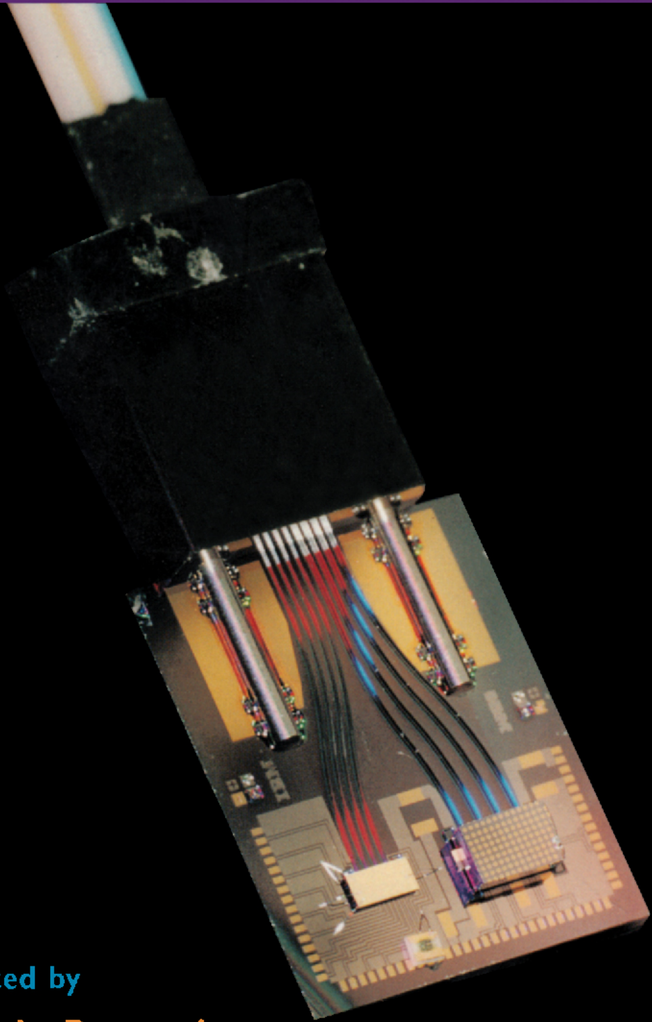
Integrated Optoelectronics



Edited by

Mario Dagenais

Robert F. Leheny

John Crow

QUANTUM ELECTRONICS

Principles and Applications

INTEGRATED OPTOELECTRONICS

QUANTUM ELECTRONICS—
PRINCIPLES AND APPLICATIONS

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INTEGRATED OPTOELECTRONICS

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ACADEMIC PRESS

San Diego Boston New York
London Sydney Tokyo Toronto

Front cover: This is a photo of a 1 Gigabit/sec per channel, 4-channel module for both the transmission and receiving of data. It has a transmitter OEIC consisting of a laser, control photodiode, and impedance matching array; and a receiver OEIC consisting of a photodiode + amplifier array. The chips are flip bonded to the carrier, and self-aligned to the lightguides on the carrier. Photo courtesy of IBM.

This book is printed on acid-free paper. ♾

Academic Press, Inc.
A Division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, California 92101-4495

United Kingdom Edition published by
Academic Press Limited
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Integrated optoelectronics / {edited by} Mario Dagenais, Robert F. Leheny, John Crow.
p. cm. -- (Quantum electronics--principles and applications)
Includes bibliographical references and index.
ISBN 0-12-200420-5 (alk. paper)
1. Optoelectronic devices. 2. Integrated optics. 3. Integrated circuits. I. Dagenais, Mario, date. II. Leheny, Robert F. III. Crow, John. IV. Series.
TA1750.I5885 1994
621.381'045--dc20 93-29840
CIP

PRINTED IN THE UNITED STATES OF AMERICA
94 95 96 97 98 99 EB 9 8 7 6 5 4 3 2 1

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Preface

Optoelectronic technology is associated with the generation, transmission, routing, and detection of optical signals. Today optoelectronics is finding widespread applications ranging from fiber optic telephone lines to notebook computer displays, CD audio systems and memories, and laser printers. These applications are building blocks for the emerging information age and optoelectronics is rightly considered a critical enabling technology. Recent studies by both private and government agencies have identified the importance of optoelectronics and have encouraged expanded investment in this technology as a means for insuring the continued development of information-age applications. As the economic vitality and variety of personal opportunities in our society become more and more dependent on effortless access to information the role that continued advancement of optoelectronics will have in pacing progress becomes even more critical.

This book is about one key technological challenge in expanding the versatility and functionality of optoelectronics: research aimed at the integration of multiple-function devices onto a single substrate or chip. The goal of this research is to enhance the performance and reliability of optoelectronic modules while lowering their manufacturing cost through the development of OptoElectronic Integrated Circuits (OEICs). The vision is to achieve the advantages that integration has demonstrated for electronic components. Over a period of 30 years the electronics industry has moved from discrete transistors to Very Large Scale Integrated Circuits (VLSI) and the cost and reliability advantages achieved through these developments have largely been responsible for enabling all the advancements in electronic information transmission and processing that have been so instrumental in transforming our society today. Electronic IC technology exploits the similarity of function of the basic building blocks (MOSFETs, CMOS, or bipolar transistors) and gains functionality and performance from the development of complex on-wafer interconnection of these devices.

Optoelectronic devices are largely based on similar materials, typically III-V semiconductor materials, and are processed or fabricated using many of the same technologies that form the basis for silicon-integrated circuit fabrication. However, optical components rely on both the optical and electronic properties of the materials they are fabricated from and they often require heteroepitaxial material with accurately controlled composition to achieve optimum performance. As a result OEICs are typically more complex in structure than silicon ICs. A further complication is that in their most versatile form OEICs are built up from components that are very different in functionality—light emitter, waveguide, intensity or phase modulator, and/or detector. Each of these different components requires different material structures to achieve optimized performance. Given this complexity OEICs require flexible processing technologies and OEIC fabrication is typically very different from the much simpler (in concept) doping operation used to realize silicon devices.

Today monolithically integrated optical receivers are already in use in compact disk and CD-ROM products (Si OEICs) and are beginning to appear in data communication products (GaAs and Si OEICs). Also, the integration of photonic components (Photonic Integrated Circuits, PICs), such as waveguide modulators or lasers with waveguides and the use of flip-chip bonding to hybrid integrate two chips together, are emerging from the development phase. The application of the technology covered by the book is therefore just beginning. The hybrid techniques are expected to migrate in the future to monolithic integration, motivated by the desire for lower cost, smaller size, and higher reliability for the same function, with the expectation that ultimately our experiences with integration will produce inventions with totally new functions not yet envisioned.

Over the past decade a number of research groups have focused on developing and demonstrating the integration of multiple optical functions with electronics and their efforts have identified and begun to address the development of an integrated optoelectronics technology. At the same time the complexity of design for discrete components to meet advanced optical systems requirements has increased. Examples include wavelength controlled laser PICs incorporating passive waveguides and gratings with quantum well active region as well as vertical cavity surface emitting lasers (VCSELs) which incorporate very high reflectivity mirrors (99%) within the laser diode structure. Progress in material deposition control, processing, and device design required to meet these device needs has led to the development of many manufacturing processes that can readily be adapted to OEICs. Today we are poised to exploit these developments.

This book brings together a group of acknowledged university and industry research experts from around the world to share their insights on the common theme of optoelectronic integration. These experts report not only on the state-of-the-art, but also on the physics and design experience that go into implementing integrated chips and modules. The editors have tried to create a cohesive set of articles that includes a discussion of the trade-offs between materials growth, device processing, state-of-the-art discrete component design, multifunctional chip design, packaging, and systems requirements. Levels of integration discussed encompass electrical, optoelectronic, and all optical devices in both monolithic and hybrid form. The editors have targeted the book for researchers, practicing engineers, and graduate students in electronic or optical science who are working with optoelectronics technology and its applications. The editors hope that newcomers to the field can use this text to find the information required for understanding the major issues involved in optoelectronic integration.

This book then is a summary of where optoelectroncis technology is at this point in time from the perspective of emerging OEIC technology. The text is organized into five parts, each covering a broad technology area important to OEICs. Each part is then subdivided into Chapters authored by experts on specific topics related to the technology area being covered. In this way the editors have endeavored to provide within each part a self-contained overview of these critical enabling technologies. The part titles provide a guide to the topics covered: system requirements for OEICs, materials growth, device processing, state-of-the-art discrete components, and finally a six-Chapter part dealing specifically with the main theme of optoelectronic integrated circuits. It is the hope of the editors that an interested reader will be able to become familar with all the enabling technologies important to optoelectronics and thereby gain insight into the field beyond what is required to understand OEICs.

Mario Dagenais
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PART I

System Requirements for OEICs

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Chapter 1

TELECOMMUNICATIONS SYSTEM APPLICATIONS FOR OPTOELECTRONIC INTEGRATED CIRCUITS

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1. WHY OPTOELECTRONIC INTEGRATION?

The rapid advances in optoelectronics have caused this technology to be a crucial element driving the transition from the Industrial Age to the Information Age [1]. For example, the development of semiconductor laser diodes and photodiodes was critical for the realization of cost-effective optical fiber communications networks. These optical fiber systems are in widespread use today for "long-haul networks" spanning oceans and continents. They are widely used in the United States and some other countries for "interoffice networks," namely the networks that interconnect major telecommunications

ISBN 0-12-200420-5

switching centers (telephone company central offices). Today we are at the threshold of another revolutionary development in the transition to the Information Age, namely the integration of optical and electronic components into optoelectronic integrated circuits (OEICs) combining features from each of these significant technologies.

The primary objectives for optoelectronic integration are similar to those for electronic integration: increase functionality and decrease cost per component. The development of electronic ICs over the past 20 years has exhibited growth from a few transistors per chip to more than 10 million transistors per chip today. Electronic integration was strongly motivated by the "connection bottleneck"—the difficulty of connecting efficiently discrete electronic components. However, integration is perhaps more important for optical technologies than it was for electronic technologies, because one of the key attributes of optics is its *inherent parallelism* (simultaneously acting on many beams or wavelengths of light, as a waveguide or lens would), as opposed to the serial nature of transistors. Unlike the development of electronic integrated circuits, which involved the replication of huge numbers of identical components, optoelectronic integration promises the aggregation of rather varied functions from fundamentally different types of components, including some based on different materials. In addition, OEICs can provide multifunction single components. Although a distinction is sometimes made between OEICs that incorporate "primarily photonic" components (such OEICs being called photonic integrated circuits) and those integrating both optical and electronic functionality, that distinction is not emphasized in this chapter.

Optoelectronic integration uses materials with very high electron mobility, ranging from about 3800 $cm^2/V\ s$ in InP and 8500 $cm^2/V\ s$ in undoped GaAs to more than 11,000 $cm^2/V\ s$ in artificially lattice-matched quaternaries ($Ga_xIn_{1-x}As_yP_{1-y}$). Thus, the OEIC electronic components will be able to operate at the requisite speeds (Gbits/s) for broadband communications. Mass production of such circuits will result in much lower costs and potentially smaller sizes (per unit component, per user, per functional component, and per system) than are possible with the use of discrete components and may offer other significant advantages as well [2]. Optoelectronic integration may allow increasing complexity and functionality along with the high reliability achievable with integration. For example, the precise alignment of a single optical fiber to an OEIC that combines many laser transmitters is much simpler (and thus more reliable) than the use of multiple discrete component transmitters to many fibers. OEICs will be necessary to take advantage of the inherent parallelism of optical systems, particularly multiwavelength systems, where OEICs may have their most significant advantages over discrete components. OEICs offer the ability to utilize the noise immunity characteristics of on-chip optical waveguides and interconnections. Finally, integration of functions will yield, through increasing complexity, new functionality unavailable and perhaps unattainable without integration.

The purpose of this chapter is to discuss possible OEIC applications that could enhance the performance and functionality of lightwave telecommunications systems and networks. The chapter is divided into three parts. In the first part, a vision of the future broadband networks is presented. The second part discusses various approaches to accessing broadband networks. The third part briefly indicates additional lightwave network applications. Specific optical network architectures are described from a functional perspective, as examples of where potential OEICs may be appropriate. In addition, a catalog of "generic OEIC chip concepts" is developed from a functional perspective, with the objective of motivating device research with a focus on potential applications (see Appendix, Figures Cat-1 to Cat-10).

2. A VISION OF THE FUTURE BROADBAND NETWORK

We begin the discussion with a brief review of some network terminology. By *network* we mean the organization of transmission facilities serving a group of nodes. These nodes represent the users; they may be individuals, computers, broadcast video sources, or entire "subnetworks." Because the number of communications links required for full connection of all the nodes increases as N^2, *switching* is required to provide connectivity among the nodes economically. Historically, transmission bandwidth has been a scarce resource. Since the advent of optical fibers, this has been changing. The transmission bandwidth of silica glass fiber is abundant (more than 10 Tbit/s for the low-loss wavelength regions from 1100 to 1600 nm in single-mode fibers), and departures from the traditional telecommunications approaches used with copper cable–based systems may be required to take advantage of this huge bandwidth.

Networks may be classified into several topological groups, such as buses, stars, meshes, rings, and trees. Switching among the nodes in these networks can be divided into two main types, *circuit switching* and *packet switching*. In circuit-switched networks, fixed bandwidth is allocated between an origin and a destination at the call setup time. Networks with circuit switching generally have a few common transmission rates and do not have network overloads—if all available bandwidth is in use, new calls are simply blocked from entering the network. On the contrary, networks employing packet switching can accommodate a diverse set of transmission rates. The data to be transmitted are divided into packets (of fixed length, or with some fixed maximum length) and then transmitted across the network. Whereas circuit switching allocates bandwidth end to end, packet techniques allocate bandwidth by link as the packet traverses the network. Temporary network overloads are allowed and are handled by each node's memory buffers. Whereas circuit switching techniques are appropriate for continuous bit-rate calls (such as voice or broadcast video traffic), packet techniques are generally more appropriate for bursty bit-rate calls (for traffic such as data or image communications) so that repetitive call setup time can be avoided.

As optical fiber technology advanced during the 1980s and optical fibers became the transmission medium of choice for the public telecommunications network, and as powerful computers based on highly integrated microelectronics were also developing, a new vision of telecommunications emerged. In this vision, a future "intelligent broadband network" will enable people, computers, and other data devices to communicate with each other, in any medium (voice, data, image, video, or multimedia), and at reasonable cost. Fulfilling this vision will require flexible topology broadband backbone optical networks (Fig. 1) linking computers and other data devices, along with voice networks and video networks, encompassing a hierarchy of networks of networks (Fig. 2).

The global importance of a broadband telecommunications infrastructure for commerce, education, and entertainment should not be underestimated. Once widely deployed, such networks will enable nearly everyone to access a broad range of information services—for example, to have access to the educational materials of the great text, image, and video libraries and databases of information. Surely the realization of this vision through broadband networks will rank as one of the major achievements of our society.

2.1. Evolution to the Broadband Network

The public circuit-switched voice network today is based on time-multiplexed 64 kbit/s channels (fixed time slots) in T1 (1.5 Mbit/s) and T3 (45 Mbit/s) backbone network trunks. These trunk groups are often multiplexed to form higher-rate point-to-point optical fiber links between telephone company switching centers. The trunk groups are then demultiplexed from the fiber links and the individual 64 kbit/s channels are switched for the end users.

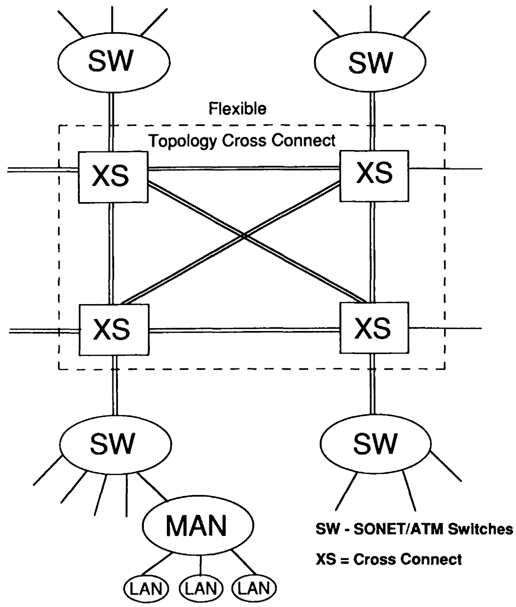

Fig. 1. Flexible topology broadband network. The figure shows central elements of a broadband network, including SONET/ATM switches (SW) and digital cross-connect systems (XS).

As this network evolves toward the broadband future, optical fiber links will be connected to digital cross-connect systems capable of reconfiguring the entire network or portions of it to provide routing diversity and fault tolerance (Fig. 1). This reconfiguration may involve switching from one set of optical fibers to another or regrouping of trunk groups. A North American standard has been adopted for an optical transmission signal hierarchy, known as synchronous optical network (SONET). SONET is also the basis for an international standard known as SDH. The SONET optical transmission rates are multiples of a basic building block of 51 Mbit/s (Table 1), rather than the 64 kbit/s rate of the current public circuit-switched network. The 64 kbit/s "atomic unit" for the current network was motivated by the characteristics of a "dominant service," namely voice traffic. Similarly, the 51 Mbit/s and higher data rates are motivated by the expectation that high-quality, full-motion video and multimedia services will be the dominant traffic for the future networks. This high-rate atomic unit required a new approach to the fundamental structure—even at only 155 Mbit/s, there are more than two thousand 64 kbit/s time slots. Thus, asynchronous transfer mode (ATM) was developed [3–6]. In this approach, specific periodic time slots are not assigned to a channel. Bandwidth is segmented into fixed-size cells, which

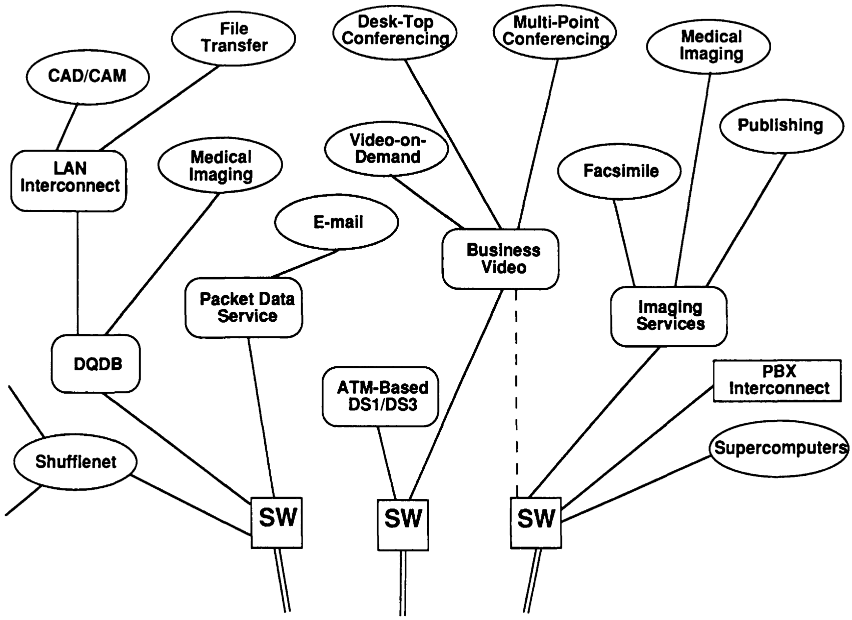

Fig. 2. Broadband network hierarchy and supported services. The broadband network will incorporate a hierarchy of networks supporting a diverse array of services.

Table 1.

SONET Optical Transmission Rates

Level	Transmission Rate (Mbit/s)
OC-1	51.84
OC-3	155.52
OC-9	466.56
OC-12	622.08
OC-18	933.12
OC-24	1244.16
OC-36	1866.24
OC-48	2488.32
OC-96	4976.64
OC-192	9953.28

can be allocated to services on demand. ATM is not restricted to a single data rate but is intended to be flexible for high-speed network growth, with higher data rate frame structures formed from the basic SONET rate. The SONET standard currently relies on optical direct detection at a single wavelength. OEICs could play meaningful roles in the implementation of integrated functions for the SONET transmitters and receivers if they could provide (1) better noise immunity than discrete components have, due to their on-chip interconnections (lack of stray capacitance, etc.); (2) more cost-effective functionality than discrete components, due to the integration; or (3) better reliability (e.g., due to alignment of a single fiber for several transmitters) (Fig. Cat-1). The SONET standard will provide network access at high transmission rates (including 155 Mbit/s, 622 Mbit/s, and beyond).

SONET transmission rates planned for the broadband network infrastructure initially will be 155 Mbit/s, 622 Mbit/s, 1.2 Gbit/s, and 2.4 Gbit/s. However, as the use of truly broadband services emerges, a growing demand will be placed on the broadband highways. This need may be met by increased utilization of the optical fiber capacity through the use of higher data transmission rates or through the use of multiple wavelengths. Multiwavelength systems are particularly attractive for expansion of capacity [7, 8], because they may utilize the same fiber links and electronic time division multiplexing and demultiplexing equipment used for single-wavelength systems. Furthermore, a multiwavelength approach does not suffer from increasingly stringent transmission tolerances, which would be associated with use of higher data rates (e.g., effects due to optical dispersion, impedance matching in the multiplexing electronics, power budget, optical reflections). It is for this future multiwavelength broadband network that OEICs may have their greatest impact.

3. ACCESS TO THE BROADBAND NETWORK

In this section we describe methods for accessing the broadband network, including examples of centralized switched access, using time-multiplexed channels, add/drop multiplexers, and very high capacity switches. We then discuss distributed access to the broadband highway, using local and metropolitan area networks (MANs and LANs). Finally we introduce Local Subscriber Loop Access. This discussion, which is principally focused on telecommunications networks and systems, is followed by a discussion of broadcast video distribution, from a head-end station to remote sites, typical of distribution in the cable TV industry.

3.1. Switched Access to the BISDN

Access to the broadband highway can be provided through very high capacity switches that can process the ATM cells being presented to the network by the user. An international agreement has been adopted, specifying that ATM cells should be used for transmitting the information in the broadband integrated services digital network (BISDN). This method allows asynchronous presentation of information to the network at a variety of different incident data rates, so that the backbone network is not sensitive to the type of service supported. The purpose of a packet switch is to route and transport a data packet from an input port on the switch to one or more output ports. ATM packet switches today are based on electronic switch architectures; however, the large capacity of optical fibers means that these packet switches could become information bottlenecks in the future, as large numbers of users access the network at high data rates. Although there are designs for very high speed electronic ATM switches, a possible alternative is to use an optoelectronic packet switch to avoid this switching capacity bottleneck. This alternative could become especially attractive if switched multicast services become widespread.

A number of possible optoelectronic switch architectures have been proposed [9–19] for both unicast and multicast designs. We illustrate this problem with a discussion of a proposal for an optical multicast packet switch fabric known as StarTrack [6, 19].

The optical ATM switch fabric is shown schematically in Fig. 3. This fabric is formed from two internal networks, a multiwavelength optical star transmission network and an electronic control track. Each input port has associated with it a unique wavelength and each output port has a tunable receiver. At the beginning (and end) of the control track is a token generator that generates control packets (tokens) and synchronizes the operation of the switch fabric. The essential operation of the switch may be understood as follows: Packets arriving on optical fiber input trunks are stored in memory at an input port. A unique transmission wavelength is associated with each input port. The switch is controlled in a cycle having two phases, a write phase and a read phase. During the write phase, input ports sequentially write information into the control tokens, indicating the output port to which a given packet is to be sent (thereby reserving that output port). The token is then sent to the output ports of the fabric, which read the tokens to determine whether they have been reserved to receive packets, and they tune their receivers to listen at the appropriate wavelengths. Finally, data at the input ports are transmitted in parallel to the desired output ports. Multicast

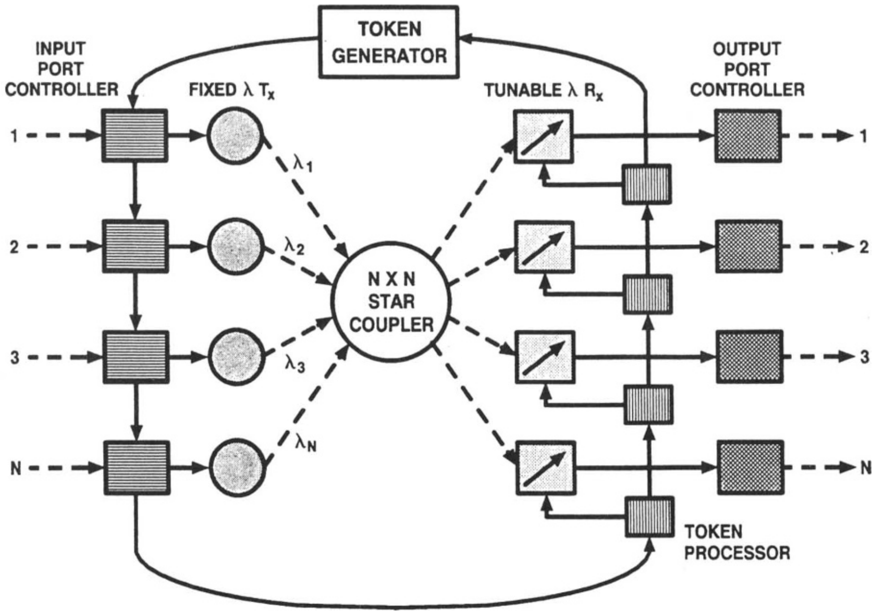

Fig. 3. StarTrack optical multicast switch. The StarTrack is formed from an optical star and an electronic control track. At the start of a cycle, input ports reserve their desired output ports writing into the token. The output ports read the token and "tune" their receivers to the appropriate wavelengths. This is followed by parallel transmission to the receivers.

transmission is easily accomplished because several output ports can simultaneously tune their receivers to the same input port wavelength. This switch fabric has a number of useful features, including easily implemented multilevel packet priorities and call splitting (partial completion of calls). Thus a 64-port StarTrack switch with a transmission rate at each port of about 2 Gbit/s could provide peak throughputs near 100 Gbit/s. Larger-capacity switches may be constructed from such StarTrack units.

In the StarTrack example, OEICs could play a decisive role in making an optical switch fabric competitive in cost and performance with more traditional electronic approaches. The optical switch fabric has the important potential advantage over its electronic counterparts that performing multicast operations is natural and packet duplication is not necessary. Thus, an OEIC (Fig. Cat-2) could implement the tunable StarTrack receivers with electronic selection from multiple fixed-wavelength receivers and incorporate an integrated wavelength demultiplexer (e.g., a miniaturized version of the design in refs. 20 and 21). It could further incorporate electronic memory buffers and "input/output port operations" such as packet accounting and control. This type of functionality could enable switch architectures like the StarTrack to be viable contenders with the next generation of electronic switch fabrics.

The performance of a StarTrack packet switch can be dramatically enhanced using multiple parallel token tracks (Fig. 4). In the multiple track StarTrack switch the input ports and output ports are divided so that each receiver needs to be tuned over only a fraction of the total wavelength range of the input ports. This significantly enhances the throughput performance of the switch (Fig. 5), while relaxing the constraints on the tunable receivers. However, this approach requires multiple tunable receivers at each output port and multiported buffer memories. The tuning time must be of the order of a packet transmission time (200–600 ns). Again, OEICs could be critical to the implementation of such a switch (Fig. Cat-3).

3.2. Distributed Access to the Broadband Network: LANs AND MANs

Data networking technology is in a rapid state of development. Local area networks (LANs) based on the Ethernet multiaccess standard at 10 Mbit/s

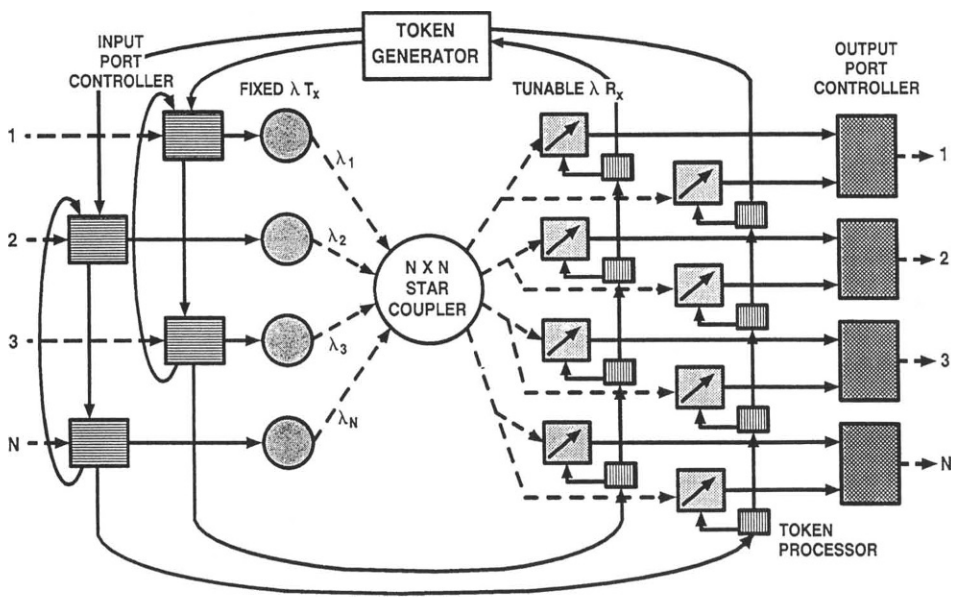

Fig. 4. Multitrack StarTrack architecture. An enhanced StarTrack with multiple control tracks. The receivers' required tuning range can be smaller than with a single track, and the switch performance increased because of the parallelism.

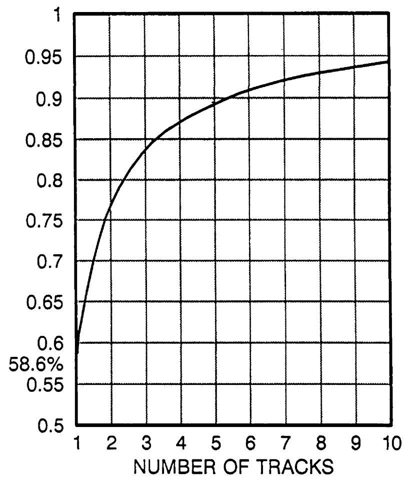

Fig. 5. Throughput performance of multitrack StarTrack. The theoretical performance of a multitrack StarTrack: performance increases rapidly with increasing numbers of control tracks.

are widespread. However, the Ethernet standard is not directly extendible to high data rates because its multiaccess protocol requires that the minimum packet duration be approximately twice the round-trip transmission delay, which requires very large (and inefficient) packets at high transmission rates. Data networks to support higher-speed LANs have been widely investigated and a standard has been adopted, the fiber distributed data interface (FDDI). The FDDI standard uses dual counterrotating rings to implement a 125 Mbit/s standard, based primarily on the use of multimode fiber and light-emitting diodes (LEDs), for compatibility with maximum internode distances of only 2 km. Again, the redundancy possible with OEICs could play a useful role, by providing replicated transceiver facilities at low cost for backup purposes. (An enhanced version of FDDI has been proposed, called FDDI-II, extending the data rate to about 600 Mbit/s, compatible with SONET rates.)

LANs can be interconnected to form metropolitan area networks (MANs), requiring more capacity and larger node distances than LANs can accommodate. A standard, distributed queue dual bus (DQDB) [22], has evolved for MANs that is useful in the 200 Mbit/s range (Fig. 6) for interconnecting LANs such as Ethernets or FDDI networks. The first offered broadband telecommunications service, SMDS (initially meaning switched multimegabit data service but today used with broader meaning), will be implemented on this platform. DQDB is based on two unidirectional buses that may be either open or loop structured. DQDB may be implemented with

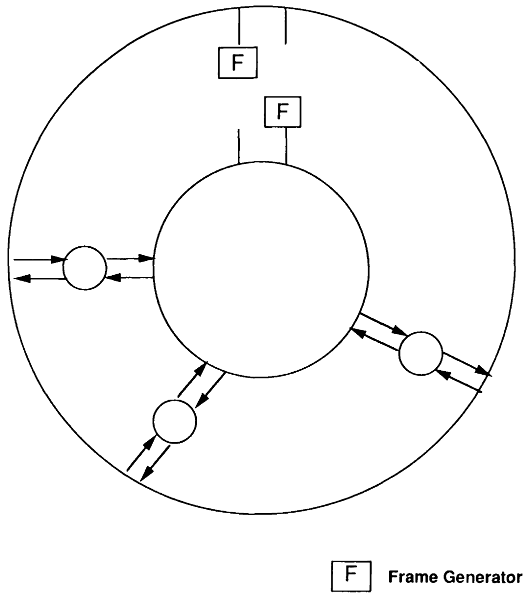

Fig. 6. DQDB architecture. The dual-bus structure with nodes access to each bus and frame generator is shown. The potential application for OEIC might be to enhance performance and reliability with redundant transmitters and more reliable connection to bus.

dual single-wavelength optical buses, where each port requires a transmitter and receiver pair for each bus. For LANs and MANs the network interface costs are critical. Thus, the opportunity for OEICs in this arena would arise principally from their potential for cost reduction compared with discrete components and from the potential reliability advantages due to integration.

FDDI and DQDB are examples of single-wavelength optical networks that do not tap the large bandwidth potential of optical fibers. In multiwavelength applications, the potential of OEICs really becomes clear. Not only do they provide redundancy or a reduced packaging cost and reliability advantage, they may even be required for any of these applications to be practical. An example multiwavelength MAN architecture is the ShuffleNet architecture, which was initially proposed by a group at AT&T Bell Laboratories [23, 24]. In the ShuffleNet architecture, users interface to a unidirectional multiwavelength optical bus through a set of network interface units (NIUs). In a simple case, each NIU has two fixed-wavelength optical transmitters and two fixed-wavelength optical receivers. The input and output ports of the NIUs are connected to the multiwavelength optical bus as indicated schematically in Fig. 7, which is assumed to have a total length of a few hundred

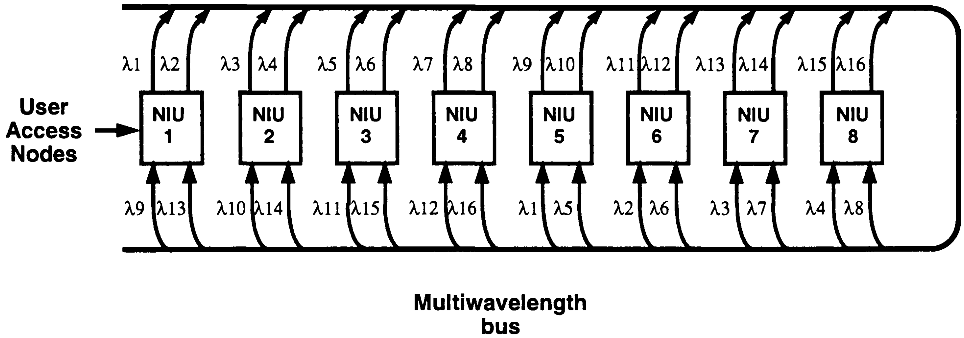

Fig. 7. ShuffleNet multihop network. The AT&T ShuffleNet LAN architecture. Users access the network interface units (NIUs), which access the multiwavelength bus at two wavelengths and receive at two different wavelengths. Each NIU incorporates a 2 × 2 packet switch. This idea can be explaned (with larger packet switches) to several wavelengths per NIU (©IEEE, 1990).

meters to a few kilometers. The data packet information loops around the NIUs, which filter the data by listening at their specific wavelength and passing data packets on, if necessary, regenerating them at their output wavelengths. The fixed-wavelength interconnects in this architecture may be arranged in a particular pattern to enhance the network performance. For example, in the ShuffleNet, the wavelengths are arranged in a "perfect shuffle" as shown in Fig. 8 for an eight-node network (hence the name ShuffleNet). At each node (NIU) this network has a 2 × 2 electronic packet switch to route the packet from the input to the output of the NIU if the received packet is not destined for this node. In this example, it is possible to get a packet from any input node to any output node in a path requiring three "hops" or less. Thus a packet from the input port at NIU-1 that is destined for the user interfaced to node NIU-3 may be transmitted on wavelength 2 to NIU-6, where it is received, and regenerated on wavelength 11 to NIU-3. A nice feature of this type of network is that alternative routes are available—for example, if a particular node is congested. In this example, a data packet may get from NIU-1 to NIU-3 by an alternative route: first use wavelength 1 to get to NIU-5, then wavelength 10 to NIU-2, then wavelength 4 to NIU-8, and finally wavelength 15 to NIU-3. The ShuffleNet is an example of a large class of multihop networks which have been extensively studied (see, for example, ref. 24).

The ShuffleNet combines the features of an optical star network (see the discussion of LAMBDANET later) and the features of a multihop ring network. Obvious extensions of this network involve larger electronic switches at each NIU and the possibility of multiple optical buses; for example, one

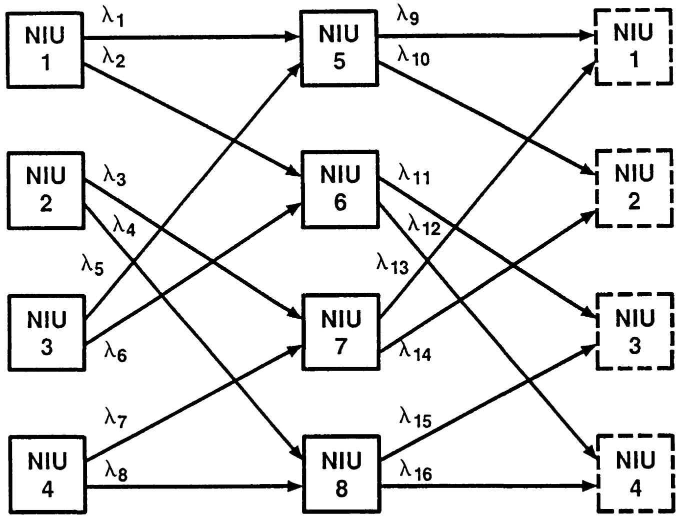

Fig. 8. Perfect shuffle routing. For routing in a ShuffleNet a perfect shuffle is chosen because of its theoretical performance characteristics. An advantage of this approach is that there are different paths to each node in case of congestion.

could consider 8 × 8 packet switches in a larger multihop network. Although such a network may have internal queueing delays, it has very attractive features from the viewpoint of OEIC application. The designs described involve optical transmitters at two (or several) fixed wavelengths and optical receivers that require wavelength demultiplexers or filters for receiving two (or several) wavelengths. Not only is the transmitter/receiver electronics a likely candidate for integration, but also the electronic packet switch at the NIU could be a candidate for inclusion in the OEIC. The maximum link distances in such a network are typically less than a kilometer and the transmission rates are only of the order of 1 Gbit/s, so reasonably low-power lasers could be used, and receiver sensitivity is not a serious constraint. Indeed, all the NIU functions could be envisioned as a single OEIC, which we will call the multihop OEIC (Fig. Cat-4). Note that for the multihop OEIC, the wavelength tuning could be performed using temperature tuning or some other relatively slow tuning mechanism. The multiwavelength optical bus needs to support a relatively small number of discrete wavelengths (less than eight) and direct detection can be used.

There are many potential variations and enhancements for the multihop architecture. For example, dynamic wavelength allocation allows the architecture to be varied so that wavelengths could be reused and real-time alternative routing strategies may be imposed. One example is the proposal for a scalable, modular, multihop wavelength routing network by Brackett [25]. This architecture (Fig. 9) shows network access nodes interconnected by a transparent optical network, with wavelength translation and wavelength routing. It directly addresses two important features, namely scalability (the ability to add more nodes) and modularity (the ability to add one node at a time). Networks with simple fixed-wavelength schemes may not always be easily expanded, particularly in small incremental units. A salient feature of this architecture is that the number of wavelengths is independent of the number of nodes. As shown in Fig. 9, the proposed network consists of access nodes (the square elements), wavelength routing cross-connection elements (the diamond-shaped elements), and a common network control to permit the dynamic rearrangeability. One way of realizing such an all-optical approach is to utilize acousto-optic switches. The rearrangeability allows the dynamic reuse of wavelength and bandwidth throughout the network to meet changing traffic, service, or performance requirements and to provide a robust, fault-tolerant network. Each network access node can transmit to and receive from several other nodes by selecting the appropriate wavelength.

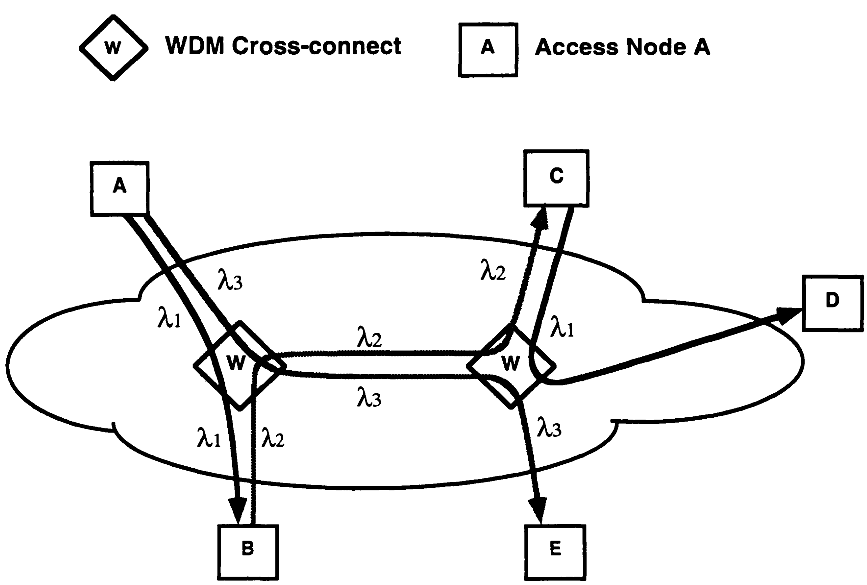

Fig. 9. Modular, scalable, multihop multiwavelength network. A MAN/WAN architecture that is both scalable and modular. The diamonds indicate the WDM cross-connects and the squares indicate the network access nodes. The internal portion of the network is all optical. This network decouples the number of wavelengths used from the number of nodes and features wavelength reuse, reducing the number of required wavelengths (©IEEE, 1992).

With a specific configuration of the wavelength routing cross-connects, this transparent optical transmission may extend over large distances. In the figure, wavelength 3 carries a one-hop signal (no intermediate detections or translations) from node A to node E, while a signal from node A to node C is carried in two hops, using wavelength 1 from A to B and wavelength 2 from B to C. Wavelength 1 is reused to carry a signal from C to D.

An expanded view of the network (Fig. 10) shows details of the transmitter and receiver elements, as well as the wavelength interchanging cross-connect portion of the network. This type of network provides several types of opportunity for OEIC technology (Fig. Cat-5), including transmitter arrays incorporating optical couplers and optical amplifiers and receiver arrays with on-chip wavelength multiplexing. Such a network can become practical only with optoelectronic integration, which is required to simplify the packaging, and alignment necessary for the laser transmitter arrays, the optical amplifiers, and the wavelength multiplexing and demultiplexing components. It is important that this network architecture is "transparent" in the

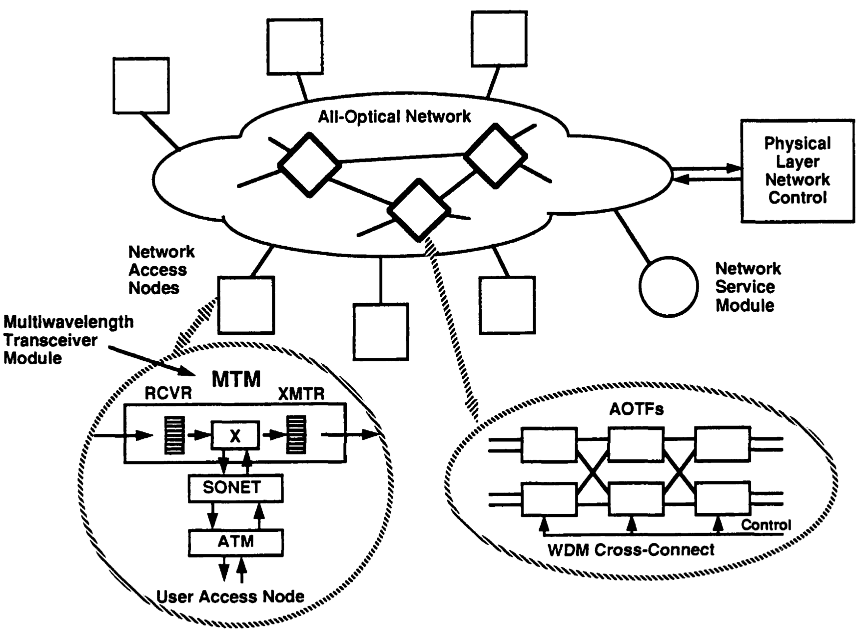

Fig. 10. Expanded view of modular, scalable, multihop multiwavelength network. An expanded schematic showing functions within the WDM cross-connects and within the network access nodes. The WDM cross-connects use acousto-optic tunable filters. The network access nodes perform various functions, including wavelength translation, using multiwavelength transmitter and receiver arrays (©IEEE, 1992).

sense that the wavelength routing that occurs does not depend on the detailed format of the data being transported. While the terminating equipment will have some dependence on the detailed format of the data, the switching of wavelengths will not.

The potential market for OEIC technology for LANs and MANs may be significant. As an indication of this market size, electronic interfaces to LANs currently number in the millions worldwide.

3.3. Fiber in the Subscriber Loop: OEICs for the Masses

In order to provide universal service, these broadband networks must extend to the individual subscribers' residences and businesses. As the network infrastructure evolves toward BISDN, optical fiber will enter the local business and residential markets or "subscriber loops." The optical fiber–based subscriber loops (fiber in the loop or FITL) will probably start as fiber to the curb (FTTC), with metallic drops from each optical network unit (ONU) serving several homes, initially to provide voice-grade service. This approach has already reached approximate cost parity (for installed first costs) with copper distribution networks for some applications, particularly in newly constructed neighborhoods. This cost parity is considered significant for the subscriber loop economics. Even though the optical fiber has more capability than the copper-based subscriber loop pairs, initial deployment will probably be based primarily on the economics of voice-grade services. Then, as *broadband services* start to penetrate into the subscriber loops, these initial systems may be simply upgraded for broadband access. Since high-performance optical systems are not required for voice-grade FTTC, these systems are more strongly driven by cost than by performance. In order to make these FITL systems cost-competitive with conventional copper loops for telephone services, very few fibers are installed (typically one or two fibers serving a small group of customers, approximately 4 to 64 homes). Initially such fiber systems are likely to require only discrete low-data-rate components. There have already been more than 100 field trials of FITL systems worldwide with more planned, and mass deployment is expected to begin in 1993 [26]. Eventually, systems with fiber extending all the way to the home (FTTH) will be developed, providing the full benefit of the fiber bandwidth and reliability.

An important problem will be how to upgrade the initial FITL systems for broadband services without costly installation of additional fibers. Many approaches are being investigated. Exactly how this is done will depend on the transmission rates required at the subscribers' premises, whether trans-