks

Ivan P. Kaminow
Tingye Li
Alan E. Willner



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About the Editors

Ivan P. Kaminow retired from Bell Labs in 1996 after a 42-year career. He conducted seminal studies on electrooptic modulators and materials, Raman scattering in ferroelectrics, integrated optics, semiconductor lasers (DBR, ridge-waveguide InGaAsP, and multi-frequency), birefringent optical fibers, and WDM networks. Later, he led research on WDM components (EDFAs, AWGs, and fiber Fabry-Perot Filters), and on WDM local and wide area networks. He is a member of the National Academy of Engineering and a recipient of the IEEE/OSA John Tyndall, OSA Charles Townes, and IEEE/LEOS Quantum Electronics Awards. Since 2004, he has been Adjunct Professor of Electrical Engineering at the University of California, Berkeley.

Tingye Li retired from AT&T in 1998 after a 41-year career at Bell Labs and AT&T Labs. His seminal work on laser resonator modes is considered a classic. Since the late 1960s, he and his groups have conducted pioneering studies on lightwave technologies and systems. He led the work on amplified WDM transmission systems and championed their deployment for upgrading network capacity. He is a member of the National Academy of Engineering and a foreign member of the Chinese Academy of Engineering. He is also a recipient of the IEEE David Sarnoff Award, IEEE/OSA John Tyndall Award, OSA Ives Medal/Quinn Endowment, AT&T Science and Technology Medal, and IEEE Photonics Award.

Alan E. Willner has worked at AT&T Bell Labs and Bellcore, and he is Professor of Electrical Engineering at the University of Southern California. He received the NSF Presidential Faculty Fellows Award from the White House, Packard Foundation Fellowship, NSF National Young Investigator Award, Fulbright Foundation Senior Scholar, IEEE LEOS Distinguished Lecturer, and USC University-Wide Award for Excellence in Teaching. He is a Fellow of IEEE and OSA, and he has been President of the IEEE LEOS, Editor-in-Chief of the IEEE/OSA J. of Lightwave Technology, Editor-in-Chief of Optics Letters, Co-Chair of the OSA Science & Engineering Council, and General Co-Chair of the Conference on Lasers and Electro-Optics.

For Florence, Paula, Leonard, and Ellen with Love—IPK
For Edith, Debbie, and Kathy with Love—TL
For Michelle, our Children (Moshe, Asher, Ari, Jacob), and my Parents with Love—AEW

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Contents

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Overview of OFT V volumes A & B

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Optical Fiber Telecommunications V (OFT V) is the fifth installment of the *OFT* series. Now 29 years old, the series is a compilation by the research and development community of progress in optical fiber communications. Each edition reflects the current state-of-the-art at the time. As Editors, we started with a clean slate of chapters and authors. Our goal was to update topics from *OFT IV* that are still relevant as well as to elucidate topics that have emerged since the last edition.

1.1 FIVE EDITIONS

Installments of the series have been published roughly every 6–8 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 multiuser 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.

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- 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.
- The present edition of *OFT, V,* (Kaminow, Li, and Willner, 2008) moves 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 takes center stage. 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" previously 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, reexamining 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 nonzero dispersion fiber. Cost considerations and ultra-high-performance systems, respectively, are driving research in plastic fibers and ultra-low-polarization-dependent fibers. We believe that these cycles will continue. Each volume includes a CD-ROM with all the figures from that volume. Select figures are in color. The volume B CD-ROM also has some supplementary Powerpoint slides to accompany Chapter 19 of that volume.

1.2 PERSPECTIVE OF THE PAST 6 YEARS

Our field has experienced an unprecedented upheaval since 2002. The *irrational* exuberance and despair of the technology "bubble-and-bust" had poured untold sums of money into development and supply of optical technologies, which was followed by a depression-like period of over supply. We are happy to say that, by nearly all accounts, the field is gaining strength again and appears to be entering a stage of *rational* growth.

What caused this upheaval? A basis seems to be related to a fundamental discontinuity in economic drivers. Around 2001, worldwide telecom traffic ceased being dominated by the slow-growing voice traffic and was overtaken by the rapidly growing Internet traffic. The business community over-estimated the growth rate, which generated enthusiasm and demand, leading to unsustainable expectations. Could such a discontinuity happen again? Perhaps, but chastened investors now seem to be following a more gradual and sensible path. Throughout the "bubble-and-bust" until the present, the actual demand for bandwidth has grown at a very healthy ~80% per year globally; thus, real traffic demand experienced no bubble at all. The growth and capacity needs are real, and should continue in the future.

As a final comment, we note that optical fiber communications is firmly entrenched as part of the global information infrastructure. The only question is how deeply will it penetrate and complement other forms of communications, e.g., wireless, access, and on-premises networks, interconnects, satellites, etc. This prospect is in stark contrast to the voice-based future seen by *OFT*, published in 1979, before the first commercial intercontinental or transatlantic cable systems were deployed in the 1980s. We now have Tb/s systems for metro and long-haul networks. It is interesting to contemplate what topics and concerns might appear in *OFT VI*.

1.3 OFT V VOLUME A: COMPONENTS AND SUBSYSTEMS

1.3.1 Chapter 1. Overview of OFT V volumes A & B (*Ivan P. Kaminow, Tingye Li, and Alan E. Willner*)

This chapter briefly reviews herewith all the chapters contained in both volumes of OFT V.

1.3.2 Chapter 2. Semiconductor quantum dots: Genesis—The Excitonic Zoo—novel devices for future applications (*Dieter Bimberg*)

The ultimate class of semiconductor nanostructures, i.e., "quantum dots" (QDs), is based on "dots" smaller than the de Broglie wavelength in all three dimensions. They constitute nanometer-sized clusters that are embedded in the dielectric matrix of another semiconductor. They are often self-similar and can be formed by self-organized growth on surfaces. Single or few quantum dots enable novel devices for quantum information processing, and billions of them enable active centers in optoelectronic devices like QD lasers or QD optical amplifiers. This chapter covers the area of quantum dots from growth via various band structures to optoelectronic device applications. In addition, high-speed laser and amplifier operations are described.

1.3.3 Chapter 3. High-speed low-chirp semiconductor lasers (*Shun Lien Chuang, Guobin Liu, and Piotr Konrad Kondratko*)

One advantage of using quantum wells and quantum dots for the active region of lasers is the lower induced chirp when such lasers are directly modulated, permitting direct laser modulation that can save on the cost of separate external modulators. This chapter provides a comparison of InAlGaAs with InGaAsP long-wavelength quantum-well lasers in terms of high-speed performance, and extracts the important parameters such as gain, differential gain, photon lifetime, temperature dependence, and chirp. Both DC characteristics and high-speed direct modulation of quantum-well lasers are presented, and a comparison with theoretical models is made. The chapter also provides insights into novel quantum-dot lasers for high-speed operation, including the ideas of p-type doping vs tunneling injection for broadband operation.

1.3.4 Chapter 4. Recent advances in surface-emitting lasers (*Fumio Koyama*)

Vertical cavity surface-emitting lasers (VCSELs) have a number of special properties (compared with the more familiar edge-emitting lasers) that permit some novel applications. This chapter begins with an introduction which briefly surveys recent advances in VCSELs, several of that are then treated in detail. These include techniques for realizing long-wavelength operation (as earlier VCSELs were limited to operation near 850 nm), the performance of dense VCSEL arrays that emit a range of discrete wavelengths (as large as 110 in number), and MEMS-based athermal VCSELs. Also, plasmonic VCSELs that produce subwavelength spots for high-density data storage and detection are examined. Finally, work on all-optical signal processing and slow light is presented.

1.3.5 Chapter 5. Pump diode lasers (*Christoph Harder*)

Erbium-doped fiber amplifiers (EDFAs) pumped by bulky argon lasers were known for several years before telecom system designers took them seriously; the key development was a compact, high-power semiconductor pump laser. Considerable effort and investment have gone into today's practical pump lasers, driven by the importance of EDFAs in realizing dense wavelength division multiplexed (DWDM) systems. The emphasis has been on high power, efficiency, and reliability. The two main wavelength ranges are in the neighborhood of 980 nm for low noise and 1400 nm for remote pumping of EDFAs. The 1400-nm band is also suitable for Raman amplifiers, for which very high power is needed.

This chapter details the many lessons learned in the design for manufacture of commercial pump lasers in the two bands. Based on the performance developed for telecom, numerous other commercial applications for high-power lasers have emerged in manufacturing and printing; these applications are also discussed.

1.3.6 Chapter 6. Ultrahigh-speed laser modulation by injection locking (*Connie J. Chang-Hasnain and Xiaoxue Zhao*)

It has been known for decades that one oscillator (the slave) can be locked in frequency and phase to an external oscillator (the master) coupled to it. Current studies of injection-locked lasers show that the dynamic characteristics of the directly modulated slave are much improved over the same laser when freely running. Substantial improvements are found in modulation bandwidth for analog and digital modulation, in linearity, in chirp reduction and in noise performance.

In this chapter, theoretical and experimental aspects of injection locking in all lasers are reviewed with emphasis on the authors' research on VCSELs (vertical cavity surface-emitting lasers). A recent promising application in passive optical networks for fiber to the home (FTTH) is also discussed.

1.3.7 Chapter 7. Recent developments in high-speed optical modulators (*Lars Thylén, Urban Westergren, Petter Holmström, Richard Schatz, and Peter Jänes*)

Current high-speed lightwave systems make use of electro-optic modulators based on lithium niobate or electroabsorption modulators based on semiconductor materials. In commercial systems, the very high-speed lithium niobate devices often require a traveling wave structure, while the semiconductor devices are usually lumped.

This chapter reviews the theory of high-speed modulators (at rates of 100 Gb/s) and then considers practical design approaches, including comparison of lumped and traveling-wave designs. The main emphasis is on electroabsorption devices based on Franz–Keldysh effect, quantum-confined Stark effect and intersubband absorption. A number of novel designs are described and experimental results given.

1.3.8 Chapter 8. Advances in photodetectors (*Joe Charles Campbell*)

As a key element in optical fiber communications systems, photodetectors belong to a well developed sector of photonics technology. Silicon p–i–n and avalanche photodiodes deployed in first-generation lightwave transmission systems operating at 0.82-μm wavelength performed very close to theory. In the 1980s, InP photodiodes were developed and commercialized for systems that operated at 1.3- and 1.5-μm wavelengths, albeit the avalanche photodiodes (APDs) were expensive and nonideal. Introduction of erbium-doped fiber amplifiers and WDM technology in the 1990s relegated APDs to the background, as p–i–n photoreceivers performed well in amplified systems, whereas APDs were plagued by the amplified spontaneous emission noise. Future advanced systems and special applications will require sophisticated devices involving deep understanding of device physics and technology. This chapter focuses on three primary topics: high-speed waveguide photodiodes for systems that operate at 100 Gb/s and beyond, photodiodes with high saturation current for high-power applications, and recent advances of APDs for applications in telecommunications.

1.3.9 Chapter 9. Planar lightwave circuits in fiber-optic communications (*Christopher R. Doerr and Katsunari Okamoto*)

The realization of one or more optical waveguide components on a planar substrate has been under study for over 35 years. Today, individual components such as splitters and arrayed waveguide grating routers (AWGRs) are in widespread commercial use. Sophisticated functions, such as reconfigurable add–drop multiplexers (ROADMs) and high-performance filters, have been demonstrated by integrating elaborate combinations of such components on a single chip. For the most part, these photonic integrated circuits (PICs), or planar lightwave circuits (PLCs), are based on passive waveguides in lower index materials, such as silica.

This chapter deals with the theory and design of such PICs. The following two chapters (Chapters 11 and 12) also deal with PICs; however, they are designed to be integrated with silicon electronic ICs, either in hybrid fashion by short wire bonds to an InP PIC or directly to a silicon PIC.

1.3.10 Chapter 10. III–V photonic integrated circuits and their impact on optical network architectures (*Dave Welch, Chuck Joyner, Damien Lambert, Peter W. Evans, and Maura Raburn*)

InP-based semiconductors are unique in their capability to support all the photonic components required for wavelength division multiplexed (WDM) transmitters and receivers in the telecom band at 1550 nm. Present subsystems have connected these individual components by fibers or lenses to form hybrid transmitters and receivers for each channel.

Recently, integrated InP WDM transmitter and receiver chips that provide 10 channels, each operating at 10 Gb/s, have been shown to be technically and