SEMICONDUCTORS AND SEMIMETALS

VOLUME 22

Lightwave Communications Technology

Volume Editor W. T. Tsang

Part E

Integrated Optoelectronics

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Treatise Foreword

This treatise continues the format established in the books of Volume 21, in which a subject of outstanding interest and one possessing ever-increasing practical applications is treated in a multivolume work organized by a guest editor of international repute. The present series, which consists of five volumes (designated as Volume 22, Parts A through E) deals with an area that is experiencing a technological revolution and is destined to have a far-reaching impact in the near future—not only in the communications and data-processing fields, but also in numerous ancillary areas involving, for example, control systems, interconnects that maintain individual system isolation, and freedom from noise emanating from stray electromagnetic fields.

That the excitement engendered by the rapid pace of developments in lightwave communications technology is universal is borne out by the large number of contributions to this series by authors from abroad. It is indeed fortunate that W. T. Tsang, who is most highly knowledgeable in this field and has made so many personal contributions, has been able to take the time to put together a work of the extent and excellence of the present series. The treatise editors are also greatly indebted to Dr. Patel and the other colleagues of Dr. Tsang at AT&T Bell Laboratories, without whose understanding and encouragement this group of books would not have been possible.

R. K. WILLARDSON
ALBERT C. BEER

Foreword

Lightwave technology is breaking down barriers in communications in a manner similar to the way barriers in computing came down thanks to semiconductor integrated circuit technology. Increased packing densities of components on integrated circuit chips made possible a phenomenal amount of information processing capacity at continually decreasing cost. The impact of lightwave technology on communications is quite similar. We are reaching a point where an exponentially increasing transmission capacity is resulting in our capability to provide vast amounts of information to the most distant reaches of the world at a nominal cost. This revolution in information transmission capacity is engendered by the rapid developments in lightwave communications.

Along with the very large transmission capacity predicted in the late fifties when the laser was invented have come a number of additional advantages. Of these advantages, I single out those arising from the nonmetallic nature of the transmission medium. These fall under the broad category of what may be called an immunity from unanticipated electromagnetic coupling. The following rank as very important benefits: freedom from electromagnetic interference, absence of ground loops, relative freedom from eavesdropping (i.e., secure links), and potential for resistance to the electromagnetic pulse problems that plague many conventional information transmission systems utilizing metallic conductors as well as satellite and radio technology. Each of these benefits arises naturally from the medium through which the light is propagated and is, therefore, paced by the progress in optical fibers.

However, what we take for granted today was not so obvious for many decades following the first practicable use of light for communications by Alexander Graham Bell in 1880. The use of heliographs in ancient Greece, Egypt, and elsewhere and the smoke signaling by various American Indian tribes notwithstanding, Bell's experiments on the use of sunlight for transmitting spoken sounds over a distance of a few hundred meters were undoubtedly the first step toward practical optical communications, since it represents a quantum jump in the increase in the bandwidth used for information transmission. The excitement he felt is keenly expressed in his words:

> I have heard articulate speech produced by sunlight. I have heard a ray of sun laugh and cough and sing. I have been able to hear a shadow, and I have even perceived by ear the passing of a cloud across the sun's disk.

The results of his experiments were presented at a meeting of the American Association of Scientific Persons in Boston, Massachusetts. But the generally favorable reaction to Bell's photophone in the popular press was tempered with some skepticism. The following paragraph is taken from an article that appeared on the editorial pages of the August 30, 1880, issue of the *New York Times,* which reported on Bell's results.

> What the telephone accomplishes with the help of a wire the photophone accomplishes with the aid of a sunbeam. Professor Bell described his invention with so much clearness that every member of the American Association must have understood it. The ordinary man, however, may find a little difficulty in comprehending how sunbeams are to be used. Does Professor Bell intend to connect Boston and Cambridge, for example, with a line of sunbeams hung on telegraph posts, and, if so, of what diameter are the sunbeams to be, and how is he to obtain them of the required size? . . .

Bell reported optical communication through free atmosphere, but the reporter unintentionally seemed to have foreseen the time when optical-fiber cables would be strung from pole to pole or buried underground.

A unique set of circumstances and a host of advances resulting from extensive interdisciplinary efforts have fueled the revolution in lightwave communications and the acceptance of this new technology. The tremendous progress in lightwave communications is a result of necessity as well as of the response of the scientists and engineers to the formidable challenges. The large bandwidth possible with lightwave communications is a direct result of the very high carrier frequency of electromagnetic radiation in the optical region. This advantage was recognized at least as early as the late fifties and early sixties. Yet almost fifteen years elapsed before lightwave communications technology became economically viable. Two primary components of the communications technology paced this development: the light source and the transmission medium. A third component, the receiver, is also important but was not the pacing one in the early years of development of lightwave systems.

The laser was invented in 1958, and within a very few years laser action was demonstrated in a variety of solids, liquids, and gases. The semiconductor injection laser, the workhorse of contemporary optical communications, was invented in 1962, but its evolution to a practical transmitter in a lightwave system took another eight years. In 1970 Hayashi and Panish (and, independently, Alferov in the Soviet Union) demonstrated the first continuous wave (cw) room-temperature-operated semiconductor laser. The potentials of small size, high reliability, low cost, long life, and ability to modulate the light output of the semiconductor laser at very high rates by merely modulating the drive current were recognized early in the game. With the demonstration of the cw room-temperature operation the race was on to exploit all these advantages.

Again, while laser light propagation through the atmosphere was considered in the mid-sixties, everyone recognized the limitations due to unpredictable and adverse weather conditions. To avoid these limitations, propagation in large hollow pipes was also studied, but again practical difficulties arose. It was the development of optical fiber technology to reduce transmission losses to acceptable levels that has led to the practical implementation of lightwave communications. While light transmission through very small-diameter fibers was demonstrated in the early fifties, it was a combination of theoretical advances by Kao and inventive experimentation by Maurer in the late sixties that resulted in the realization of 20-dB/km fiber. Additional fuel was thus provided to speed up the revolution.

Today, new records are continually being set for the longest and the highest-capacity lightwave communications system. Yet these records are thousands of times below the fundamental bandwidth limits set by the carrier frequency of optical radiation on the rate of information transmission. Furthermore, from very fundamental considerations of light-transmitting materials, there is no reason why the currently achieved lowest losses for optical fibers, in the region of 0.1 dB/km at 1.55 μm, will not be considered too high in the future. It is not inconceivable that fiber losses as low as 10^{-4} dB/km may someday be achieved. It does not take a great deal of imagination to realize the impact of such development.

This is where we are. What future developments will pace the exploitation of lightwave communications? The five-volume minitreatise on lightwave communications technology aims both to recapitulate the existing developments and to highlight new science that will form the underpinnings of the next generation of technology. We know a lot about how to transmit information using optical means, but we know less than enough about how to switch, manipulate, and process information in the optical domain. To take full advantage of all the promise of lightwave communications, we have to be able to push the optical bits through the entire communications system with the electronic-to-optical and optical-to-electronic interfaces only at the two ends of the lightwave communications system. To achieve this, we will need practical and efficient ways of switching, storing, and processing optical information. This is a must before lightwave communications is able to touch every single subscriber of the present telephone and other forms of communications technology.

We have come a long way since Bell's experiments of 1880, but there is a lot more distance ahead. That is what the field of lightwave communications is all about — more challenges, more excitement, more fun for those who are the actors, and a greater opportunity for society to derive maximum benefit from the almost exponentially increasing information capacity of lightwave systems.

AT&T Bell Laboratories C. K. N. PATEL
October 9, 1984

Preface

When American Indians transmitted messages by means of smoke signals they were exploiting concepts at the heart of modern optical communications. The intermittent puffs of smoke they released from a mountaintop were a digital signal; indeed, the signal was binary, since it encoded information in the form of the presence or absence of puffs of smoke. Light was the information carrier; air was the transmission medium; the human eye was the photodetector. The duplication of the signal at a second mountaintop for the transmission to a third served as signal reamplification, as in today's electronic repeater. Man had devised and used optical communications even long before the historic event involving the "photophone" used over a hundred years ago (1880) by Alexander Graham Bell to transmit a telephone signal over a distance of two hundred meters by using a beam of sunlight as the carrier. It was not until 1977, however, that the first commercial optical communications system was installed. Involved in the perfection of this new technology are the invention and development of a reliable and compact near-infrared optical source that can be modulated by the information-bearing signal, a low-loss transmission medium that is capable of guiding the optical energy along it, and a sensitive photodetector that can recover the modulation error free to re-treat the information transmitted.

The invention and experimental demonstration of a laser in 1958 immediately brought about new interest and extensive research in optical communications. However, the prospect of practical optical communications brightened only when three major technologies matured. The first technology involved the demonstration of laser operation by injecting current through a semiconductor device in 1962 and the achievement of continuous operation for over one million hours in 1977. The second technology involved the attainment of a 20-dB/km doped silica fiber in 1970, the realization that pure silica has the lowest optical loss of any likely medium, the discovery in 1973 that suitably heat-treated, boron-doped silica could have a refractive index less than that of pure silica, and the recent achievement of an ultralow loss of 0.157 dB/km with Ge-doped silica-based fibers. The third technology is the development of low-noise photodetectors in the 1970s, which made possible ultrahigh-sensitivity photoreceivers. It is the simultaneous achievement of reliable semiconductor current-injection lasers, low loss in optical fibers, and low-noise photodetectors that thrusts lightwave communications technology into reality and overtakes the conventional transmission systems employing electrical means.

Since optical-fiber communications encompasses simultaneously several other technologies, which include the systems area of telecommunications and glass and semiconductor optoelectronics technologies, a tremendous amount of research has been conducted during the past two decades. We shall attempt to summarize the accumulated knowledge in the present series of volumes of "Semiconductors and Semimetals" subtitled "Lightwave Communications Technology." The series consists of seven volumes. Because of the subject matter, the first five volumes concern semiconductor optoelectronics technology and, therefore, will be covered in "Semiconductors and Semimetals." The last two volumes, one on optical-fiber technology and the other on transmission systems, will be covered in the treatise "Optical Fiber Communications," edited by Tingye Li and W. T. Tsang.

Volume 22, Part A, devoted entirely to semiconductor growth technology, deals in detail with the various epitaxial growth techniques and materials defect characterization of III – V compound semiconductors. These include liquid-phase epitaxy, molecular beam epitaxy, atmospheric-pressure and low-pressure metallo-organic chemical vapor deposition, and halide and chloride transport vapor-phase deposition. Each technique is covered in a separate chapter. A chapter is also devoted to the treatment of material defects in semiconductors.

In Volume 22, Parts B and C, the preparation, characterization, properties, and applications of semiconductor current-injection lasers and light-emitting diodes covering the spectral range of 0.7 – 1.6 μm and above 2 μm are reviewed. Specifically, Volume 22, Part B, contains chapters on dynamic properties and subpicosecond-pulse mode locking, high-speed current modulation, and spectral properties of semiconductor lasers as well as dynamic single-frequency distributed feedback lasers and cleaved-coupled-cavity semiconductor lasers. Volume 22, Part C, consists of chapters on semiconductor lasers and light-emitting diodes. The chapters on semiconductor lasers consist of a review of laser structures and a comparison of their performances, schemes of transverse mode stabilization, functional reliability of semiconductor lasers as optical transmitters, and semiconductor lasers with wavelengths above 2 μm. The treatment of light-emitting diodes is covered in three separate chapters on light-emitting diode device design, its reliability, and its use as an optical source in lightwave transmission systems. Volume 22, Parts B and C, should be considered as an integral treatment of semiconductor lasers and light-emitting diodes rather than as two separate volumes.

Volume 22, Part D, is devoted exclusively to photodetector technology. It includes detailed treatments of the physics of avalanche photodiodes; avalanche photodiodes based on silicon, germanium, and III–V compound semiconductors; and phototransistors. A separate chapter discusses the sensitivity of avalanche photodetector receivers for high-bit-rate long-wavelength optical communications systems.

Volume 22, Part E, is devoted to the area of integrated optoelectronics and other emerging applications of semiconductor devices. Detailed treatments of the principles and characteristics of integrable active and passive optical devices and the performance of integrated electronic and photonic devices are given. A chapter on the application of semiconductor lasers as optical amplifiers in lightwave transmission systems is also included as an example of the important new applications of semiconductor lasers.

Because of the subject matter (although important to the overall treatment of the entire lightwave communications technology), the last two volumes will appear in a different treatise. The volume on optical fiber technology contains chapters on the design and fabrication, optical characterization, and nonlinear optics in optical fibers. The final volume is on lightwave transmission systems. This includes chapters on lightwave systems fundamentals, optical transmitter and receiver design theories, and frequency and phase modulation of semiconductor lasers in coherent optical transmission systems.

Thus, the series of seven volumes treats the entire technology in depth. Every author is from an organization that is engaged in the research and development of lightwave communications technology and systems.

As a guest editor, I am indebted to R. K. Willardson and A. C. Beer for having given me this valuable opportunity to put such an important and exploding technology in "Semiconductors and Semimetals." I am also indebted to all the contributors and their employers who have made this series possible. I wish to express my appreciation to AT&T Bell Laboratories for providing the facilities and environment necessary for such an endeavor and to C. K. N. Patel for preparing the Foreword.

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Lightwave Communications Technology

Part E

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Contents

Chapter 3 **Optical Amplification by Semiconductor Lasers**

Takaaki Mukai, Yoshihisa Yamamoto, and Tatsuya Kimura

CHAPTER 1

Principles and Characteristics of Integratable Active and Passive Optical Devices

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I. Introduction

Lightwave communications technology is based on the technologies of its building blocks: the source, the processing unit, the transmission medium, and the detector. The invention of the laser in the early 1960s and the subsequent advent of low-loss fibers provided the impetus for a concerted effort in the research and development of lightwave communications technology. The concept of "integrated optics" emerged in the late 1960s in an effort to make optical systems compatible with modern thin-film technology. The idea was to build various optical devices on a common substrate and then to interconnect them by thin-film waveguides. As integrated optics developed in ensuing years, it became apparent that material compatibility was a key problem. The objectives of integrated optics have since evolved from total optical integration to partial optical integration and from developing an encompassing integrated-optics technology to exploring and realizing guided-wave optical devices that are potentially integratable. It is in this spirit of integration that the subjects in this chapter are treated.

The technical subjects are divided into five parts. The first part, presented in Part II, deals with passive dielectric waveguides. Waveguides are needed not only to provide interconnections between two optical devices but also to confine the optical beam in an optical device to optimize the device performance. At the present state of integrated optics, waveguides are more widely used in the second role than in the first role. The second part, presented in Part III, treats composite waveguide systems that involve interactions between guided waves. Many optical devices utilize the interaction of two waves of the same or orthogonal polarizations and two waves propagating in the same or opposite directions. The discussion in this part prepares a common background for optical devices to be presented in subsequent parts.

The third part, presented in Part IV, discusses guided-wave control devices. In a communications system the processing unit constitutes an essential building block for pulse regeneration or for modulation and demodulation of optical signals. Even though in the near future a major part of signal processing is expected to be performed by electronic circuits rather than by optical circuits, optical devices can serve simple and unique functions that