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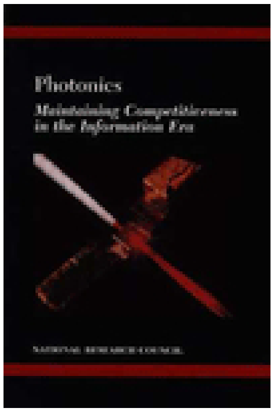

Photonics: Maintaining Competitiveness in the Information Era

Panel on Phototonics Science and Technology Assessment, Solid State Sciences Committee, Board on Physics and Astronomy, National Research Council

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Photonics: Maintaining Competitiveness in the Information Era

Panel on Photonics Science and Technology Assessment
Solid State Sciences Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Foreword

This report is a timely study of a critical emerging technology. While many readers of both the technical and the popular press have been transfixed by the yet-to-be-realized promises of superconductivity that have emerged in the past two years, optical technology has been building a technological armamentarium of proven science and advanced technology throughout the past three decades.

As the report correctly points out, many U.S. problems in this field stem from commercialization difficulties. Firms in other countries such as Japan have managed to apply photonic technology to useful, attractive, saleable products well before products from our own companies have been able to reach the market.

The Japanese, for example, have succeeded in focusing substantial technical and business attention on photonic technology and have earned a position of technical excellence. In a number of areas, Japanese optoelectronic technology is more advanced than the best available in this country. Development by the Japanese of the full potential inherent in photonics could threaten America's leadership in several areas of electronics.

This competitive situation is a central predicament, and the policy recommendations spelled out in the report are responsive to it. Both governmental and private actions could lead to new products using photonics. It is interesting to note that Japanese leadership in photonics has developed in consumer electronics—traditionally the segment least affected by government-based technology development efforts and most leveraged by private sector initiatives.

The promise of optical technology to bring improvements in bandwidth, information processing, information storage, and sensing to the consumer at substantially lower cost must be a major driving force for the commercialization of photonic technology in this country. If we are to advance as rapidly as our competitors, our experience must in considerable part be based on high-volume manufacturing of consumer products. Development of marketable consumer products based on photonic technology (such as the automotive application discussed in relation to demonstration projects) must be a keystone of national strategy.

Specialized equipment for the fabrication of photonic devices poses problems not only for laboratories and educational institutions, but also for industry. These problems mirror those found in the semiconductor industry, where many small equipment suppliers have been unable to stay in business throughout the economic cycle.

The report shows the need for complementary private and public sector initiatives in advanced technology development. There is a tendency to place emphasis on calls for broad government support of research in optical science and technology. In the final analysis, however, this nation's success or failure in photonics will rest not on governmental policies alone, but at least equally on the effectiveness of our commercial establishments in deriving benefit from the market opportunities presented.

Photonics is at the stage where high-temperature superconductor technology may be 10 or 15 years from now. If we are to be ready to take advantage of superconducting technology when it is properly developed, we should start by "practicing" on photonics.

The Council of the NAE, which commissioned this project, is grateful to chairman John Whinnery and the members of the photonics committee, as well as Donald C. Shapero, Robert L. Riemer, Jesse Ausubel, and other members of the staff of the Academy complex, for bringing this thoughtful and complete report forward for public debate and consideration.

ROBERT M. WHITE
PRESIDENT
NATIONAL ACADEMY OF ENGINEERING

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Executive Summary

Photonics is concerned with the use of photons to work with or to replace electrons in certain communications, computer, or control applications traditionally carried out by electronics. It is a key high-technology area, well established in long-distance fiber-optic telecommunications and rapidly growing in other areas of great importance to society. In this report the panel has concentrated on technical areas where the overall worldwide market for equipment approaches $400 billion per year. After reviewing the present status of each of these areas of technology, the panel identifies some of the key enabling technologies needing development or research. Because of the intense international competition in photonics, more general policy issues and recommendations aimed at strengthening the U.S. position in this industry are included in a final chapter.

TELECOMMUNICATIONS

The worldwide market in telecommunications equipment exceeds $100 billion per year. Fiber optics is firmly established for long-distance and moderate-distance point-to-point applications because of the large information capacity, the greater distance between repeaters, and the freedom from electrical interference. Starting with 800- to 900-nm (nanometer) light and multimode fibers in the 1970s, it has passed through three generations to 1300 nm light and single-mode fibers, with work toward 1500-nm light for the future. Enabling technologies identified as ripe for development include items related to fiber cables, high-performance transmitters, improved receiver modules, and several critical passive components. (For a full list with explanation, please see the section on "Enabling Technologies" in Chapter 2.) Technologies needing continuing research include coherent communication systems, components for wavelength-division multiplexing, low-noise avalanche photodiodes, optical amplifiers, external modulators, fibers with low loss and low dispersion over extended bandwidths, and practical integrated optics technologies. Much of the potential for future growth of fiber optics will come from local area networks, metropolitan area networks, and broadband integrated service digital networks. Needed developments for these fields must stress low cost and high reliability, with emphasis on easy access to the fibers and rapid movement toward monolithic integration. Continuing research is needed on optical switching components, optical amplifiers, and monolithic integration of both optical and electronic functions. Studies of network architectures are needed to make full use of the capabilities of photonic networks. Improved performance materials are also needed. Military applications for optical communications will require progress in all of these areas, with emphasis on high performance, resistance to radiation, and ruggedization.

INFORMATION PROCESSING

The market for information processing is also estimated at $100 billion per year worldwide and is predominantly electronics. Photonics offers the potential advantages, for both analog and digital applications, of almost limitless bandwidth, immunity from electromagnetic interference, and the easy use of side-by-side channels. These advantages have been used in synthetic aperture radar and other military analog applications and in commercial laser printers and scanners. Research and development needs for analog photonic systems include high-performance spatial light modulators, improved materials, and development of integrated optics modules. The present use of photonics in digital information processing is largely in the interconnections: computer to computer, and computer to storage input/output device. In this application area, computer systems are migrating from centralized single-processor centers to distributed multiprocessor complexes, including clusters of high-speed workstations. The interconnection network becomes a critical component in the performance of such a complex. High speed, high packaging density, and high reliability photonics—compatible with the electronic integrated circuit technology used in computers—has yet to be developed. Early technology connected box to box, with a potential for connection technology to go to board-to-board and chip-to-chip connections, where congestion in communication lines can limit system performance.

For hardware implementation, hybrid approaches to integration of the electronic logic and the photonic interconnects are promising for the near term, but monolithic integration is desirable for the long term. Work on heteroepitaxial materials, such as gallium arsenide (GaAs) on silicon (Si), is needed, and free-space interconnections should be investigated. There is much present interest in the question of all-photonic digital computation because of the fast response of optical devices, but this is still very much in the research stage. Research is needed on materials with larger optical nonlinearities, on new algorithms, and on new architectures to match the special characteristics of optical logic elements. Optical neural networks are being investigated as one approach to such architectures.

OPTICAL STORAGE AND DISPLAY

On-line, rapid-access storage is currently dominated by magnetic storage media and is a more than $50 billion per year industry. The archival storage industry is even larger, so that the information storage application is likewise greater than $100 billion per year. Optical storage media offer higher density storage by a factor of 500 times or so and thus offer potentially lower cost. Optical storage has been developed for archival storage where the information is written once by the user but can be read many times, and for read-only storage where replicas of a master disk are distributed to users. Optical storage for the multiple read and write system is only now beginning to be marketed. Japan is dominant in each of these technologies. A particularly promising application of optical storage is for an "interactive encyclopedia" in which a stored subject consists of words, pictures, and video movies to fully describe the subject. Enabling technology needs for optical storage include higher power lasers or laser arrays for the read/write heads, low-mass read/write heads, multiple-track reading and multiple-platter systems, and development of planar, self-aligned optical and optoelectronic elements for ease of manufacture. For the read/write applications, better reversible high-contrast materials are needed. Long-term research is especially needed on the reversible materials and on laser sources.

Displays convert electronic information to images and text for human viewing. The market of about $8 billion per year is dominated by cathode-ray displays, with plasma panel displays and electroluminescent panels also important. Photonic displays are those addressed by light beams, as when a laser writes on a liquid crystal cell. Such displays may have specialized uses but are not likely to displace existing electronic display technologies in the foreseeable future. Research should continue on new materials and new systems concepts that might lead to superior display technologies in the future. Multiple-beam addressing systems, the incorporation of holograms for three-dimensional displays, and improved resolution materials are some of the directions for such research.

OPTICAL SENSORS

Although the sensor market is modest ($3 to 5 billion per year) and highly fragmented, sensors provide the critical enabling technology for many large systems. Photonic sensors include fiber-optic sensors and focal plane arrays (FPAs). The former have been developed for sensing of temperature, pressure, displacement, magnetic fields, and other physical or chemical environmental parameters. They are accurate, can operate in harsh environments, and are compatible with optical telemetry. High-performance fiber-optic hydrophones, gyros, and magnetometers have been demonstrated for military applications. The barrier to increased use does not seem so much the development of appropriate technology as a need for standardization and demonstration of the advantages of well-engineered all-optical systems based upon these sensors.

Focal plane arrays using primarily charge coupled and charge injection device concepts have, in the last two decades, led to a revolution in data handling and processing of radiation-induced signals in the infrared and visible regions. They have been used in strategic and tactical military applications, ecologic monitoring, and such consumer applications as the miniature video camera. Although there is reasonable control over device parameters in visible spectrum FPAs using Si, there is more nonuniformity in the infrared (IR) devices using indium antimonide (InSb) and HgCdTe material systems. Continued research is needed on materials, interface improvements, and fabrication yield. Equally important is the need for software to support FPA data acquisition and processing. The long-term goal should be the development of algorithms and processors to permit the processor to fit in a volume comparable with that of the sensor unit.

POLICY ISSUES

Although much of the research in photonics was done in the United States, there is tremendous international competitiveness in developing high-quality, low-cost products; Japan is the leader in many fields. There have been many government and National Research Council (NRC) studies of the competitiveness issue (see Appendix C), and it is clear that much needs to be done if the United States is to maintain its competitive position in this and other high-technology areas. The greatest burden for responding to the challenge falls on industry. The federal government also has a role to play. The panel addresses the following suggestions to industry:

- It is essential to increase our industrial competitiveness in product development, manufacturing skills, and marketing.

- There must be continuing industrial effort in long-range research and innovation.
- The photonics industry should consider the advantages of an industry association that could help organize consortia to conduct cooperative research and address technical problems and policy issues beyond the scope of any one organization.
- Government contractors who receive a percentage of sales for their independent research should devote a sizable fraction to projects with a life span of 5 to 10 years.

The panel addresses the following recommendations to the federal government:

- Government should play a more active role in assessing technological opportunities and catalyzing development of technology in industry. Consideration should be given to a national photonics demonstration project. Federal support for research and innovation in photonics should continue.
- Regulation, antitrust, and tax policies must be considered carefully as they relate to industrial investment in the transfer of technology from research, in the development of manufacturing processes for low-cost/high-volume production, and in providing new services.

It is important that there be high-quality education in this important field and specialized equipment for universities active in photonics. In view of the expense of obtaining and operating such equipment, the panel recommends shared use of existing molecular-beam epitaxy (MBE), metallo-organic chemical vapor deposition (MOCVD), and other specialized microfabrication equipment. This should be encouraged by a variety of incentives, e.g., tax credits and supplemental grants. When requests for new units do appear to be justified, it should be determined that the institution is being realistic regarding the source of funds for proper operation of the equipment. Additional postdoctoral positions in the national laboratories should be established.

1

Introduction

For centuries, light has been an important tool in mankind's technological development, but a marked discontinuity occurred in 1960 with the demonstration of the laser. It was quickly seen that coherent light from lasers had potential application to communications, information processing, medicine and surgery, measurement, materials processing, and a variety of defense and scientific uses. These applications have been developed and are all now key elements of our technology, but the field is still a rapidly developing one with many new applications and improvements in existing applications possible.

Recent rates of change are especially remarkable in employing light in communications and information processing, which is often referred to as "photonics." This study is concerned with that field.

The proposal for this study stated:

> Recognizing the vital role of communication and information processing, the Board on Physics and Astronomy, through its Solid State Science Committee, proposes a 1-year assessment of the science and technology base for photonics. The purpose of this study on photonics will be to define the field and present a descriptive yet concise report on the scientific and technology needs and opportunities over the next 10 years.

The Photonics Science and Technology Assessment Panel was then set up with the following task:

> The Panel will address the following goals: (1) assessment of science and technology achievements to date; (2) identification of the areas of research that are currently ripe for development; (3) assessment of the prospects for their potential commercial applications; (4) assessment of the prospects for use of optical circuits in special

> applications where existing technologies are in need of enhancement such as image processing and recognition, sorting, radar-array signal processing, and machine vision; and (5) assessment of the relationship to other active technology areas such as microelectronics and software. The audience addressed will be broad, including policy makers at the federal government level, in industry, and in academia.

The field of photonics is extensive and is growing very rapidly. Its present commercial size is several billion dollars with potential for growth to more than $100 billion. It is generally viewed as one of the key technologies of the information age. Fields such as optical signal processing, storage, and communications also have considerable potential for military applications. Thus the field of photonics must be viewed as strategically important both commercially and militarily. A workshop was set up in April 1987 featuring presentations from a number of experts. Recognizing that the field was too large to cover in all its aspects, the panel chose the following subjects for study by subcommittees:

- Telecommunications (Chapter 2)
- Information Processing (Chapter 3)
- Optical Storage and Display (Chapter 4)
- Sensors (Chapter 5)

It is believed that these cover important applications that also include representative opportunities and problems for the future. Although the division is by field of application, it is clear that much of the advance will be through new materials, new devices, and integration of elements (integrated optics and optoelectronics). Thus the critical enabling technologies are key parts of each of the chapters.

In some applications, such as long-distance, high-data-rate information transmission, photonics is now the dominant technology. For other applications, it is clear that electronics will remain superior for some time. It is tempting for an enthusiast to envision most things now done by electronics as being replaced by all-photonic systems, but electrons and photons are different, with different transmission and control properties. Electronics is well embedded in several dominant areas of information processing such as computing and switching. Very high levels of integration of electronic circuits have been obtained in manufacture. Many of the control functions common in electronics have yet to be demonstrated with photonic circuits, although the potential is great. It thus seems likely that photonics and electronics will be complementary and that optoelectronic circuits, which combine the advantages of photons with electrons, will be important for the foreseeable future.

Of the policy issues considered by the panel, international competition in this field is clearly the most important to this country. It has become increasingly evident over the last few years that the countries that develop and use high technology in their industries will control the world economy. The United States has seen its lead in high technology slip in many fields. Although the NRC, the National Academies of Science and Engineering, and various government agencies have studied the competitiveness issue, a resolution of the issue has been elusive and it remains a critical matter. For photonics, the United States has been a leader in research and invention but is already a follower—or worse, an observer —in developing many of the commercial products of the field. The products from abroad are too often cheaper, more reliable, or of higher quality. The causes are too fundamental to be solved in any one field alone, but changes have to start somewhere. Chapter 6, "Policy Issues and Recommendations," includes some suggestions for such changes.

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6. Tsang, W.T., ed. 1985. Lightwave Communications Technology. Parts A, B, C, and D of Vol. 22 of *Semiconductors and Semimetals* deal with a variety of technical issues concerned with materials, devices, and systems.
7. See also a special issue of *Physics Today* devoted to optoelectronics, Vol. 38, No. 5, May 1985.
8. Popular magazines devoted to photonics include *Laser Focus, Photonics Spectra,* and *Lightwave*. See also Appendix C.
9. Many regular journals are concerned with photonics, and numerous review articles or special issues of other journals have reviewed the state of the art. Additional sources of information on photonics are listed in Appendix C.

2

Opportunities in Telecommunications

INTRODUCTION

Telecommunications is a big business. The market for network equipment purchased by companies in the United States that offer public network telecommunications services (e.g., local exchange carriers, long-distance interexchange carriers) exceeds $20 billion per year. When one considers the market for all telecommunications equipment in the United States, the number is substantially larger. The total world market is several times greater than the U.S. market. Thus, depending on what one defines as telecommunications equipment, the total worldwide market exceeds $100 billion per year.

Up until the late 1970s, telecommunications systems depended on advances in electronics to provide new capabilities, increased performance, and lower costs. Until that time, the media used for transporting information from place to place were copper cables and radio (including terrestrial microwave links and satellites). As fiber-optic technology emerged from the research lab and field experiments and entered large-scale deployment, the impact of this photonic technology on telecommunications was dramatic. For long-distance (> 100 miles) and moderate-distance (5 to 100 miles) point-to-point applications, fiber displaced copper cable and radio as the medium of choice. Today, the deployed U.S. base of long-distance and moderate-distance point-to-point fiber systems has an information carrying capacity (e.g., measured in equivalent voice circuits or in bits per second) far in excess of the total deployed base that existed in the late 1970s. Thus in less than 10 years, this technology has revolutionized many transmission aspects of telecommunication networks and has had a very big impact on the competing technologies by displacing them.

In this chapter the panel examines a number of different telecommunications applications environments and the potential of emerging photonic technologies to either facilitate those applications or displace existing technologies currently used in those applications.

TELECOMMUNICATIONS APPLICATIONS: DESCRIPTIONS AND TECHNOLOGY STATUS

Long-Distance and Moderate-Distance Point-to-Point Connections

In the late 1970s fiber-optic technologies emerged from the research and field-experiment phases and were deployed on a large scale in the transmission systems that interconnect telecommunications switching systems and provide the information-carrying capabilities used by customers attached to networks employing those transmission and switching systems. Fiber offered the ability to transmit large amounts of information over long distances without requiring as many repeaters to remove the effects of loss and distortion. This was in contrast to existing metallic cable and radio facilities, which have limited information-carrying capabilities for a variety of physical reasons.

The impact of fiber was twofold. The ability to transmit information for long distances without repeaters or with fewer repeaters (and without the interference and security problems of radio) made it possible to build transmission systems with lower initial equipment costs, lower right-of-way costs, and lower maintenance costs. The large information-carrying capability of fibers is a latent attribute that can be called on in the near future to economically transport video signals that can make use of that capability. Since fiber was first employed in long-distance and moderate-distance applications, the marketplace (purchasers of transmission equipment) has demanded products with ever-increasing information-carrying capability and ever-increasing distances that can be spanned without repeaters.

The technology has passed through three generations since the late 1970s, starting with multimode fiber and 800- to 900-nm wavelength light, then moving briefly to multimode fiber and 1300-nm wavelength light, and now using single-mode fiber and 1300-nm wavelength light. The promise of lower light losses points toward the use of 1500-nm wavelength light in the future. In addition, the promise of more sensitive receivers (and therefore longer achievable spans without a repeater) points toward the potential future use of coherent technologies.

Long repeaterless spans are important because of the costs of locating, powering, and maintaining repeaters, in addition to the cost of the repeaters themselves. This is particularly true in long-distance terrestrial and undersea cable systems. In undersea cable systems, reliability and power consumption are, in addition, more critical than in terrestrial applications. A figure of merit for point-to-point transmission is the product of repeaterless span and information-carrying capability. The product of repeaterless span and data rate in commercially available equipment has increased from 5 km × 45 Mbits/s in 1979 to over 40 km × 560 Mbits/s today. This represents an increase by a factor of over 100 in 8 years (approximately doubling every year) for deployed products. This progress is expected to continue. Commercial products operating at nearly 2 Gbits/s have been announced. In the laboratory, systems have been demonstrated with (simultaneously) data rates of several gigabits per second and repeaterless spans beyond 100 km, for a data rate times distance product more than 10 times that of the commercially available equipment cited above.

Local Area Networks

In the context of this report, a local area network is defined as a communications interconnection system deployed in an office, a factory, or a multibuilding campus (distances typically < 1 mile) to allow computing devices and peripherals to exchange information in electronic form via a shared networking facility.

Local area networks emerged about a decade ago in response to the proliferation of moderate- and low-cost computing devices (and peripherals) and the need to interconnect them. Early local area networks were based on copper-cable media (e.g., coaxial cable). Because local area networking is a relatively young concept, there is still much to be learned about requirements that local area networks should meet in various applications. For example, even the best choice for the physical layout of the local area network cabling and electronics is still not completely understood, although much has been learned as a result of early installations of various designs.

A number of alternative fiber-optic-based local area networks have been proposed, designed, or deployed in recent years. These have various physical topologies (star, ring, bus), various capabilities (peak data rate, delay, number of accessing computing devices that can be accommodated), and various target applications. The components used in these local area networks include many of the components used in point-to-point telecommunications applications plus some additional components unique to the local area networking application. Examples of these additional components are access couplers, which allow light to be partially added or removed from a fiber at an access point; star couplers, which allow light arriving at an input to the star coupler to be split amongst several outputs of the coupler; and optical switches, which allow remotely controlled reconfiguration of the network for maintenance or rearrangement of connectivity patterns.

Low cost and high reliability are required in local area networks with a large number of access ports on the network to which relatively modest cost-computing devices (e.g., terminals) can be attached. Since the computing devices to be attached might cost only a few hundred or a few thousand dollars each, and since there are more places to attach computing devices than there are attached devices themselves, each access port must be very inexpensive compared to the cost of the accessing device. Local area networks with many access ports require high reliability of individual components in order to provide acceptable maintenance costs and acceptable system downtime. Local area networks that have only a few accessing devices or accessing devices that are relatively expensive (e.g., minicomputers and specialized peripherals) can tolerate more expensive components, if that is the only alternative.

Metropolitan Area Networks

Metropolitan area networks, in the context of this report, are connectivity systems for allowing communication between geographically dispersed local area networks and isolated terminals (typical distances are 1 to 10 miles). They have characteristics similar to those of a local area network. Typically, information carried between points on a metropolitan area network can share transmission paths with other types of telecommunications traffic. Costs of optical components are not as critical in metropolitan area networking because of the larger numbers of computing devices sharing the use of those components (the local area network concentrates traffic onto the metropolitan area network). However, given equally good technical alternatives, the least expensive components will be selected. Because of the potentially large amounts of information traffic carried by metropolitan area networks, higher-speed components and wavelength/frequency multiplexing technologies are increasingly desirable. Metropolitan area networks are early versions of the broadband integrated service digital networks (for business applications) described in the next section.

Broadband Integrated Service Digital Networks

The concept of a broadband integrated services digital network (BISDN) is to provide a high-bit-rate communications transport capability to a community of unrelated users for voice, data, image, and video communications. It is the

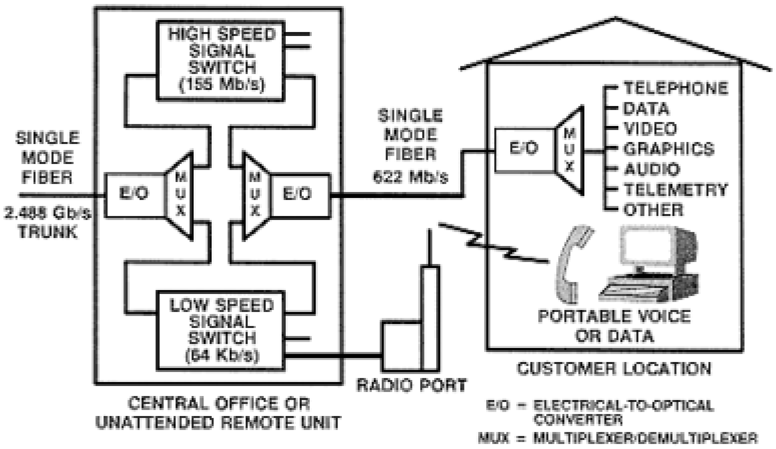

Figure 2.1
Setup for a typical office BISDN.

vision of the future. Fundamental to such a concept is bringing fiber to businesses and residences since copper wire cannot carry the required data rate. Figure 2.1 shows a typical realization of a BISDN. Various high- and low-speed digital signals are combined by electronic multiplexing in a central office or remote (unattended) switching unit and are converted to optical form for transmission to the customer over an optical fiber. At the customer's premises the optical signal is converted back to electronic form, and its various information components are distributed to appropriate terminals. There are now over 100 million copper-wire access lines in U.S. telephone networks. If I percent per year of these were converted to fiber, this would amount to a demand for millions per year of optical transmitters, receivers, and other optical components as well as millions of kilometers per year of fiber. If the installed cost of a fiber access line was initially about $3000 and declined toward $1000 as production volume increased and technology improved, then converting 1 million copper-wire access lines per year would represent a $1 to 3 billion market. If the changeover rate grew to 5 percent a year, then the market would be $5 to 15 billion in the United States alone. The total U.S. market (100 million lines) for conversion is more than $100 billion. Thus the BISDN marketplace represents a very important application for photonic technologies. Key to this marketplace will be low-cost fiber cables, low-cost transmitter and receiver modules, and possibly novel approaches to the distribution network architecture to reduce the need for active electronic components in the outside plant (in unattended locations). Also key to the timely deployment of BISDNs in the United States is an appropriate regulatory and long-term investment climate that will encourage the large capital investments required and will allow BISDNs to be deployed in an economically efficient manner. There is a worldwide race to develop the necessary technology.

Photonic Technologies Within Equipment

As telecommunications moves toward the higher data rates associated with BISDNs, the ability to perform functions such as multiplexing, switching, and internal component interconnects at these high data rates becomes a limiting factor in cost and practicality. Higher-speed electronic circuits consume more power, which creates the thermal management problem of keeping components from overheating. Higher-speed electronic circuits also experience bottlenecks in the flow of electronic signals between circuit elements because of the limited bandwidth of metallic interconnects, even very short-distance interconnects between circuit elements on a monolithically integrated circuit. A question often raised is whether photonic (optical) devices can help to resolve these problems in a way analogous to fiber-optic technology's opening up almost unlimited bandwidth in transmission systems.

Various scientifically interesting photonic components can perform a switching or routing function in the laboratory, and there has been much speculation as to how these components might revolutionize the capabilities of switching and computing systems. However, the large technological gap between these laboratory devices and practical systems needs to be filled by scientific breakthroughs as well as by engineering. When these gaps will be filled is an open question.

There are, however, some near-term possibilities. Very often it is the interconnects between components that represent the most troublesome engineering problem in equipment operating at high data rates. Here optical interconnects in the form of optical waveguides (fibers) on plug-in boards and backplanes, accessed directly by components with optical input-output capabilities, show much promise. Optical interconnects between plug-in boards or arrays of components based on free-space optics (arrangements of lenses and mirrors) also appear attractive. Fiber interconnects between backplanes are becoming increasingly popular.

Small numbers of incoming and outgoing optical fibers may be rearranged by interconnecting them with optical switching devices that act as a remotely controlled patch panel. Such remotely controlled patch panels have possible applications for protection switching, which allows a network of interconnected fibers to recover from a fiber or equipment failure, or for rearranging the connectivity pattern of fiber networks in response to the physical movement of users.

Photonic Networks

Today's telecommunications networks have architectures that evolved to conform to the capabilities of the technologies—copper cable and radio transmission systems, and discrete electronic components—available when these networks were being designed and developed. With the advent of fiber optics, advanced optical components, and highly integrated high-speed electronic circuits, one can ask whether a telecommunications network should retain the existing architecture and use modern technologies to substitute for older technologies or should adopt a new architecture tailored to derive the maximum benefit from the new technologies. New architectures that have been suggested tend to capitalize on the ability of fibers to carry very large amounts of information with very little marginal cost once a fiber is in place. They tend to push switching toward the edges of the network: large amounts of information are distributed throughout the network, and the desired information is selected, as needed, by the terminals connected to the network or by gateways at the edges of the network that stand between the network users and the network. These approaches often build on optical wavelength-division multiplexing (WDM) or optical frequency-division multiplexing (coherent techniques) to deliver these large bundles of information throughout the network. It remains to be determined whether these architectural concepts will be preferable to architectures with more switching internal to the network.

Military Telecommunications

Military telecommunications applications for fiber-optic systems closely parallel the commercial applications discussed previously. For example, there are fixed land-based applications for high-data-rate, long-distance, point-to-point links. There are land-based, shipboard, and airborne applications for local area networks for computer interconnects and for BISDNs to support combinations of voice, data, video, and other signals. Certain attributes of optical fiber systems have greater importance in military applications than in commercial applications. Among such attributes are immunity to electromagnetic interference, relative security from eavesdropping, spanning of long distances without electronic repeaters, and low cable weight. Military applications also impose additional requirements on fiber-optic systems, e.g., wider operating and storage temperature ranges; ability to withstand severe vibration, shock, and other mechanical stress; and robustness of system performance in the presence of multiple simultaneous subsystem failures. Many of these additional requirements are satisfied with appropriate packaging and other physical design measures as well as with appropriate system design, without any direct implication for the photonic devices. However, certain requirements place the fiber and photonic components in the critical path of viable applicability and lead to photonic technology challenges. An example is the design of optical fibers and cables that are resistant to radiation, can operate over a wide temperature range without excessive attenuation increase due to a phenomenon called microbending, are capable of sustaining high strains without breaking (e.g., for fiber guided missiles), and can withstand severe chemical environments (a requirement not necessarily more stringent than some for commercial applications such as oil well logging cables). Another example is the design of optical emitters and detectors that are radiation resistant and can operate in high-temperature environments. On balance, however, the requirements of the military applications for fiber-optic systems are being addressed successfully. The only key enabling technology to be emphasized, one that is needed for commercial applications as well, is a high-reliability optical transmitter and receiver module that can operate over standard military specification ranges of temperatures with failure rates of less than 1 per million device hours. For commercial applications low cost is also critical but should follow from high-volume automated production.

ENABLING TECHNOLOGIES

All of the important technologies that are required for successful exploitation of the markets identified in the section "Telecommunications Applications" can be divided into two categories: (1) technologies requiring continued or increased emphasis on development in the next 5 years so that U.S. corporations can maintain or strengthen their competitiveness in existing but evolving markets, or can ensure that they will compete successfully in emerging markets, and (2) technologies that are enabling but are underdeveloped so that increased or continued research is appropriate at this point. In this report these two types of technologies are referred to as enabling technologies ripe for development and enabling technologies requiring continued research.

Long-Distance and Moderate-Distance Point-to-Point Connections

Enabling Technologies Ripe for Development

- Fiber cables with low loss and low dispersion (variation of group velocity with wavelength) at 1.3-micron wavelength, and with low microbending loss and high strength. Note: to date the United States has demonstrated competitiveness in this technology, and there are several U.S. companies currently marketing high-quality, low-cost fiber cables. Continued development of manufacturing technology is needed to reduce costs in this increasingly competitive market.

- Fiber cables with low loss and low dispersion at 1.5-micron wavelength, and with low microbending loss and high strength. Note: U.S. fiber companies appear to be competitive in this emerging technology.
- Transmitter modules with high performance in terms of output power into an integral single-mode fiber, single-frequency (longitudinal mode) operation, narrow line width, low chirp (frequency shift under modulation), long lifetime in an unconditioned ambient temperature, high-modulation-speed capability, tolerance to elevated ambient temperatures for short durations without disruption of performance, and low power consumption. Note: although U.S. companies have thus far been able to produce transmitters containing lasers for systems deployed to date, the increasing performance demands of the marketplace combined with the generally acknowledged lead of the Japanese in laser technology suggest that escalated development effort will be necessary to retain U.S. competitiveness. It is believed that this is a development challenge rather than a research challenge. (In this context "development" focuses on manufacturing technology as well as on design for low-cost manufacturing.)
- Receiver modules with high performance in terms of sensitivity, dynamic range, bandwidth, and linearity. Note: although U.S. companies have thus far been able to produce receivers for their systems that result in reasonably competitive system performance, non-U.S. companies (e.g., the Japanese) have been aggressive recently in developing high-sensitivity, high-dynamic-range receivers that appear to outperform U.S. counterparts. Since much of the research in low-noise, long-wavelength avalanche photodiodes (APDs) and in low-noise amplifiers originated in the United States, it is suggested here that increased development effort is needed to retain U.S. competitiveness in this key technology.
- Passive components for wavelength multiplexing and demultiplexing and for related technologies such as transmitters with stable and predictable wavelengths. These are needed to deploy wavelength-multiplexed systems with moderate numbers of concurrent wavelengths.

Enabling Technologies Requiring Continuing Research

- Transmitter and receiver subsystems incorporating very narrow line width, single-frequency lasers for coherent communications systems (coherent detection).
- New types of ultralow-noise APDs.

- Components for advanced versions of WDM with very closely spaced optical wavelengths.
- Optical amplifiers suitable for providing gain over a wide wavelength range for multiple optical carriers in a wavelength-multiplexed system.
- Low-loss fiber cables having low dispersion over a wide range of wavelengths.
- Integrated optics technologies to reduce component counts and increase the reliability of coherent optical communications systems.
- External modulators for higher speed modulation of lasers.

Local Area Networks and Broadband Integrated Services Digital Networks

Enabling Technologies Ripe for Development

- Low-cost optical cables with easy access to fibers. Note: local area network and BISDN applications will require lower cost (per fiber meter) cables than will long-distance applications (see the sections "Local Area Networks" and "Broadband Integrated Services Digital Networks" above); however, it is assumed that U.S. companies that have been competitive in the long-distance market will remain competitive by investing in manufacturing engineering and equipment necessary to bring costs down as these high-volume markets emerge.
- Low-cost, high-reliability optical transmitter and receiver modules. Note: it is assumed that automated assembly will be critical initially and will be followed by increased use of monolithic integration and clever physical designs. This key enabling technology is ripe for development and represents a worrisome area in light of traditional Japanese leadership in low-cost manufacturing of electronic assemblies.
- Low-cost optical connectors, multifiber connectors, and optical couplers.

Enabling Technologies Requiring Continued Research

- Integrated optoelectronic devices to reduce parts count and lower costs.
- Optical amplifiers with gain over a wide wavelength range to make up for losses in passive power dividers and accumulated losses of couplers.
- Optical switching components and subsystems to eliminate optical-to-electronic conversions where feasible.

Photonic Technologies Within Equipment

Enabling Technologies Ripe for Development

- Low-cost, high-reliability transmitter and receiver modules for short-distance point-to-point interconnections between boards and shelves to replace metallic cable connections. Note: although a number of U.S. companies successfully market transmitter and receiver modules for point-to-point interconnections within equipment and between pieces of equipment, continued diligence to increase reliability and reduce cost is required as this market grows.

Enabling Technologies Requiring Continued Research

- Optical traces ("conductors") on circuit boards and backplanes to replace conventional metallic traces.
- Optoelectronic assemblies to interconnect to optical traces on circuit boards and backplanes (transmitter and receiver components integrated with electronic devices).
- Free-space optical interconnects.
- Optical transmitter and receiver arrays for parallel interconnects.

Photonic Networks

Enabling Technologies Requiring Continued Research

- Tunable optical transmitters and receivers.
- Optical amplifiers with gain over a wide wavelength range.
- Photonic switching devices and subsystems.
- Coherent communications technologies.

Military Applications

Enabling Technologies Ripe for Development

- Ruggedized versions of commercial technologies with increased tolerance to physical abuse (e.g., temperature range for storage and operation, vibration, shock, corrosive environments, and radiation).

Enabling Technologies Requiring Continued Research

- Ruggedized versions of commercial technologies indicated previously as candidates for continued research.
- Higher-performance versions of commercial devices (e.g., ultralow-loss optical fibers, higher-power optical transmitters, ultrasensitive optical receivers) that may not be practical for high-volume or widespread commercial deployment but that may be practical for specialized military applications with high tolerance to cost.

THE IMPORTANCE AND IMPACT OF STANDARDS AND MODULARIZATION

In commercial point-to-point telecommunications applications of fiber-optic technologies, network providers have procured various components of these systems separately. By taking advantage of standard or open interfaces (e.g., interfaces with publicly documented and stable specifications) between major components of a system, network providers can purchase optical fiber cables from one manufacturer, optical line and span-terminating repeaters from another manufacturer, and multiplexing equipment from yet another manufacturer. This approach allows more competitors to enter the marketplace, since potential competitors with specialized capabilities need not develop capabilities in all aspects of the system in order to offer products. This approach will likely be followed as BISDN (fiber to the home and business) procurements are made. It is likely that large-volume purchasers of local networks will want to have the option of procuring fiber cables separately from terminal equipment.

From a purchaser's viewpoint, this approach typically results in lower cost due to increased competition. From a seller's viewpoint, it is a two-edged sword. A seller offering a complete range of system technologies might prefer that procurements be made on a system basis so that fewer competitors are capable of making an offering. On the other hand, a seller who lacks one or more key technologies (or who does not desire to invest in one or more key technologies) would prefer the disaggregated procurement approach.

From a U.S. competitiveness viewpoint, disaggregation can prevent U.S. companies from being locked out of a large market because of weakness in one or more key technologies that individually represent only a small part of a much bigger system.

SUMMARY

Although fiber optics has become the dominant technology for point-to-point long- and moderate-distance telecommunications applications and has emerged as a multibillion-dollar-a-year business in the 1980s, the largest applications of fiber and related photonic technologies in local area networking, metropolitan area networking, and BISDNs are yet to come. As existing and emerging markets evolve, low cost, high reliability (quality), and high performance will become increasingly important. Whereas research and engineering that precede transfer of technology to the factory will continue to be important, increased emphasis on perfection of manufacturing processes (manufacturing engineering) will likely be critical to U.S. competitiveness in these markets in the future. Manufacturing success will require the close cooperation of people concerned with materials, devices, and systems. Certain key technologies ripe for development have been identified, all of which emphasize development of lower-cost, higher-quality versions of existing technologies. Numerous areas requiring continued research activity necessary to enable certain new markets or to reduce costs in existing or emerging markets have also been identified. The impact of standards and open interfaces on increasing competition and preventing particular technologies from becoming bottlenecks to competition in larger system procurements was also discussed. (Refer to Appendix D for additional technical data.)

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3

Opportunities in Information Processing

INTRODUCTION

At the heart of today's information society is the capability to use the enormous amounts of information we are able to send from one place to another. In using information, we filter, digest, consolidate, reorganize, add, and share; i.e., we process information before deciding to selectively retain it or send it to other users. All of this processing adds value to the information by making it more useful for various applications. In some cases, value is created by feeding the input information into a computer program that is designed to diagnose a condition or to predict or calculate a result based on such input.

The importance of information processing to our society is pervasive. It is vital for commerce, manufacturing, national defense, finance, education, transportation, environmental monitoring and control, efficient energy utilization, biomedicine, and all areas of scientific research. The worldwide market for information processing hardware and software, including computer systems, office automation equipment, and input/output (I/O) peripherals (but not including displays, data storage devices, communications equipment, and consumer audio, video, and personal products) is around $100 billion per year. The U.S. market share is around 55 percent, Japan's share is around 20 percent, and Western Europe's (Germany, United Kingdom, France, and Italy) combined share is 25 percent. This market is currently growing at around 13 percent per year and is projected to grow threefold by the year 2000.[1,2]

Today, almost all information processing is done electronically. Electronics brings an ever-enlarging range of applications to all segments of society.

However, the use of lightwave technology is an exciting extension of the electronic technological approach. While electronics combines speed, control, and precision with low cost, it has shortcomings in the bandwidth (amount of information) that can be carried on an electronic channel, and it suffers from susceptibility to electromagnetic interference. Although bandwidth can be effectively increased by implementing many side-by-side electronic channels, this approach requires that special attention be paid to isolating each channel from the others, resulting in increased size and higher cost. The result is that electronics suffers from a mismatch between the speed of handling information within a processor and the rate of sending information between processors or from a processor to an outside user. Thus there is a communications bottleneck inherent in electronics. Photonics offers some significant advantages that can greatly expand the performance capability of information-processing systems, such as nearly limitless bandwidth and immunity from electromagnetic interference. In addition, light is a natural vehicle for conveying information in many side-by-side channels, an aspect known as connectivity. These advantages are technically available, and the existing widespread commercial use of photonics in long-distance telecommunications systems has provided a seed from which the use of photonics in information processing might grow.

CURRENT TECHNOLOGICAL STATUS

Digital Technology

In digital applications, information is coded into binary form, where a voltage near one standard value represents a 1 and a voltage near another standard value represents a 0. A robust digital information system is one that can recognize the value of a bit (1 or 0), carry out logic operations on bits, and cascade bit-processing operations without a significant probability of making an error, thereby permitting numbers to be represented and manipulated over many orders of magnitude with ultrahigh precision.

Present-day digital electronics uses transistors both to carry out logic operations and to store the bits. Transistors for digital applications feature three terminals, standard system-wide voltages, and high gain with large noise margins. Three terminals ensure isolation of the output from the input; standard voltages are established by the system-wide bias voltages and system ground, not by the transistors themselves; high gain with large noise margins keeps the output values standardized despite the variability (10 to 20 percent) in the characteristics of the individual transistors. These features also combine to permit a single device to drive many other devices (fan-out) or many devices to drive a single device (fan-in), while maintaining the standard voltage levels. A robust circuit of transistors may be designed that allows for some degradation of voltages throughout the circuit while still providing bit values that are recognizable without a significant probability of error.

The silicon (Si) integrated circuit is the transistor technology of choice for general purpose digital electronics. The worldwide market for Si integrated circuits exceeds $20 billion.[1] Si microelectronics is low-cost because of mass fabrication methods. The simultaneous fabrication of many millions of devices on a large Si wafer, coupled with the lack of need to test, adjust, or repair individual devices (except for quality-control testing), ensures low cost. Si integrated circuits reliably carry out logic and memory functions despite the variations of the characteristics of individual devices that mass production entails.

Examples of successful, mass-produced Si integrated circuits are microprocessors and dynamic random access memory (DRAM) chips. Microprocessors can now be produced with circuit densities of 200,000 devices/ cm^2 operating at cycling rates of 100 MHz, while dissipating only 0.05 pJ/ switching cycle. This means that only 1 W/cm^2 of heat is generated at the maximum operating rate, a heat load easily dealt with using today's cooling technology. The cost of readily available DRAM chips puts the cost per device at less than 0.01 cent, packaged, tested, and ready to plug in. DRAM chips with 4 Mbits of storage are already being produced in pilot line facilities. These numbers are by no means static, with improvements being developed at a rapid pace.

These standards must be not only matched but also exceeded by alternative technologies. Devices that are going to compete with Si transistors must be able to reproducibly switch between two (or more) easily recognized states, must show gain if they are to be cascadable, must be immune to undesirable feedback from the output to the input, and must be inexpensively mass produced. Furthermore, in applications that call for rapid, repeatable cycling, the power dissipation must be kept within cooling capacity limits.

Turning to alternative materials for transistor electronics, a semiconductor that has received serious attention as a competitor for Si is gallium arsenide (GaAs). Since 1970, GaAs electronic devices that operate at higher speeds than Si devices have been fabricated and studied. The higher speed is a consequence of higher carrier mobility and lower intrinsic carrier concentration in GaAs. Other advantages over Si include potentially lower heat dissipation, higher temperature operation, greater resistance to ionizing radiation, and optoelectronic capability. However, there are disadvantages with GaAs that are rooted in present fabrication technology. Gallium arsenide is chemically less stable than Si, it does not form a stable self-oxide as a good insulator, it is harder to control the stoichiometry, and there are difficulties with fabricating reproducible contacts and interfaces. These features make it more difficult to realize low-cost, reliable, mass production of GaAs integrated circuits. Nevertheless, the advantages, particularly in speed, have enabled GaAs to find widespread use in certain select applications. For example, discrete devices such as radio frequency oscillators and amplifiers used for communications purposes are made from GaAs or related III-V materials. Current medium scale integration (MSI) GaAs technology can produce 1-kbit memory chips. For applications that require more speed than Si can provide, GaAs integrated circuits represent the most mature alternative and are commercially available.

The integrated circuit has clearly experienced widespread success. But as engineers have devised methods of placing more and more devices on a single chip and have figured out efficient ways to interconnect more complex chips, they have come up against serious weaknesses that limit further improvements in this technology. While the fastest Si transistors can switch in less than 0.1 ns, the fastest cycling time for a Si microprocessor is only ~ 10 ns. This limitation is imposed by the limited capacity of electrical interconnects on the chip. Electrical striplines have to be large enough to reduce attenuation of high-speed signals, and they have to be placed far enough apart to minimize cross talk. Other problems are ground loops and clock skew (the problem of synchronizing pulses distributed over many circuits). Equally serious is the problem of electrically connecting chips to other chips or modules of chips to other modules. The number of I/O electrical pads that can be fabricated on a chip is limited by the space they occupy and the power consumption they demand. Furthermore, the number of wires that can be bonded to these pads is limited by yield. In addition, the number of I/O connections that can be simultaneously switched is limited by the resulting rate of change of current (di/dt), a factor that produces noise in other parts of the circuit. The resulting I/O bottleneck, limited by the number of connections (connectivity) and the bandwidth of each connection, limits the throughput of a chip. These connectivity and bandwidth problems become even more difficult to overcome when dealing with interconnects at the board-to-board and processor-to-processor level. Taken together, these problems place practical limits on the performance of all-electronic information processing systems.

Analog Technology

While digital information processing is preeminent when precision over many orders of magnitude is required, there are many applications where analog information processing is used to handle large amounts of information at speeds that cannot be achieved with digital technology. These applications are already using photonic technology. Much progress has been made in specialized coherent processors that employ laser sources and utilize both amplitude and phase information on the optical beam.[3] In particular, specialized preprocessing of data is carried out in an analog fashion for imaging, mapping, pattern recognition, and spectral analysis, applications that are primarily of value for military systems. For example, synthetic aperture radar (SAR) utilizes conventional optical elements (e.g., lenses) for coherent optical processing to scan through large amounts of data or images previously recorded on photographic film. Another example is that of real-time, wide-bandwidth spectral analysis, in which the signal to be analyzed drives an acousto-optic (Bragg) cell that deflects a light beam that then passes through conventional lenses before being detected by a detector array. Bragg cells use traveling acoustic waves to create an index grating in a crystal that diffracts and shifts the frequency of an optical beam passing through the crystal. These cells are available commercially for operation in the gigahertz (GHz) range. In these applications, after the analog preprocessing, the data are digitized and handed off to conventional digital computers. Such analog processing is now carried out photonically rather than electronically, because the inherent coherent parallel processing capability of optics allows greater throughput, system simplicity, speed, and a high time-bandwidth product, while maintaining the necessary accuracy (dynamic range and resolution).

A commercial application of analog technology is in laser printers and scanners, where a laser beam is deflected across a target to be written on (for printers) or read (for scanners). A rotating mirror or a spinning holographically ruled disk is used for large angle deflection. For example, in laser printers that have a single laser as the light source, a multifaceted rotating mirror provides a raster scan, while the rotating photosensitive drum that captures the image provides an orthogonal scan. The laser diode is turned on and off, and the lenses keep the beam focused on the surface of the drum (Figure 3.1).

PHOTONICS LEVERAGE

As stated in the introduction, the potential leverage of photonics on information-processing stems from inherent advantages of optics, including ultrawide bandwidth, freedom from electromagnetic interference, connectivity, and coherent parallel processing capabilities. Fiber-optic technology featuring ultrahigh bandwidth and freedom from interference is already available commercially and can be harnessed for information-processing applications. Development activities in interconnection/communications that utilize these advantages do not require a change in current analog or digital processor architectures, thus allowing the technology to be more immediately useful in information-processing systems. However, the ultimate leverage of photonics will be exploited if pragmatic ways of capitalizing on the full parallelism of optics can be found. This calls for intensive applied research on new techniques and devices, including new processor architectures and optical nonlinear (i.e., logic) device arrays.[4]

The inherent advantages of photonics are now discussed in more detail. The leverage offered by the nearly limitless bandwidth of optics relative to

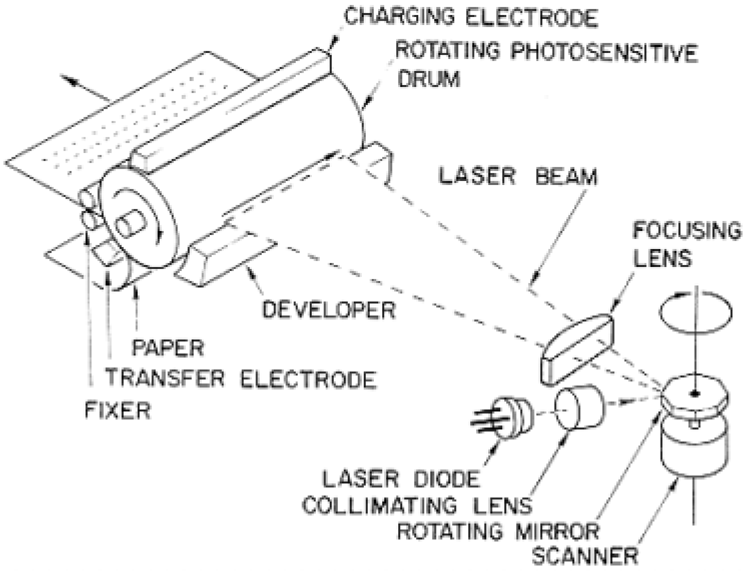

Figure 3.1
Schematic of a laser-electrophotographic printer showing a many-faceted rotating mirror for raster scanning and a rotating photosensitive drum that provides the orthogonal scan.

electronic technology can be viewed in many ways. Wide bandwidth implies capability for ultrahigh-speed channels, on the order of 10^{10} bits/s by today's research results. This means that the entire text of the *Encyclopaedia Britannica* can be transmitted over an optical fiber in just 1 s. This same bandwidth can be parceled out to many parallel users (e.g., 10^4 users at 10^6 bits/s with time-division multiplexing). Furthermore, light as a signal carrier offers the potential for increasing the information-carrying capacity from today's 10^{10} bits/s to more than 10^{14} bits/s.[5]

The immunity from electrical interference is another major source of leverage of photonic technology. Here, problems with ground loops, pick-up, and susceptibility to electromagnetic interference and radio frequency interference are significantly reduced because the optical carrier signal is generally at least 4 orders of magnitude removed from electrical interference frequencies. Such basic considerations are already leading to use of fiber optics rather than electrical cables to interconnect computers. Present advanced development activities are probing how far into a computer this optical interconnect approach will penetrate; many people feel that optically interconnecting printed circuit boards will become a widespread reality.

A closely related advantage of optics for interconnects is freedom from cross talk; i.e., two beams of photons can pass through one another with negligible interaction. The same is obviously not true for electrons flowing in crossed wiring. This advantage can lead to numerous interconnection advantages, especially with the use of optical elements such as lenses, holograms, and waveguides to direct beams.

Freedom from cross talk leads to another advantage of optics, connectivity. For example, a lens can transmit a large spatial array of optical signals through free space onto a matched array of receivers. The resolution is limited by diffraction effects, and one may easily conceive of transmitting millions of parallel signals using 1-micron wavelength light, f/1 optics, and source and receiver arrays having cross sections of centimeters. Implementing the equivalent connector in electronics is inconceivable.

Finally, freedom from cross talk leads to the last important leverage point for photonic technology, coherent parallel processing capability. For example, by passing a coherent beam of light from an object (e.g., a photographic plate) through a lens, one obtains, at a particular location, the spatial Fourier transform of the input. This important signal-processing transform dissects the input image into spatial frequency components. The lens is the sole element responsible for this parallel processing transformation, whereas to do the equivalent operation electronically would require a relatively large processor and numerous interconnections and switches. Powerful optical analog processing of this type is already being harnessed in practical systems, as described under "Analog Technology" in the "Current Technological Status" section.

AREAS RIPE FOR PRODUCT DEVELOPMENT

Digital Interconnect Technology

As pointed out above, progress in electronic digital computers is being limited by communications considerations. The fastest transistors switch in 5 ps, whereas the fastest systems run with a cycle time of ~ 5 ns. The source of this 3-order-of-magnitude disparity can be traced to communications constraints such as bandwidth and connectivity. Photonics can ease these communications constraints through the use of optical interconnections exploiting the large bandwidth of optics. Optical fibers are already being used to provide high-speed, computer-to-computer communications. Several computer manufacturers are, or soon will be, using optical fibers to connect their centro processing units and their storage systems (e.g., disks and magnetic tapes). Some manufacturers are already using optical fibers to interconnect modules within their processors. The evolution of this process is illustrated in Figure 3.2.

In assessing what is ripe for development in photonic interconnect technology, it is important to note that there are distinct differences in photonic technology needs for telecommunications and information processing. These

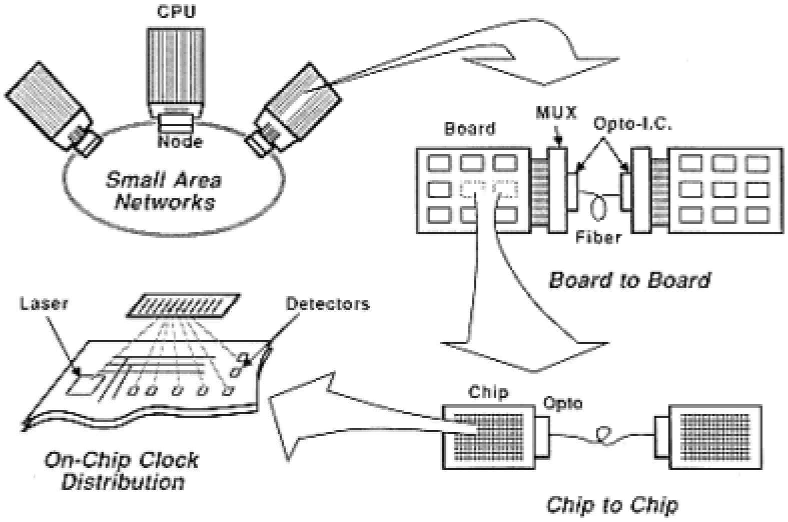

Figure 3.2
Scenario for the evolution of optical interconnects within computing systems.

differences stem primarily from the short distances (< 1 km, usually < 100 m) of information-system interconnection links, where the emphasis is on multiple parallel channels, many components, and affordability. Furthermore, photonic devices for information processing systems must be compatible with high-packing-density integrated circuit processing and package operating temperatures. Long-distance telecommunications optoelectronics is dominated by indium phosphide (InP)-based lasers and detectors because they operate in the spectral region (1.3 to 1.5 micron) where fibers have lowest loss and highest bandwidth (i.e., low dispersion). Since the wavelengths emitted by these InP-based sources are not effectively detected by Si detectors, the long-term ability to form totally integrated interconnection circuits is severely limited, as will be discussed further. On the other hand, GaAs-based sources, which emit at shorter wavelengths (approximately 0.85 microns) and are compatible with optical fiber characteristics for the great majority of applications in information-processing interconnects, can be effectively utilized with Si detectors. In light of the relatively well-developed GaAs materials growth and electronic circuit technology and the development of inexpensive sources for the commercial market (e.g., compact disk and laser printers), it is inherently reasonable to concentrate much of the photonic product development effort on GaAs technology.

One important area is the fabrication of components that provide both electronic and optoelectronic functions. Both hybrid and monolithic approaches show promise for this purpose. In the hybrid approach, optoelectronic chips are mounted along with electronic circuits on a common board. The advantage of this approach is that present and future yield and reliability of individual components can be maximized separately. Since envisioned interconnection applications will require relatively few connections between the electronic and photonic devices, economics will favor this approach for the relatively near future. Both present and advanced hybrid schemes should be further developed with emphasis on utilizing electronic packaging advances and reducing cost, especially in the attachment of multiple fiber pigtails to a single module. In this hybrid approach, one could imagine InP- as well as GaAs-based modules being developed, but for reasons cited previously regarding cost and Si compatibility, it is felt that GaAs is the appropriate material system for information-processing product development.

While hybrid components can provide the functionality desired, the scaling of production for large-volume applications and the use of photonics in a broader class of information-processing applications will require the development of monolithic circuits. These devices, referred to as optoelectronic integrated circuits (OEICs), could be formed in GaAs and would take full advantage of the state of development of GaAs electronic integrated circuits and optoelectronic components (Figure 3.3). The OEICs that could be most effectively developed today include detector/amplifier/multiplexer arrays. Circuits involving sources could also be pushed to the product level, but for reasons involving heterojunction materials compatibility between laser/LEDs and electronic circuits, further development will be necessary. These issues are

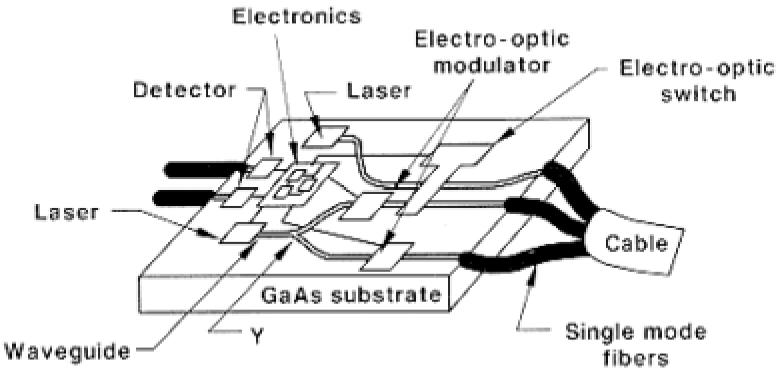

Figure 3.3
Schematic of a model optoelectronic integrated circuit (OEIC).

further discussed in the following section, where areas of sustained research are described. Closely related components that are, however, ready for product development are individually addressed laser arrays and detector arrays.

A technological driver for incorporating OEICs into existing computer architectures comes from the potential for reduction in power requirements and power dissipation. Arguments have already been advanced for the increase in communications bandwidth offered by an optical channel over an electrical channel. But even with the same bandwidth, optical interconnects would lead to a reduction in the drive power requirements for the I/O connections when compared to that required for electrical lines that need to be terminated to prevent reflections. Thus, when power requirements are a limiting factor, optical interconnects have an advantage for chip-to-chip communication at data rates of around 100 Mbit/s or higher.[6]

Analog Technology

Advances in analog optical processing in many cases will be linked to advances in photonic devices. For example, a spatial light modulator (SLM) provides the equivalent of real-time film or image planes and can be electrically or optically addressed.[7,8] Devices that are reliable, economical, and provide at least TV frame rates are under development at a number of companies. The SLM is a key component that will greatly add to the capabilities of analog optical processors and should receive accelerated development. The SLM will improve the practicality of vector-matrix multipliers and other optical analog information processing systems that provide enhanced real-time processing. Advances in two-dimensional detector arrays (already commercial products) will also enhance the performance of such systems.

Guided-wave or integrated optic devices are also attractive for analog processing. These structures consist of optical circuits on a chip (analogous to electronic circuits or to planar versions of bulk-optic circuits) that provide high speed, high reliability, potential low cost (due to batch processing), and low drive power.[9] Impressive laboratory and developmental demonstrations have been made in information processing. Examples of their use include forming a monolithic spectrum analyzer, a high-speed (gigahertz) analog-to-digital converter, and high-speed modulators for optical-microwave applications (e.g., fiber-optic-based phased-array radar signal distribution). These devices, usually formed in lithium niobate ($LiNbO_3$) or GaAs, are just becoming commercially available and have applications in telecommunications (switching) and sensors (gyros), as well as in information processing.[10]

AREAS APPROPRIATE FOR SUSTAINED RESEARCH

This section first addresses research areas that are extensions of those discussed in the previous section, dealing with devices and systems for interconnect technology and analog information processing. Then a discussion is presented of devices and architectures that have as their ultimate goal all-optical information processing.

Digital Interconnect Technology

In the area of OEICs, sustained work is needed, especially in the area of light-emitting chips. The development of low-cost, high-yield OEICs with lasers, LEDs, and/or modulators is a challenging area because the optoelectronic and electronic circuits have quite different materials and processing needs that complicate device fabrication. Many applications require extremely low-threshold (< 1 mA) lasers and/or surface (rather than edge) emitting lasers. While impressive research results have been achieved in all these technologies, much work remains to be done. An attractive alternative to forming on-chip lasers or LEDs is to form on-chip optical modulators. In many cases, this can reduce the drive-power requirements, simplify the geometry, and simplify circuit fabrication.

A closely related area that should be supported is the growth of hetero-epitaxial material such as GaAs on Si or GaAs on InP and formation of high-quality devices in this material. GaAs/Si technology is particularly exciting for information processing because it carries the integration ideas described previously several steps further (e.g., formation of a GaAs source, GaAs multiplexer, and Si capacity-coupled metal-oxide silicon (CMOS) circuit). The research status of the technology today is that while, in only a few years of work, electronic circuits in both Si and GaAs are fairly comparable to those formed on conventional substrates, the fabrication of lasers on GaAs/Si is at quite an early stage of development (e.g., short lifetimes comparable to early 1970s results on GaAs substrates).

With each of the above technologies, the use of free space for interconnection, rather than guided wave media (e.g., optical fibers or polymer waveguide circuit boards), should be investigated. Success in this area could be particularly valuable in interconnecting two-dimensional laser and detector arrays and in parallel connections between very large scale integrated (VLSI) circuits or printed circuit boards.

As mentioned previously, optical fibers are being used to connect city to city, computer to computer, in some cases board to board, and eventually chip to chip. Even gate-to-gate connections with optical fibers are being contemplated. There are several difficulties associated with this evolutionary approach that further research might help to overcome, thereby accelerating the introduction of this new technology. One difficulty is that this evolutionary approach takes advantage only of the bandwidth of optics and not the connectivity. The retrofitting of one technology into architectures optimized for another puts optics at a disadvantage. Compatibility issues limit the performance of optics to that of electronics and thus compromise its viability. Economic issues force optics to compete directly in terms of costs with other wide-bandwidth interconnects such as coaxial transmission lines.

One of the great unexploited advantages of optics is its connectivity. A lens can easily handle a 100 × 100 array of communication channels, each with more than a thousand times the capacity of a microwave link. The equivalent 10,000-pin connector would be very difficult to implement in electronics. Research should be carried out to find architectures that utilize all of this connectivity.

Analog Technology

In the area of analog optical processing, several devices are under study that should be given additional support. High-performance SLMs are attractive. These devices have potentially high frame rates and signal clocking that is particularly attractive for signal processing applications. Holographic optical elements and advanced SLMs could also provide means for optical interconnects.

Materials and Algorithms

The need for additional research in materials for photonics must be emphasized. Many of the devices already described would be more attractive if they were made from materials having higher electro-optic/acousto-optic/nonlinear optic figures of merit than those currently available.[11] Research in algorithms is equally important. Available devices will be even more useful if algorithm research intensifies its focus on utilizing the bandwidth, freedom from interference, connectivity, and coherent parallel processing capabilities of photonics. In addition, increased interaction between algorithm and device researchers could lead to invention of devices with special characteristics that algorithm developers request.

Digital Optical Devices

The ultimate benefit of parallel photonic processing could occur if practical optical logic could be developed.[7] This would minimize the conversion of information between electronic and optical formats. Present research in optical digital computing concerns the speed, power requirements, and noise margins of optical logic devices. It is clear that there are optical nonlinearities that react in the order of femtoseconds; the question is, how can they be practically exploited? Research efforts are aiming at developing better materials, especially those that would have larger nonlinearities, reducing the optical power requirements through the design of better devices, and exploring better ways of cooling. One direction of device research is to exploit the properties of semiconductors and microelectronics fabrication techniques. One promising optical logic device is based on a photodiode and an electro-optic modulator (Figure 3.4). Another promising device is a semiconductor optical resonator.[12] Semiconductor-based optical logic gates have the potential to compete with transistors in terms of very high speed and low power requirements, but there is much research and development that needs to be done to make them practical. Organic polymers have been shown to have interesting nonlinear and electro-optic properties. Much research is now going on in this field and should be continued.

Another important direction in optical digital information processing involves neural networks, a concept based on analogies to the central nervous system. Synthetic neural networks are being implemented both in electronics and in optics.[13,14] The basic approach models the behavior of a neural network by using a connection matrix between an array of inputs and an array of outputs and nonlinear feedback to the inputs from all of the outputs to modify the strength of the connections. This approach is being applied to pattern recognition and optimization problems. In the case of pattern recognition, a neural network can be made to automatically learn to distinguish between various patterns without the need for programming. In the case of optimization, these networks will search in parallel for a minimum in a multiparameter space. In this application, a significant advantage of optics is connectivity.

CONCLUSIONS

Photonics will have an enormous impact on information-processing technology. The more conservative, evolutionary pathway is to find ways for photonics to penetrate as far as possible into the interconnect technology of information processing. Such a pathway will enhance, by many orders of

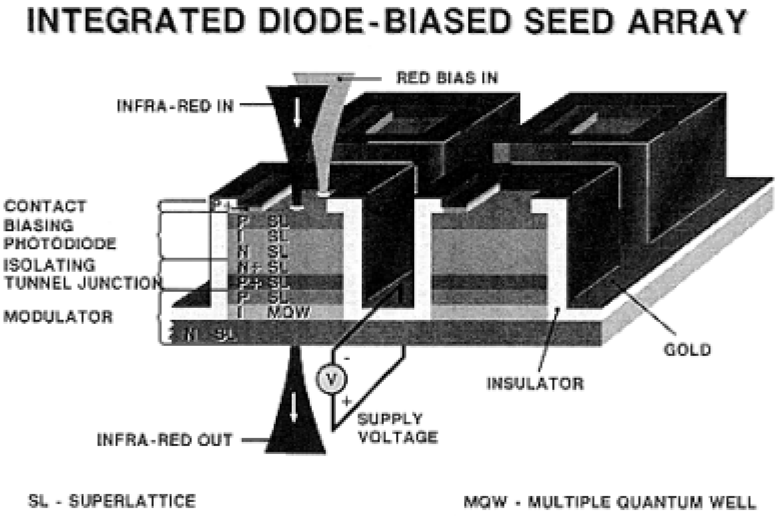

Figure 3.4
Three-dimensional schematic of an array of three-terminal optical logic devices. Each device consists of a photodiode, which absorbs the red bias input light, and a modulator (self-electro-optic effect device, or SEED), which has its infrared transmission controlled by the photodiode.

magnitude, the speed of handling and the density of packing information. This route is already having a practical impact at the machine-to-machine level. The more daring, revolutionary pathway is to replace electronic logic and memory devices by photonic devices and devise new architectures to take fuller advantage of the leverage of photonics. This pathway offers the tantalizing, long-term prospect of far more powerful information-processing technology but must be considered speculative until practical optical logic devices are developed.

These visions demand that photonics research and development be pursued at a vigorous pace to keep the United States at the forefront of information processing science and technology.

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4

Opportunities in Storage and Display

INTRODUCTION

Optical storage and display subsystems are used for input and output of data in information processing systems. Optical printers, which use optical beams to write on drums that transfer the image to the paper, are also part of the input/output subsystem but are not treated in this report.

There is already a large U.S. industrial and military market for these optical subsystems, but they also have a strategic importance for future information-handling systems. As information-processing systems grow in complexity to handle an ever-broader range of applications as well as more sophisticated applications, the demand to store massive amounts of data and to display and print large amounts of data becomes critical. The optical technologies used in these subsystems promise the capability to store and display more information than their mechanical, electronic, and magnetic counterparts. Therefore, having a strong technology base in these optical and optoelectronic materials and devices is potentially critical to having a leading-edge information-processing system.

The word *data* is to be interpreted in this section in its broadest sense, that is, information relating to entertainment, culture, education, and business as well as the more common scientific connotation of the word. Thus these information systems affect virtually all human activity.

OPTICAL STORAGE

Importance of Optical Storage

Measured in the hundreds of billions of dollars, information storage is an industry that is vital to this country's military, cultural, and economic well-being. One type of storage, archival storage, is dominated by printing on paper (95 percent of the words written are on paper). The other type of storage is on-line, rapid-access storage, which is currently dominated by magnetic storage media such as tapes and disks. On-line storage itself is more than a $50 billion per year industry and is growing at a rate of about 15 percent per year. The long-term trend, as cost permits, is to store all information electronically on-line because of the inherent ease in accessing, manipulating, and disseminating the information. This chapter will thus emphasize on-line storage applications.

Optical storage media store information more densely than their magnetic counterparts and thus potentially at lower cost. Therefore optical storage technology could displace large segments of the magnetic storage market. Optical storage also has the potential of storing information much more densely than paper and thus could also displace this market segment, although in the near term optical storage technology is too expensive for many archival applications.

In computer data storage, for example, an optical disk can store 500 times more data than a floppy disk of comparable size. For high-speed data access, an optical disk can store 50 times more data than the competing magnetic rigid disk. With "jukebox" configurations where the disks are interchanged on a disk reader, the storage can be greatly expanded at the expense of access time. A more detailed description of this application has been given by Chi (1981).[1]

In the area of archival storage, one optical disk is capable of storing the entire *Encyclopaedia Britannica* of 43 million words and 24 thousand pictures. Ten optical storage boxes could store all of the information currently contained in the Library of Congress. This type of system has been described in detail by Bartolini (1982).[2] In the entertainment/arts field, the compact disc—an optical disk—is already replacing the phonograph record. In this case, the larger storage capacity coupled with digital encoding has been utilized to improve audio fidelity.

The exceptionally large storage capabilities of optical media make possible a third, unique application based on combining digital and video information on the same disk.[3] As an example, consider a future "interactive encyclopedia" where a stored subject consists of words, pictures, and video movies to fully describe the subject, complete with user-activated cross-references or elaboration capability. This application today is a $100 million per year industry that is projected to be a $1 billion industry by the 1990s. Besides having an economic impact, this technology could lead to new concepts in learning, literature, or the arts, that go beyond what is available in a written textbook. For example, the "interactive novel," which allows its reader to select from many potential plots and thus to take part in the story, is made more feasible with a large, quickly branchable, storage medium such as optical storage.

Since the storage of data is so critically important in today's world and since future generations of data storage are likely to include optical storage, the United States must gain and maintain a leadership position in optical storage technology. This critical need is amplified even further when one considers that optical storage can displace many types of storage technology in various fields, from computers to literature to audio/video. As with many of the optical technologies, the dominant development activity appears to be in Japan.

Storage Systems

Storage systems can be divided into three types. The first is the multiple read and write system, currently a $70 billion per year industry that is dominated by magnetic media. Optical storage systems of this type are under development at many major computer and communications companies worldwide.[4] The second type is archival storage where media are written once by the user but can be read many times. Today's market is dominated by magnetic tapes, micro-film, and printed paper. The audio and video disk technology has already been reengineered in Japan and introduced into this storage market. The third type of system is the read-only system, where replicas of a master disk are distributed to users. In this case, only preexisting data are available to the user, who cannot generate data on this system. This market is immense and difficult to quantify as it includes photographic film (including movies), phonograph records, and printed paper. As mentioned above, optical storage has penetrated the audio application segment of this market and is starting to penetrate the printed paper segment. For the read/write applications, high storage density and data access speed comparable to those of the magnetic hard disk are key technical requirements, whereas in archival storage applications, the cost and permanence of the stored information are critical.

Technology Elements

An optical storage system consists of a number of key technology elements. These are the storage media, the reading and writing head, and the electronic interfaces and system design and software.[5,6] As shown schematically in Figure 4.1, semiconductor lasers are used as a source of light that is focused onto a very small spot on the optical storage media. The small spot causes a material change when the information is to be written. The spot is read by a change in the light reflected off the small spot (of the order of 1 micron in size). The spot

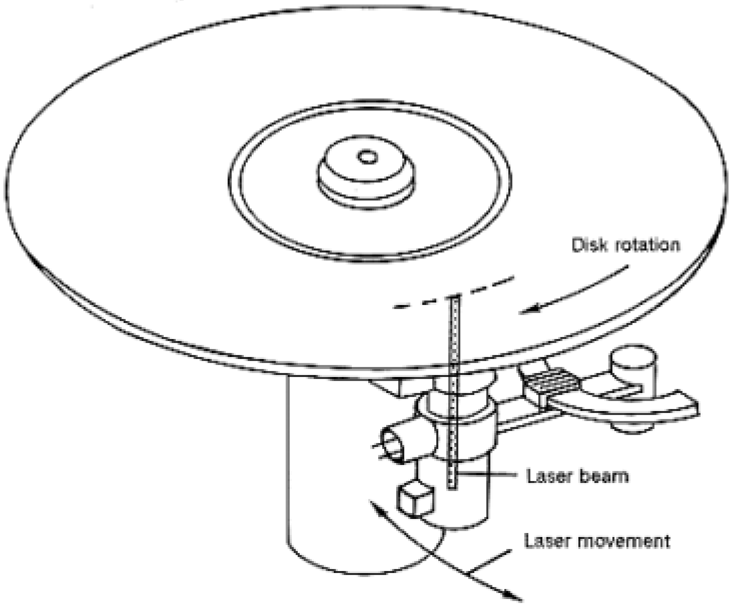

Figure 4.1
Diagram of optical storage system. The same laser may be used for both reading and writing.

sequence is converted to valid data or information sequences by the storage system protocols and sent to the data processing system or to a specialized "librarian" computer.

Media

There are a number of different materials for recording these dots of information. Table 4.1 lists some of these materials, the storage processes, and the relative advantages of each. The main approaches used today are ablative for archival storage and phase change for read/write writing, coupled with magneto-optical readout. Key issues in the media today are the read and write optical power required, media lifetime, and media cost. Current methods for writing information on optical disks use the laser as a heat source for removing small spots of material (the ablative process) or for causing a phase change in a small spot of the material. The photonic nature of the laser beam is utilized only in that the light wavelength sets the limits on the size of the written spot. Because of the heating requirement, high-power lasers (of the order of 50 mW) are critical for the writing process. The reading of optically stored information is based on a change in reflectivity or a change in polarization of the reflected light; this process requires less laser power, only enough to obtain an adequately noise-free signal.

Table 4.1 Various Optical Storage Media and Characteristics

Type	Storage	Advantages	Disadvantages
	Read-only		
Injection molding	Pit formation	Stability Low replication cost	High mastering cost
	Write-once		
Ablative (Te alloy)	Pit formation	Sensitivity Most developed Data permanence	Optical write power Potential for bit error
Ablative (dye polymer)	Bubble formation	High SNR Low manufacturing cost	Stability Potential for bit error
Phase change	Optical reflectivity change in contact overcoat	Lower write power	Lifetime Low SNR
	Reversible		
Magneto-optic	Magnetic domain switching Kerr effect readback	Reversibility Most advanced technique	Low SNR Media expense Media passivation
Phase change	Optical reflectivity change	High SNR (potential) Simpler optical system Single-pass overwrite	Limited reversibility Higher write power
Dye polymer	Materials flow	Cost Stability	Limited reversibility Lifetime Read/write speed

Read/Write Head

The key element of the read/write head is the semiconductor injection laser. Critical issues are the optical output power, device lifetime at high power, shorter light wavelength for smaller spots and high recording density, modulation speed, and optical beam quality. Expensive, bulky gas lasers are available for writing but are limited primarily to the equipment that makes "masters." Adequate injection lasers for small spot writing (about 50 mW of single-mode optical power with adequate product life) are only beginning to be developed.

Read-only injection lasers are available, with Japanese industry the primary supplier. The reflected light is read by a photodetector, usually segmented into four quadrants, for use in tracking a spot's position and improving the signal strength with respect to system noise. The beam is focused by a series of optical lenses and beam splitters and a miniature beam-positioning system based on "voice coil" actuators. The key attributes are efficiency in delivering power to a small spot and low mass so that the head can be rapidly repositioned.

Storage System Architecture

The architecture of an optical storage system refers to the way the data are formatted onto the disk, the way the data are read from the disk, and the way the computer system interacts with the optical storage system. For example, in read-only memory, contiguous data sequences are rearranged into noncontiguous dot patterns on the disk and coded with error-correcting codes in order to reduce the number of erroneously read bits by more than 7 orders of magnitude. These formats are often critical to the practicality of a technology for an application. For example, a factor retarding the use of an ideal write-once storage with infinite storage capability and zero cost is the lack of good ways to store various copies of a particular piece of information so that the proper (i.e., the most recent) copy is retrieved efficiently. (It appears that the human brain is ahead of computer science in this respect.) The panel will not cover these architectural aspects of optical storage systems in detail, except to point out where they seem to be controlling the development of the hardware.

Competitive Environment

Initial research in optical storage systems was carried on by a number of U.S. and European labs: Philips on laser tracking concepts and error correcting coding, RCA on high-powered lasers and archival systems, IBM on magneto-optic read/write media, and IBM/MCI and AT&T Bell Labs on ablative media. Products were developed but never introduced in the commercial marketplace (e.g., Storage Technology Corporation's gigabit file system), largely because U.S. industry could not identify near-term large markets. Today the primary research and development and product work is done in Japan at the large electronic companies. Current products are compact audio and video disks and archival systems for personal computer and workstation applications. Read/write systems are near the product introduction stage. In this as in other areas reviewed in this report, the lack of leadership in optoelectronic and photonic manufacturing technologies in the United States represents a serious threat to a significant, emerging area of economic competition.

Key Enabling Technology Needs

In a number of areas in optical storage, technological improvements are critical to product competitiveness. Technology elements that are in a position to be incorporated into products in the next 5 years are called enabling technology. Elements that need a longer, sustained research effort are considered in the next subsection.

- In the area of read/write heads, there is clearly a need for improved high-power laser sources. Maintaining good beam characteristics and demonstrating long life at high power are key issues. High power may come from more efficient single devices or from arrays of interacting lasers. There is good reason to expect that these enabling improvements are possible. New advances in the quality of compound semiconductor growth, such as the use of molecular-beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD), are allowing new laser structures to be explored. Lasers with quantum well confinement, new alloy compositions, and nonabsorbing mirrors are being researched; the result could be lower laser threshold currents, improved efficiency, shorter wavelength, and the ability to operate a device at higher power without damage. Planar-processed laser structures might lead to better ways of coupling the optical beam from the laser or improving the beam properties. An alternative approach to high optical power is to pump small Nd-YAG rod lasers with diode lasers. This approach is not as attractive from a wavelength, packaging density/mass, or efficiency viewpoint.
- Manufacturable packaging technology for lasers and the optical head is an important component of assuring a good optical source. Migration from the assembly of miniature but discrete optical elements to planar-processed, self-aligned elements is critical to offering a competitive technology.
- Low-mass read/write heads are important to fast data access. The integration of signal source and detection and perhaps some of the processing functions into an OEIC chip could provide a low-mass head with enhanced capability and functions for optical storage systems. Advances in laser sources as well as in optoelectronics require a high degree of sophistication and materials control in the processing of compound semiconductors. These areas will require sustained research and development activity, even though some forms of integration can be developed today.
- Another aspect of faster data access lies in multiple-track reading and multiple "platter" systems. The integration mentioned above helps packaging density in these types of systems but needs to be extended to cover arrays of function, for example, arrays of read/write lasers that are simultaneously and independently accessing tracks on the disk.

- The key problem in read/write applications is the availability of a reversible, high-contrast material. Improvement of existing materials must be vigorously pursued. The photo-induced change in optical reflective properties must occur rapidly and be stable for long periods of time without degradation. Finally, it must be possible to repeatably read and write the memory without degradation. The challenge here is similar to that for the optical logic applications: a large optical change triggered by a small optical impulse (a large optical nonlinear effect) is desired to clearly delineate two optical states. The problem is compounded by the need for large areas of this nonlinear material (compared to a logic chip), but the regions do not have to be interactive or wired. Currently available systems are based on films that can be cycled between stable and metastable phases with accompanying reflectivity or Magnetic Kerr effect changes. The quality of such films is limiting current applications, and significant advances in the storage media would have a major impact on read/write technology.

Key Research Areas

- A longer-term need is the advance of laser technology, particularly small semiconductor injection diode lasers. Here a key development is the migration of lasers to shorter wavelength, either by new laser materials or by frequency doubling of existing lasers. Basic materials research is needed in nonlinear optical materials for frequency doubling, with emphasis on compatibility with low-mass read-write heads.
- In the area of storage media, basic materials research is fundamental to future development. In this context, a variety of other phenomena have been explored for optical information storage. These include photochemical hole burning, holographic storage, and ferroelectric polarization-change storage. Although attractive in some respects, photochemical hole burning requires ultralow temperatures for long-term stability. Holographic storage mechanisms maybe of considerable importance in image processing (discussed in Chapter 3) but may not be competitive with the already high information storage density capability of optical compact disks. Ferroelectric ceramic materials may become important if the recent rapid progress continues in developing thin-film materials with good storage characteristics and low voltage requirements. However, these materials also appear to be of greater importance in image processing due to the inherently fast read/write speed of this medium. While all these areas are long-shot technologies, research into new methods of optical storage should be encouraged. All the current methods, as illustrated in Table 4.1, utilize thermal heating by a laser beam for writing information, and

this inherently requires appreciable power. Other approaches based on photonic effects in materials should be possible, for example, an absorbed photon causing either a photo-induced charge-transfer reaction or a photo-induced change in molecular conformation leading to a metastable change in optical properties. One might hope that other phenomena based on photonic effects in materials would lead to significant improvements in read/write head requirements or media stability.

- The ability to store exceedingly high densities of information in archival systems is coming and may lead to conceptually new applications. Advances may depend critically on nonhardware factors such as storage system design (software and architecture) and the storage-computer system interface. New architectures are needed to organize and access vast quantities of information at a high rate of speed. As software and application development has historically occurred at a slower rate than development of hardware, it is important to encourage early work in this area by sponsoring seed research and by supplying early prototypes to system designers.

OPTICAL DISPLAYS

Importance of Optical Displays

Displays take electronic information and convert it to images and text for human viewing. Since displays are viewed, they necessarily involve optics. However, their operation is better described by how they are addressed or written; in this sense they can be either electronic or photonic. The commercial market in displays was about $7 billion in 1986 and is projected to be over $9 billion by 1990.[7] The market is dominated by the cathode ray tube (CRT) display, which is currently at about 75 percent of the market share. There is a growing market in flat panel display technology, driven by the desire for compact, low-voltage (light-weight, low-power-consumption) displays.

Today's displays are addressed primarily by electrons and hence are electronic displays. Examples are the beam-addressed CRT and the matrix-addressed flat panel displays (Figure 4.2). Photonic displays are addressed by light beams. An example is a display where a laser beam writes on a liquid crystal cell (thermal writing process). Although U.S. and European corporations are involved in research and development and commercialization of displays, the main effort appears to be from the major Japanese electronic corporations. One reason for their dominance may be that the Japanese internal market is also the largest in the world.

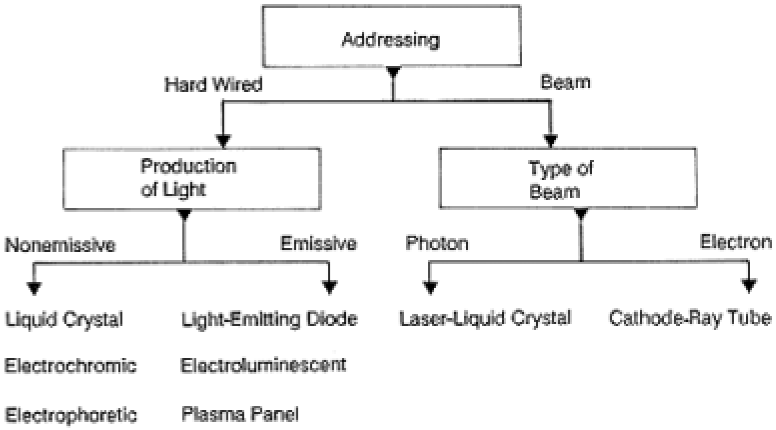

Figure 4.2
Examples of beam-addressed and matrix-addressed displays.

Display Status

Flat Panel Displays

The major activity in flat panel displays today is in electronically matrix-addressed panels. A voltage is applied to each picture element either to induce light to be emitted (emissive) or to cause a change in optical transmission or reflection of light from an external light source (non-emissive). As these displays are not "photonic" in the above defined sense, their characteristics and status will be covered only briefly.

The relative advantages and disadvantages of some representative display technologies are summarized in Table 4.2. A more detailed description of these displays was given in a special issue of *IEEE Spectrum* (1985).[8] The liquid crystal display, matrix addressed, is the dominant flat panel technology (at about a 15 percent share of the total display market in 1987), primarily in applications that cannot use CRTs. Earlier problems of slow switching speed and low contrast have been solved by active matrix elements involving thin-film transistors or diodes in conjunction with the liquid crystal at each picture element. High (30:1) contrast is now possible at video refresh rates and large viewing angles. The challenge remaining is to manufacture such displays at costs competitive with those of CRTs in order to penetrate the higher-volume market. In addition, new materials such as ferroelectric liquid crystals, which can respond more rapidly to external fields and can exhibit memory, could have a significant impact on a variety of applications for this display technology.

Table 4.2 Relative Advantages and Disadvantages of Representative Display Technologies

Type	Advantages	Disadvantages
	Beam-addressed	
Cathode ray tube	High resolution Good addressability High contrast Flexibility Color capability High luminous efficiency	High voltage Large depth High ambient lifetime Corner edge focus circuitry High maintenance cost Heavy
	Emissive flat panel	
Light-emitting diode	Extremely fast High resolution Rugged Reliable Low voltage	Short persistence Poor luminous efficiency Brightness uniformity High peak currents No blue light Expensive in large arrays
Electroluminescent display	Rugged High contrast Inherent memory	Moderate luminous efficiency Moderate luminance Expensive drivers
	Non-emissive flat panel	
Liquid crystal display	Passive display crystal Memory possible Very high resolution No contrast loss in ambient light	Low switching voltage External illumination required Temperature range Addressing, multiplexing Viewing angle
Electrochromatic display	Passive display High contrast Inherent memory	Contrast limitations External illumination required Difficult to matrix-address Electrode and electrolyte stability Slow switching speed

Plasma panel displays and vacuum fluorescent displays, utilizing a gas discharge to emit light from a picture element to the viewer, represent a slowly growing market (from 8 percent of the market in 1987 to 9 percent in 1990), primarily in specialized, high-information-content displays.

Electroluminescent (EL) panels are also present in the marketplace. [9,10] Materials research directed toward improved EL efficiency, better reliability, and fall color would benefit this technology. A common problem in the "gas" displays is the high cost of driver electronics.

Photonic Displays

Laser beams have been used to write on liquid crystals or photoconductive media to produce images, much as an electron beam writes on a phosphor in a CRT. Large-area and high-resolution displays have been demonstrated in specialized applications.

Interactive Displays

The interaction between the display and its viewer is distinct from how the display is made or addressed but may be impacted by photonics. An example is the eye-controlled display, where the orientation of the viewer's eyeball determines the display's cursor position.[11] Although the concepts and necessary technology are available, a successful product has not emerged. An exciting application would be a variable resolution display, where the portion of the display being focused on by the user is high-resolution (with greater information content), while the peripheral region has low resolution (minimum information density displayed).

Key Enabling Technology Needs

The key technology developments needed in displays are in the flat panel electronic displays. The panel does not currently see any key enabling technology elements in photonic displays that would allow them to displace existing electronic display technologies or open new fields of application.

Key Research Areas

There should be continued research in new materials and subsystem configurations, which might lead to a photonic display that is superior to its electronic counterpart in the long term. Potential advantages of using photonics could result from the fact that light beams do not interact, leading to novel multi-beam addressing schemes. In addition, new photoexcited display media may have higher resolution or image-storage capability. The promise of the hologram as the key element of a three-dimensional display remains a tantalizing goal. New concepts are needed to advance photonic displays if they are to become competitive. Some of the technologies developed for optical information processing or optical storage may be applicable to photonic displays.

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5

Opportunities in Sensor Technology

INTRODUCTION

In automated control systems, sensors represent one of the critical technologies that determine performance and the level of automation that is achievable. Although often overlooked, sensors in many cases represent the critical enabling technology. The computer processor, which usually appears to be the heart of an automated system, in reality cannot provide performance beyond that dictated by the sensor performance. Failures often are traceable to the malfunctioning of some inexpensive sensor component. As the push toward automation continues, the demands on the types, performance, and cost of sensors will grow. Optical sensors appear to offer performance and cost advantages that will enable many new applications to become possible.

While the sensor market itself is a modest $3 to 5 billion a year market in the United States, it is the sensor performance and availability that enable many applications to occur. The total market for automated controls is roughly $50 to 75 billion per year. Relatively inexpensive sensors are in many cases embedded in expensive control systems, and it is the performance of the sensors that determines the marketability of the total system. Sensor technology can be highly leveraged and thus has significant economic impact. The difficulty in the sensor marketplace, however, lies in the fact that the marketplace is highly fragmented and diverse. Sensors that are useful in aircraft may have only marginal utility in the chemical industry. Market development and penetration of new products are hindered somewhat by an inhomogeneous marketplace. In spite of this, optical sensor technology is viewed as an enabling technology with the ability to create new areas in automated control.

There are many different types of sensors in use today,[1–3] and the application in many cases determines the requirements of sensor performance. In process control applications such as are found in chemical processing plants or in power generation plants, it is desired to be able to determine fluid flow rates, liquid levels, temperatures, pressure, rates of mixing, status of various components such as valves and switches, and electrical currents and voltages; to inspect remotely various pieces of equipment; and to monitor personnel status. Sensors to perform these functions must be tied together with a robust telemetry system capable of providing the required bandwidth and, in some cases, able to survive such adverse processes as electromagnetic interference (EMI) and corrosion. Today conventional copper wire serves as the conduit in a telemetry system and connects numerous sensors, many of which are incompatible with each other and therefore require special interfacing units.

In moveable platforms, such as automobiles, ships, and aircraft, sensors are used for status monitoring as well as performance determination and alarming. Stringent environmental constraints are placed on the sensors in many of these applications. For jet engine monitoring, high temperatures as well as severe EMI and space constraints are often encountered. Pressure, temperature, and flow sensors, among others, are subjected to conditions that accelerate degradation. Sensor telemetry also may dramatically affect the performance and survivability of a sensor suite.[4] For example, damage control systems—which are commonly made up of smoke detectors and sensors for liquid level, temperature, and rate of temperature rise—often fail in a fire not because of damaged sensors but because of the rapid loss of the telemetry system when it is exposed to severe heat conditions. Robotic devices, as they become more autonomous, must be able to sense the presence of objects, manipulate these objects, and place them in the proper location. As an example, small, sensitive pressure sensors located remotely in robotic hands are an important part of the control system for the arm. The ability to reliably sense pressure at a remote location is currently inadequate, and device improvements are desired.

In automotive applications, small inexpensive sensors must function in the presence of high temperatures and EMI and in small spaces. Improvements in pollution and engine monitoring devices are highly desirable. In exploration for natural resources, highly sensitive sensing devices are often used. In oil exploration, for example, long, sensitive arrays of acoustic sensors are used to locate promising geological formations. Echoes of transmitted acoustic probe signals yield valuable information about the composition and structure of underlying strata. In well drilling, gyroscopes are used to determine the direction of the drilling while other sensors attempt to determine the local well-hole geology. In this application, high temperatures and corrosive gases that affect device reliability are often encountered.

Most of the sensors described above refer to devices that directly probe physical phenomena. Another very important sensor class detects visible or infrared radiation and is used for surveillance or position monitoring. In robotic vision, solid-state cameras are used to obtain data on object location, size, and orientation. The data are processed with various algorithms and are used to control the movement of robotic devices. Solid-state cameras and processors are widely used for monitoring security perimeters, for damage determination, and for autonomous vehicle control. Focal plane arrays, which are microelectronic chips with two-dimensional arrays of photodetectors, also are finding use in passive optical radars such as IR search and track (IRST) equipment, for satellite imaging applications, and potentially for autonomous equipment control.

PHOTONIC SENSORS

Two of the principal classes of photonic sensors are fiber-optic sensors and focal plane (FPA) array imaging sensors. Both are currently in development and commercially available and promise significant advances in capabilities over current approaches. Foreign competition in both areas has proven to be substantial, and foreign manufacturers are in an excellent position to dominate in the area of FPA in particular, since the operative technology involves microelectronic integrated-circuit approaches. If an edge exists for the United States in FPA and fiber sensor technology, it is due in large part to military investment in these areas.

FIBER SENSORS

After 8 years of development, optical fiber sensors are beginning to emerge as competitive devices for performing sensing tasks such as those required for aircraft engine and flight controls, for shipboard machinery and damage controls, for medical probing, and for industrial process controls. Fiber sensors operate by having the perturbation to be measured (e.g., temperature, pressure, or displacement) modulate light propagating in a fiber.[1,2] This can be accomplished by placing specially designed coatings on the fiber or by using the fiber to conduct light to and from some material, placed in the fiber path, that reacts to the perturbation to be sensed and modulates the fiber-guided light. Fiber sensors have proved to be accurate and capable of operation in harsh environments contaminated with high EMI, explosives, or corrosive gases. Because of these attributes, fiber sensors offer unique opportunities to solve

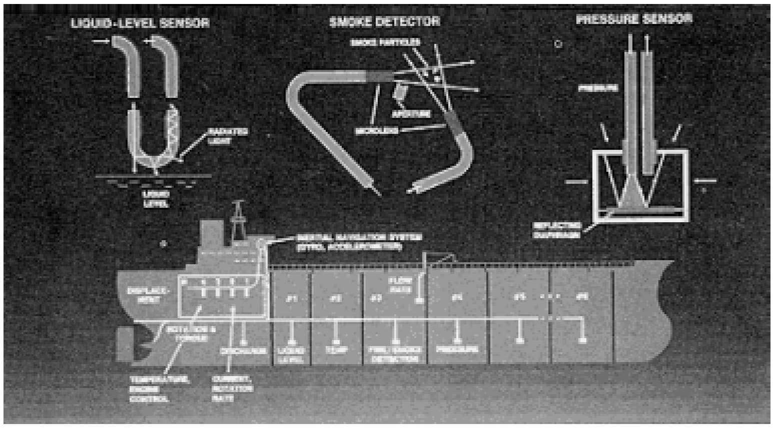

Figure 5.1
Examples of fiber-optic systems applications for marine use.

existing sensor problems encountered in many applications. Additionally, the compatibility of optical sensors with optical telemetry makes possible the development of all-optical, multielement sensor systems capable of supporting large numbers of high-bandwidth sensor elements while at the same time eliminating the requirement for transmitting electrical power to the sensor site from the monitoring site.[4] This combination of compatible fiber sensors and fiber telemetry represents an intrinsic advantage over conventional electrical technology. In Appendix E, the operation of fiber sensors is detailed, and the state of the art outlined. An example of systems applications is shown in Figure 5.1.

Fiber-optic hydrophones, gyros, and magnetometers make up several of the high-performance sensor types.[1,2] Performance parameters of these and other fiber sensors are shown in Table 5.1. Fiber hydrophones constructed with fiber interferometers have demonstrated detection sensitivities equal to or better than conventional piezoelectric devices. One of the main advantages of fiber-optic sensors is the spatial versatility of the sensing head. For an element with 30 m of fiber, the element can be a 30-m-long straight, extended element or a compact golf-ball-size omnidirectional element. The versatility also allows for a planar type of configuration as well as shaded, extended elements. A number of hydrophones for evaluation purposes have been successfully tested at sea. Single-element phones display state-of-the-art hydrophone performance. There has been considerable interest in both the United States and Europe in hydrophone arrays. In this application, multi-element sensors (driven by a single laser) with various types of multiplexing have been considered to reduce the cost of the array. As of yet, only small demonstration arrays with a few sensors have been built.

Two types of fiber-optic magnetic sensors have been demonstrated,[1] the Faraday effect sensors, which are useful for measurement of large magnetic fields (>1 Oe), and interferometric sensors utilizing magnetostrictive materials for high-sensitivity devices (<1 mOe). In typical sensor designs, the sensor fiber is bonded to a magnetostrictive material. As the magnetic field changes, the strain in the material is transferred to a strain in the fiber core. Minimum detectable DC fields of 10^{-6} Oe and AC fields of 10^{-8} Oe range have been reported, which makes their performance equal to or better than existing, competing room-temperature nonfiber magnetic sensors.

Fiber-optic gyros fabricated with fiber Sagnac coils have provided performance in the laboratory equaling the state of the art as achieved by the best ring-laser gyros.[5] Nearly all gyro applications have relatively stringent size requirements ranging from volumes of 1 ft^3 in airplanes to volumes of a few cubic inches in missiles. This makes packaging considerations important in any engineered device. One of the leading approaches used today is the all-fiber technique. Since the light never leaves the fibers, discrete optical component-alignment problems are avoided, minimizing gyro degradation due to vibration or thermal cycling. Recently, a ruggedized packaged fiber gyro for oil well-logging applications has been developed. This gyro is designed to operate to depths in the earth of 2000 ft over temperatures ranging from 0 to 125° C and to be able to withstand shocks to 100 g and vibrations of 40 g. This gyro can detect 0.05° rotations in azimuth and 0.2° in inclination and illustrates the state of the art in fiber gyro packaging.

There are many reasons why fiber-optic gyros are currently attracting substantial interest. Fiber gyros are all solid-state and have no moving parts, implying reduced maintenance compared to present-day spinning mass gyros. Fiber gyros appear to have better potential sensitivity performance than the corresponding theoretical limits for ring-laser gyros, as is indicated in Table 5.1. They also do not have many of the problems that have plagued ring-laser development, such as optical lock-in, which required mechanical dithering, and precision block and high-quality mirror fabrication. Finally, they are constructed from inexpensive components and have the potential to be inexpensive devices when compared with other technologies. Counterbalancing these advantages is the fact that the fiber gyro is still in an earlier stage of development than the technologies with which it is competing. Engineering issues of dynamic range and drift remain to be satisfactorily resolved. Recalling that the ring-laser gyro, which is now enjoying a successful introduction into commercial applications, required a development period of two decades, one expects that the much newer fiber-optic implementation will probably require another 5 to 7 years before it, too, successfully competes in a commercial marketplace.

Table 5.1 Performance Parameters of High-Performance Sensor Types

Type of Sensor and Parameter of Interest	Commercial Competing Device	Competing Device Performance	Key Parameters: Theoretical (Measured)* or Sensor Type Measured
Hydrophone (pressure)	Piezoceramic	30 dB re: 1 micropascal	-5 dB re: 1 micropascal with 100 m fiber (20 dB re: 1 micropascal)*
Magnetic field sensor	Fluxgate	10^{-4}-10^{-6} Gauss	10^{-9} Gauss with 100 m of fiber, 1 mW optical power, room temperature (10^{-5} Gauss DC field, 1 m fiber, 1 mW optical power)*
	Hall	10^{-4}-10^{-3} Gauss	
	NMR	10^{-6} Gauss	
	SQUID	—	
	Cryogenic	10^{-9} Gauss	
Gyroscope (rotation rate)	Spinning mass	$10^{-2\circ}$ /h	$10^{-4\circ}$ /h at 5 km fiber, 1 mW optical power ($10^{-3\circ}$ /h at 0.8 km fiber, 0.1 mW optical power)*
	Ring laser gyro	$10^{-3\circ}$ /h	
	Electrostatic gyro	—	
Position sensors (displacement)	Linear and rotary accuracy	10–12 bits	Position: (12-bit, 10^{-3} in. resolution; dynamic range: 0.6 in.)*; rotation: (0.4° resolution; dynamic range: 40°)*
Pressure sensor	Various sensor types	0-5,000 psig at 24% accuracy typical over any part of range	Various ranges and fiber transduction mechanisms

Type of Sensor and Parameter of Interest	Commercial Competing Device	Competing Device Performance	Key Parameters: Theoretical (Measured) * or Sensor Type Measured
Vibration sensor (acceleration)	Piezoelectric	10^{-6} g range 10^{-6} g resolution	Cantilever: (0.01–32 g)* Interferometric: (10^{-6}-10 g)*
Flow sensor	Ultrasonic Turbine Vortex	±5% ±1% ±1%	Vortex shedding: (0.5–20 m/s)* Laser doppler: (10^{-6}-10^{-5} m/s)* Fiber strain: (1–7 liter/s)*
Liquid-level sensor	Ultrasonic	~1 mm typical	Refractive index: 0.5 mm (off/on); optical radar: 1 mm (continuous)
Oil pollution monitoring sensor	Electric Dielectric Acoustic	— — 200 ppm	— 15 ppm (in field) 1 ppm (in lab)
Temperature sensor	Pt resistance	-180 to 1000° C ± 1° C; 0.07-Hz bandwidth	Interferometric: (0–100° C ± $10^{-3\circ}$ C)*; amplitude: (0–100° C ± 0.2° C)*
	Thermocouple	1400° C ± 0.15° C; 10-Hz bandwidth	
Pressure	Membranes	0–300 mm Hg	Fiber probed membranes: 0–300 mm Hg ± 5% accuracy
pH	Glass electrode		Based on Absorption: 6.8–7.4 ± 0.01 Fluorescence: 6.0–8.0 ± 0.02 Reflectivity: 7–12

* Entries are achieved (measured) performance.

Type of Sensor and Parameter of Interest	Dynamic Range, Stability, Drift, Linearity	Overall Status
Hydrophone (pressure)	Vibration sensitivity: comparable to other technologies; geometric variations: demonstrated planar, linear, cylindrical; temperature sensitivity: < 5% from 0–55° C; dynamic range: 140 dB	Demonstrated state-of-the-art performance in variety of high-performance lab devices; demonstrated several prototype devices in ocean environment; optical multiplexing of many sensors on a single fiber may be possible
Magnetic field sensor	Dynamic range: $\sim 10^{6}$; stability: $\sim 10^{-3}$ Gauss/13 h; linearity: ~100 ppm	Laboratory development under way to demonstrate theoretical sensitivity;, several prototypes demonstrated for field testing
Gyroscope (rotation rate)	Dynamic range: $\sim 10^{5}$; scale factor stability: $\sim 10^{-2°}$ / h, linearity: ~10 ppm	Low-precision gyros: ~0.1%/h drift for oil exploration, antenna control; requires 10° dynamic range for most navigational applications; current efforts aimed at packaging to increase stability, dynamic range, and linearity; strong potential for low-cost market < $500 per axis
Position sensors (displacement)	Low-cost/high-yield fabrication techniques need improvement; environmental stability: 0.1 in. over temperature range of -50° C to 100° C	Environmental and life-cycle testing under way; production techniques and packaging to be improved for reliable, low cost units
Pressure sensor	Similar to conventional probes	Many types fabricated with fibers (e.g., microbend, photo elastic, and diaphragm); performance compares well with conventional technologies; miniature fiber pressure probes used in laboratory equipment

Type of Sensor and Parameter of Interest	Dynamic Range, Stability, Drift, Linearity	Overall Status
Vibration sensor (acceleration)	+0.01 accuracy, 0.1 g resolution 10^{-6} g resolution	Low cost; field-tested in several applications
Flow sensor	Accuracy/resolution 1000 ppm/0.5 m/s 1000 ppm/10 m/s	Ideal for flow measurements in inaccessible or dangerous locations; small perturbations to flow if at all; 100-micron probes developed for medical applications
Liquid-level sensor	Accuracy for index-of-refraction type: 0.5 mm; accuracy/resolution for continuous level type: 1 mm	Coupled with fiber-optic telemetry, several kilometers of pipeline leaks have been monitored; optical radar type sensors provide high accuracy and continuous range readings; low cost
Oil pollution monitoring sensor	Ability to distinguish between oil and solid pollutants; proven ability in a hazardous environment	Standard telecommunications lab devices installed in 800 vessels; multi-wavelength beam techniques under development to solve oil/solid identification problems
Temperature sensor	Interferometric sensors: typical dynamic range of 10^6, but accuracy ~ 1%; amplitude sensors: typical dynamic range of 10^4; repeatability in both: 1%	In use in several hazardous environments and in medical applications; cost too high for general usage to date; 10^{-8}° C and 100-dB dynamic range possible for interferometric sensor (time-varying temperatures change sensitivity—not absolute)
Pressure	Repeatability adequate: similar to conventional probes in performance	Mostly laboratory prototypes; employed in several clinical studies; miniaturization realized
pH	Probe size 0.5-mm diam., 3 mm long 4-mm diam. 2-mm diam., 10 mm long Response time ~30 s ~90 s ~300 s	In vivo testing in animals; further miniaturization possible; main potential for use is medical testing

Fiber-optic sensors appear to be ideally suited for machinery and process monitoring and control. In control applications, extreme sensitivities are not generally required, whereas a premium is placed on cost, simplicity, and reliability. The military is examining the use of fiber-optic monitoring and control sensors and has actively pursued the development of several sensor types. Functions important for aircraft and ship controls are control of surface displacement, rotation, torque, and speed. Although these functions are also important in commercial processing and control, the high-EMI environment of military platforms that results from extensive radar and radio communication operations provides an excellent incentive for the development of fiber-optic position sensors. At present both military and commercial companies are developing fly-by-light flight control systems. Linear and rotary position as well as differential hydraulic pressure sensors have been developed. Position sensors operate as optical shutters, providing reflection, transmission, or absorption of light supplied by a source fiber in accordance with a pattern or mask inscribed in the moving member of the position sensor. These fiber-optic devices replace conventional resistive bridges or magnetic induction position sensors. The first industrial application of these devices will undoubtedly be in hazardous/explosive environments where the all-dielectric nature of fiber sensors enhances safety. As indicated, improved fabrication, packaging, and production techniques are required to produce cost-competitive fiber-optic position sensors.

Oil-pollution-monitoring sensors are important for shipboard as well as industrial processing control. Fiber-optic-based sensors have demonstrated substantial improvements in accuracy over conventional devices and have demonstrated the ability to distinguish between oil and solid pollutants. Fiber sensors have been installed on over 800 vessels.[2]

Fiber-optic control sensors appear ideally suited for machinery and process monitoring. They generally possess adequate sensitivity for those applications. Power plant equipment and heavy electrical machinery appear to be prime candidates for early usage. The possibility of building distributed fiber sensors and embedding fiber sensors in material promises to satisfy numerous longstanding requirements. Fiber sensors embedded in composites, for example, should provide strain-probing capabilities of parts in motion. Additional opportunities exist in aircraft and ship flight and machinery control systems. The military has actively pursued the development of several sensor types, including control and monitor sensors (e.g., for damage control and fuel status). These are currently being evaluated and are expected to find application.

Lower-sensitivity fiber sensors have been incorporated into numerous control system demonstrations, and many control-type fiber sensors are commercially available. Included in this group are temperature, pressure, flow, torque, current, liquid-level, and several other types of fiber sensors. These are described in greater detail in Appendix E along with other fiber sensors used in medical applications.

SOLID-STATE IMAGING DEVICES

Since 1970, extensive research and development have been devoted to metal-oxide (MOS) semiconductor technology utilizing charge-coupled device (CCD) and charge-injection device (CID) concepts, leading to a revolution in data handling and processing of radiation-induced signals. Significant advances in multiplexing and amplifying signals from optical and infrared detector arrays have resulted. Devices resulting from these advances are finding application in strategic, tactical, and ecological reconnaissance and surveillance, both from the ground and from the air, as well as in consumer products such as miniature video cameras for various uses. Silicon technology was the early basic technology used in charge-coupled devices, and the first imaging CCDs were sensitive in the spectral region of 0.4 microns to 1.0 microns. Other windows at 3 to 5 microns and 8 to 12 microns have subsequently become accessible using indium antimonide (InSb) and mercury-cadmium telluride (HgCdTe) material systems. Imaging for regions below about 2 microns can be carried out with ambient or active illumination, whereas for longer wavelengths, the objects' own thermal radiation provides the signal to be detected. Research with InAsSb strained-layer superlattices, gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs), and other materials for use in IR devices also shows promise. Charge-coupled and/or charge-injection concepts have yielded, and promise to continue to yield, significant improvements in the performance of large-scale integrated detector arrays. Substantial increases in sensitivity with savings in weight, size, power dissipation, and cooling requirements have been realized with these new arrays. Increased scene information, coupled with evolving improved signal/clutter-processing technologies, offers capabilities for autonomous detection and classification that were heretofore unattainable. Area arrays of 256 × 256 element complexity are becoming available in all spectral regions, with larger visible arrays having already been demonstrated. These will replace linear, mechanically scanned arrays in many applications, thus eliminating several moving parts, reducing size, and increasing reliability.

In the visible and near infrared, large, buried-channel silicon CCD arrays have been used in the space telescope. Silicon imagers now can incorporate both storage and time-delay-integration (TDI) modes, which increases sensitivity significantly. Monolithic platinum silicide Schottky barrier IR-CCDs have demonstrated important improvement in scene uniformity, with good near-IR sensitivities. Many of these devices have already found their ways into both military and commercial cameras. Because of these detector improvements, video cameras have shrunken in size during the last decade by over an order of magnitude, a development that has opened up a vast consumer market to these products.

In the infrared, scanned linear detector array technology continues to dominate. However, with continued progress in IR area staring arrays, it is expected that these new arrays will replace many of the scanning systems, thus eliminating the need for a conventional scanning mechanism and simplifying focusing optics. However, to compensate for array nonuniformities, correction on a pixel-by-pixel basis must be incorporated. Additionally, detector responsivity and readout nonlinearities require increased computations to correct for these flaws in an array output. These arrays, therefore, need to be closely coupled with a solid-state processor in order to perform properly.

It is becoming clear that, as CCD/CID technology evolves, sophisticated, autonomously operated devices become possible, which in the future will affect many systems. For the first time, focal plane arrays permit image generation in a small, efficient sensor head. These imagers, when coupled with the appropriate processors and algorithms, permit target detection in clutter and object identification. These capabilities are becoming pacing requirements for advances in robotics, autonomous vehicles, surveillance, and data collection. Small, inexpensive imagers/processors would permit widespread use in applications where the size, orientation, and position of various objects are desired. Passive IR search and track radars are required for ship and aircraft navigation and protection, whereas small, smart seeker heads are required for guided munitions, as well as for a variety of consumer products, such as collision-avoidance devices and home protective systems.

ENABLING TECHNIQUES

Fiber-optic sensors have been in development for several years, and adequate performance has been demonstrated. One of the barriers to commercialization has been the diversity of the sensor market. While several fiber sensors are commercially available, compatibility among the sensor types has not been realized, and serious packaging of laboratory devices has occurred in only a few cases. Most of the fiber sensors listed in previous sections perform adequately in laboratory environments; however, drifts in calibration, due to environmental changes and other problems, have been encountered when poorly engineered or packaged devices have been fielded. It appears that an the components needed to fabricate fiber sensors are available, so that future development efforts can concentrate on making commercially viable sensors. Compatibility of packaging of several types of fiber sensor will lead to the ability to multiplex multiple sensors on a common optical fiber. This in turn will lead to cost and performance advantages that will make fiber sensors the technology of choice. The strength of optical fiber sensors lies in the ability to use a common technology base to sense numerous physical parameters. Automated manufacture of fiber sensor arrays and associated telemetry promises significant cost advantages over current practices. This fact, coupled with resistance to EMI and corrosive environments and competitive performance, should ensure the widespread use of this technology.

As for the many other technologies emerging from U.S. laboratories, the difficulty in commercializing the technology rapidly relative to foreign competition is a major concern in the optical fiber sensor area. Projects to standardize fiber sensors, so that compatibility issues are resolved, and to integrate fiber telemetry are desirable. The military will, in all probability, perfect the sensitive surveillance types of fiber sensors, and these will diffuse into the commercial marketplace with time.

Focal plane array development, on the other hand, requires more research to address fabrication problems even though many commercial FPAs are currently available. The FPA technology is still evolving, and continued research is required to develop better materials-growth approaches, interface improvements, fabrication yield improvements, and signal processing to support image acquisition and processing. Nonuniformity of detector response from pixel to pixel requires considerable post-processing for IR-FPAs and reflects the difficulties in materials growth and fabrication of the array. Array yields remain low, which reflects the evolving nature of designs and of processing approaches. Considerably better control over device parameters has been realized with visible FPA structures versus IR-FPAs. This is traceable to the use of highly developed silicon technology in the visible region of the spectrum—whereas InSb and HgCdTe material systems and processing techniques for IR-FPAs are less developed. Funding and incentives are needed to make focal plane arrays cheaper and more reliable.

Of equal importance is the development of custom processing hardware and software to support focal plane array data acquisition and processing. The lack of very efficient image processing algorithms limits the ability to perform real-time feature extraction, clutter suppression, and related data manipulation and determines the size of the processor needed to perform a function. In many cases, a small sensor head with a volume of a few cubic inches creates sufficient data to require a VAX-size or larger computer for processing. The long-term goal, which is supported by the potential of the technology, is to develop algorithms and processors efficient enough to permit the processor to also fit into a volume comparable to that occupied by the sensor. This will open the door to many autonomous vehicle, robotic, and military applications.

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6

Policy Issues and Recommendations

Policy issues considered by the panel included the issue of competitiveness, the matter of education for photonics, and the question of facilities—especially those for growing and characterizing superlattice materials.

COMPETITIVENESS

This, in the panel's view, is the critical issue. There is no question concerning the increasing importance of photonics, but the future role of the United States in this field is not so clear. There is excellent work being done in Germany, France, the United Kingdom, and other countries of Europe. There is also evidence of future strong competition from Korea, Taiwan, and the People's Republic of China. However, as in so many high-technology fields, the major competition at present comes from Japan. The issue of competitiveness will consequently be discussed in relation to the Japanese effort.

The semiconductor laser was first demonstrated in this country (by four groups, almost simultaneously)[1] and the double-heterostructure version—which made the device practical—was also first demonstrated in the United States.[2] Yet, the largest number of such lasers are now produced in Japan, from the high-volume, low-cost version used in compact disc players to high-performance, high-cost versions designed for long-distance, fiber-optic communication systems. There are many other examples of photonic concepts originating in this country but developed as products in Japan. The only major counterexample in the photonics field where the United States continues to play a dominant role is optical fibers. Here there has been an excellent coupling between research and development and manufacturing.

In a 1986 *Fortune* survey of experts in various high-technology fields, Japan was rated well above the United States and Europe in optoelectronics, an evaluation epitomized in the following statement: "Everyone concedes that the Japanese lead the world hands-down in one important new technology originally developed in the U.S."[3]

Due to the critical nature of Japanese competition in high-technology fields, there have been many studies of the reasons, with recommendations for improvement of the U.S. position. Many of these studies conclude that the differences in competitiveness arise largely from structural differences in the two societies. Certainly, there is more effective central planning concerning technical objectives in Japan than in the United States, as well as a more consistent set of government policies concerning direct government support, taxation, and tariff structures to support these objectives. Japan's lower interest rates and different methods of financing development work also encourage longer-term objectives than is the case in the United States. To the extent that changes in major national policies are desirable, the impetus for such change will have to come from a top level, with consideration of the effects on all elements of society. The remainder of this discussion will consequently focus on issues specific to photonics, with suggestions to industry and recommendations for the federal government that the panel believes could be implemented.

Some of the recent studies of the competitiveness issue related to photonics include the 1984 NAE/NRC study, *The Competitive Status of the U.S. Electronics Industry*[4]; the NSF-sponsored, Japanese Technology Evaluation Program's (JTEC) 1985 report, *Opto- and Micro-Electronics* [5]; and the 1986 NRC state-of-the-art review, *Advanced Processing of Electronic Materials in the United States and Japan*.[6] According to the JTEC report:

> In optoelectronics, in particular, the Japanese have made major, original contributions and, while their adaptive ingenuity can be expected to continue to produce market-oriented products, their original creative contributions to this field are expected to increase steadily in the future. Of particular significance are the collaborative interactions between industrial organizations, and between these organizations and the Japanese government, with the Optoelectronics Joint Research Laboratory as a clear example.
>
> The Japanese government, which plays an important role in promoting its industries through such means as protectionist trade policies, does not dictate selection and development of specific technological options. Industrial organizations in Japan have made long-term commitments to these technologies, and they are not deterred from pursuing them even if the payoff is not immediate or is not generic in character. [5–9]

The NRC *Electronic Materials* report states:

> At present, the Japanese are ahead of the United States in the development and application of advanced processing technologies. At least ten of the major semiconductor companies in Japan have vigorous programs targeted for projects with an expected payoff 7 to 10 years later. There are only a few, perhaps two, U.S firms similarly involved. Japan seems to have evolved a successful approach for identifying and implementing critical technologies within the commercial environment. [6]

The latter report cites these key ingredients in the Japanese success story: *commitment*—the willingness to start developments that are expected to take 10 or more years to bring to the marketplace; *coupling* —effective coupling between exploratory research and development and device fabrication; *commerce*—the 10 or more semiconductor companies with large research and development efforts; and *creativity*. It should be noted that the Japanese have built much of the base for their success on consumer products. Thus the development of marketable consumer products should be a major goal for U.S. industry. A proposed national photonics demonstration project that supports this goal is described later in this chapter.

Recommendations

The following are suggestions to industry offered by the panel:

- It is essential to increase our industrial competitiveness in product development and manufacturing and in marketing skills. This industrial effort requires university and national laboratory support. One or more centers should be established to emphasize the manufacturing problems of photonic devices and systems. This effort should be a joint industry/university/national laboratory effort—the industries being those with experience in manufacturing photonic products and the universities and national laboratories being those with a broad range of experience with specialized photonic techniques. Photonics is vital to information storage and transmission, and deterioration of our national position cannot be allowed to continue.
- There must be continuing support for, and industrial effort in, long-range research and innovation, a source of this country's strength.
- The photonics industry should consider the advantages of an industry association that could help organize consortia to conduct cooperative research and address technical problems and policy issues beyond the scope of any one organization.

The following are recommendations to the federal government offered by the panel:

- Government should play a more active role in assessing technological opportunities and catalyzing development of technology in industry. Careful consideration should be given to creation of a national photonics project with widespread industrial and university participation. The project should be one that no single company would do by itself but that could have potential advantages for several. It would have limited life. Persons from universities and several industries would seek leaves-of-absence from their permanent affiliations. The temporary affiliation would be similar to that of the national laboratories organized for specific tasks during World War II and would have as its goal a major photonics project. The purpose would be to build a demonstration system aimed at promoting information transfer that has a mix of near-term enabling technologies (e.g., field-testing advanced, low-loss, fiber-optic connectors) and demonstrating advanced devices such as OEICs in an experimental photonic-oriented architecture. The project should be defined and carried out by an industry/government team, with specific tasks assigned to the university community. It would be best if the project had both commercial and military payback and leverage. Examples of possible projects are given at the end of this chapter.
- The panel is recommending stable, basic research funding with an increased emphasis at the interface of research and development. Materials research should be an integral part of this supported effort.
- Government contractors who receive a percentage of sales for their independent research should devote a sizable fraction to projects with a life span of 5 to 10 years. Longer-term research needs to be encouraged, and in view of the difficulty in proceeding from research to products, some funds might even be set aside for pilot plants to test the ease of manufacturing new products.
- Regulation and antitrust and tax policies must be considered carefully as they relate to industrial investment in the transfer of technology from research, in the development of manufacturing technologies for low-cost/high-volume production, and in providing new services. Policies designed for mature and stable industries often impede progress when there are rapid technological changes, high-technology investment costs, and an international suite of competitors. The government should provide the necessary legal changes to promote broadband information technology into our communication infrastructure.

EDUCATION IN PHOTONICS

Since 1985, the Society of Photo-optical Instrumentation Engineers has conducted surveys of optics-related programs in U.S. universities. [10] The 1985 *Optics in Education* summary listed 30 schools with such programs; 50 were listed in 1986 and 62 in 1987. The Optical Society of America, the Lasers and Electro-optics Society of the IEEE, and SPIE all do a good job of publicizing the field and of hosting tutorial sessions along with their technical meetings. There are many new texts—both on basic and specialized subjects—as the textbook exhibits at the recent Conference on Lasers and Electro-optics demonstrated. Thus the growth in educational opportunities in photonics is encouraging. Nevertheless it must be recognized that the promise of this field will not be reached without a continuing supply of high-quality people who are well educated in the fundamentals of this subject.

Although there need not be a common curriculum for photonics, exchange of innovative ideas in a new field such as this can be especially helpful. Excellent tutorial articles on photonics are appearing in *Optics News, IEEE Transactions on Education*, and various trade journals, but a more concerted effort could be made for regular tutorials and exchange of information on photonics educational programs. This might be done in a regular section of one of the above journals or as a separate publication in the spirit of the *American Journal of Physics* . The latter might be the product of a joint endeavor similar to that responsible for the *Journal of Lightwave Technology*. Exchange of information on modern optics laboratories is especially important in view of the great amount of faculty time needed to develop a good laboratory.

It is well-known that there are widespread equipment deficiencies in the universities of this country for teaching and research in all fields. The National Science Foundation (NSF), Department of Defense (DOD), and other government agencies have initiated programs to help with this problem, but it is not yet solved. Since photonics is such a new field and because of the rapid growth in programs as described above, the equipment deficiency for photonic teaching laboratories is especially acute. It is recommended that the several government agencies concerned with this field, together with industry representatives, mount a joint program extending over several years and designed to alleviate this shortage. Awards should be competitive, based on critical reviews of proposals.

SPECIALIZED EQUIPMENT FOR PHOTONICS RESEARCH AND DEVELOPMENT

The problem of inadequate equipment for photonic teaching laboratories has been addressed above. The cost of obtaining and maintaining the fabrication and diagnostic equipment for modern photonics research and development organizations represents an even greater problem. Excellent microfabrication facilities for semiconductor optoelectronics devices are available in a number of universities but are extremely expensive to operate and maintain. The increasing need for access to MBE, MOCVD, or other units for fabrication of quantum well and other superlattice devices adds greatly to the cost. MBE units are priced at a minimum of $750,000 (although educational discounts may be available) and require budgets of at least $100,000 per year to operate. MOCVD is in some ways simpler to operate but presents a serious safety problem that may require special protective facilities. During the past fiscal year the NSF had many more requests than could be funded for MBE and MOCVD units. Even if funds were available for purchase of these, the budgets for continuing operation would present a serious problem. To add to these worries, newer techniques such as gas-source MBE[11] may make some of these units obsolete. This problem exists not only for universities but also for the smaller industrial laboratories.

It seems clear that not every research laboratory that should have access to one of these specialized growth units can afford its own facilities. The National Nanofabrication Facility at Cornell University—available to researchers throughout the country—represents one approach to the problem. Another bright spot is the increasing use of industrial facilities and those of national laboratories by university researchers through joint research programs, university/industry centers, or merely by informal arrangement.

Recommendation

- The panel recommends shared use of existing MBE, MOCVD, and other specialized microfabrication equipment. This should be encouraged by a variety of incentives, e.g., tax credits and supplemental grants. When requests for new units do appear to be justified, it should be determined that the institution is realistic regarding the source of funds for proper operation of the equipment. Additional postdoctoral positions in the national laboratories should be established.

SUGGESTIONS FOR A NATIONAL PHOTONICS PROJECT

A specific photonics project would be very beneficial for accelerating efforts to develop the enabling technologies described in this report. It would provide a focus for developing and evaluating technology, and it would serve as a showpiece of the technology developed. Many possible projects could be selected to advance the enabling technologies. Although choosing a particular project or setting specific goals or resource requirements is better done by the photonics project organizers, the panel has suggested two sample projects below (one for the automotive industry and one for the information-processing industry) and has outlined the attributes that the project should encompass. Also mentioned are some important technology activities with suggested ways of implementing the project.

In general, the project should address a potentially large market and should focus at least partly on inexpensive manufacture of photonic components. These components and resulting systems should be suitable for industrial environments, thereby giving them potential widespread use. It would be highly desirable to include multiple photonic applications such as sensing, information processing, and telecommunications in such a project. The project could be located at one research center or distributed among several locations.

One possible project focuses on the automotive industry, with the major goal being a safer, high-performance automotive prototype. First, vehicles could be instrumented with photonic technology to demonstrate not only functionality and reliability but also ability to perform new functions. Examples of instrumentation include sensors and networks (e.g., engine sensors in previously inaccessible areas, fiber-optic gyroscopes, antiskid braking sensors, optical data systems, and display systems). In this activity, attention should be given to fundamental issues of environmental ruggedness and reliability. Such characteristics are needed for most applications beyond telecommunications and information processing in controlled environments and present a different set of criteria by which to evaluate a particular technology. In automotive applications photonic devices such as lasers and fiber connectors can be required to have a 99.98 percent reliability over a -40 to 125°C range with a 7-year (60,000-hour) lifetime. In addition, photonic technology could be brought to the automotive factory in the form of sensors and control systems, robotic tactile and vision systems, and data-processing systems. For each case, emphasis would be on pushing technology well beyond today's capability.

An alternate project is to build an advanced supercomputer prototype. This project could focus on architectures, in particular multiprocessors, optical link technology such as board-to-board and chip-to-chip connections, and component technology such as optoelectronic integrated circuits. In the latter two areas, research activity could focus not only on new technological concepts but also on questions of ease of manufacture. Much emphasis should be placed on materials and basic process development. Further issues involving packaging include automated optical alignment and environmental stability.

Both of these sample projects emphasize demonstrating approaches that can lead to manufacturable and reliable systems. Such considerations will be the basis of a critical assessment of programs for the project. For example, any effort involving new architectures should use components and link technology viewed as available in some predetermined time frame. In addition, the project should be structured to emphasize technology rather than system architecture or system development. The demonstrations should not be related closely enough to any particular application to be perceived as product development. Thus the example systems mentioned above would be more a generic control system and an information-processing demonstration.

A national photonics project must be organized to obtain maximum cooperation among universities, industry, and government. Industry can perhaps best set the goals and define needs. The project should emphasize new concepts and devices (e.g., laser diodes that operate effectively at high temperature) but should also include some network/architecture work. If too much emphasis is placed on demonstrating ease of manufacture, industry may be reluctant to participate due to patent conflicts. There are numerous methods of avoiding such issues—for example, by conducting a basic research program (generally at universities) in parallel with technology demonstrations (at industrial labs) or by having a large part of the program carried out at a national laboratory. A national laboratory may be a particularly attractive choice because of its key generic attributes. These could include a stable staff and facility, an existing program involving and related to photonics that does not involve commercial products, and a charter that is not purely military, so that industrial involvement and guidance could be facilitated. The project should be coordinated with other major government-sponsored (e.g., the NSF, U.S. Air Force Office of Scientific Research, Office of Naval Research, Army Research Office) specific photonic thrusts to provide the desired unique thrust towards manufacturable enabling photonic technologies. Finally, it is important to have good communication and high levels of commitment among the scientists and engineers involved in the project. These can be fostered by meeting frequently or by having the majority of the technical participants contiguously located (i.e., within easy driving distance) if the project is not confined to a single laboratory site.

A national photonics project having the attributes described above would enhance the U.S. competitive position. In addition to demonstrating specific technology, it would serve the essential function of providing more technological experience for this country's present and student photonic scientists and engineers.

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Appendixes

Appendix A

Panel and Subcommittee Members

John R. Whinnery, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA, Chairman

Venkatesh Narayanamurti, Sandia National Laboratories, Albuquerque, NM, Vice-Chairman

John Crow, IBM T. J. Watson Research Center, Yorktown Heights, NY

Thomas G. Giallorenzi, Optical Science Division, Naval Research Laboratory, Washington, DC

Alan J. Heeger, Department of Physics, University of California, Santa Barbara, CA

Nick Holonyak, Jr., Department of Electrical Engineering, University of Illinois, Urbana, IL

Alan Huang, AT&T Bell Laboratories, Holmdel, NJ

Frederick J. Leonberger, United Technologies Research Center, East Hartford, CT

Robert D. Maurer, Corning Glass Works, Corning, NY

Stewart D. Personick, Bell Communications Research, Red Bank, NJ

S. Thomas Picraux, Sandia National Laboratories, Albuquerque, NM

James J. Wynne, IBM T. J. Watson Research Center, Yorktown Heights, NY

Subcommittees

Telecommunications: R. D. Maurer, V. Narayanamurti, S. D. Personick
Information Processing: A. Huang, F. J. Leonberger, J. J. Wynne
Storage and Display: J. Crow, A. J. Heeger, S. T. Picraux
Sensors: T. G. Giallorenzi

Appendix B

Workshop and Other Outside Speakers

Workshop of April 1–2, 1987

Wednesday, April 1, 1987

Introductory Remarks - J. R. Whinnery*

Session I: V. Narayanamurti, Presider

Overview of Future Lightwave Communications Systems - Paul Henry, AT&T Bell Laboratories

Broadband Networks - S. Personick*

Optical Logic - Alan Huang*

Optical Logic in the Light of Computer Technology - Robert Keyes, IBM T. J. Watson Research Center

Session II: J. Wynne, Presider

Policy Issues Affecting New Ventures in Photonics - Amnon Yariv, California Institute of Technology

Observations of Cooperative Research in Japan - James Merz, University of California, Santa Barbara

Optical Recording and Memory - R. Bartolini, David Sarnoff Research Center

Overview of Competitive Optical Storage Technologies - Victor Jipson, IBM, San Jose

Photonics Materials - Paul Fleury, AT&T Bell Laboratories

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* Panel Member; See Appendix A.

Thursday, April 2, 1987

Session III: F. Leonberger, Presider

Photonics in Display Technology - Richard Garwin, IBM T. J. Watson Research Center

Optical Information Processing - R. Williamson, Lincoln Laboratories

Optical Signal Processing and Phase-Only Pattern Recognition - Joseph Horner, Hanscom Air Force Base, Rome Air Development Center

Optical Sensors - T. Giallorenzi*

Other Outside Speakers

June 4, 1987, Ted Berlincourt, DOD, "Basic Research, Key to Technology Advances"

June 4, 1987, Richard Nicholson, NSF, "The Proposed Science and Technology Centers"

June 5, 1987, Lee Giles, AFOSR, "Optical Neural Networks"

June 5, 1987, Henry Kressel, E. M. Warburg, Pincus & Co., "The Role of Venture Capital in Photonics"

Appendix C

Selected Professional Societies, Journals, Review Articles, and Reports

Selected U.S. Professional Societies Concerned with Photonics

Institute of Electrical Engineers, Lasers and Electro-Optics Society (IEEE-LEOS), 345 E. 47th St., New York, NY 10017

Optical Society of America (OSA), 1816 Jefferson Place, Washington, DC 20036

American Physical Society (APS), 355 E. 45th St., New York, NY 10017

Society of Photo-Optical Instrumentation Engineers (SPIE), P.O. Box 10, Bellingham, WA 98227-0010

Laser Institute of America (LIA), 5151 Monroe St., Suite 102W, Toledo, OH 43623

Society for Optical and Quantum Electronics (SOQE), P.O. Box 245, McLean, VA 22101

Selected Journals with Major Photonics Content

IEEE Journal of Quantum Electronics (IEEE)
Journal of Lightwave Technology (IEEE-OSA)
Applied Optics (OSA)
Optics Letters (OSA)
Journal of Optical Society of America, A and B
Applied Physics Letters (American Institute of Physics)
Journal of Applied Physics (American Institute of Physics)

Laser Focus/Electro-Optics (Penwell Publishing Co.)

Lasers and Optronics (Gordon Publications, Inc.)

Fiber and Integrated Optics (Taylor and Francis)

International Journal of Optoelectronics/International Journal of Optical Sensors (Taylor and Francis)

Electronics Letters (IEEE)

Optical Engineering (SPIE)

Selected Review Articles and Books Concerning Photonics

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12. IEEE. 1986. Special Issue on Broadband Communication Systems. Journal on Selected Areas in Communications SAC-4 (July).
13. IEEE. 1988. Special Issue on Fiber Optic Local and Metropolitan Area Networks. Journal on Selected Areas in Communications SAC-6 (July).
14. IEEE. 1988. Special Issue on Photonic Switching. Journal on Selected Areas in Communications SAC-6 (August).

NAS, NAE, and NRC Reports on Competitiveness (National Academy Press)

1. 1987. Balancing the National Interest: U.S. National Security Export Controls and Global Economic Competition.
2. 1983. International Competition in Advanced Technology: Decisions for America.
3. 1986. The Positive Sum Strategy: Harnessing Technology for Economic Growth.
4. 1985. Technological Frontiers and Foreign Relations.
5. 1987. Technology and Global Industry: Companies and Nations in the World Economy.
6. 1987. Technology and Employment: Innovation and Growth in the U.S. Economy.
7. 1984. The Competitiveness Status of the U.S. Electronics Industry.
8. 1988. The Technological Dimensions of International Competitiveness.

Appendix D

Technology Status of Optical Telecommunications

Lasers

A key element of all long-haul optical communication systems is the semiconductor laser. The desirable characteristics of the semiconductor laser are determined in large measure by the characteristics of the optical fiber and the lightwave system architecture. Future lightwave systems are likely to contain a large number of closely spaced channels operating in the 1.5- to 1.6-micron wavelength band of low loss. In addition, high-bit-rate systems (> 1 Gbit/s) require narrow-line, single-frequency lasers to offset the chromatic dispersion of the fiber.

Two types of lasers have been extensively investigated for obtaining single-wavelength emission. They are the external cavity laser and the distributed feedback (DFB) laser. External cavity lasers that have been extensively investigated include the cleaved-coupled cavity laser (C^3 laser); graded-index, external cavity laser; fiber external cavity laser; the silicon chip Bragg reflector (SCBR) laser; and InP-based, external Bragg reflector lasers. The line width of the semiconductor laser is determined by the fluctuations in the phase and intensity of the photon field in the laser cavity. These depend markedly on the cavity length. Continuous wave line widths on the order of a few kilohertz (kHz) (necessary for coherent applications) have been obtained for external cavity lasers compared to those of many megahertz (MHz) for DFB lasers. It is likely that some form of external cavity laser will be the laser of choice for the next generation of high-data-rate, coherent transmission systems.

Among key desirable features of such external cavity lasers would be the fabrication of a truly compact, robust laser. Multielectrode lasers capable of wavelength tuning over the gain spectrum of the laser will become important for closely spaced wavelength WDM applications. Even though tuning features have been demonstrated in the laboratory, we do not to date have a stable, compact, widely tunable, single-frequency semiconductor laser suitable for practical commercial use. Further research in this area is warranted. Another important problem is the behavior of the laser under modulation conditions. "Chirping" (change of frequency during a pulse interval) of the laser under direct modulation is an important limitation as one goes beyond about 2 Gbits/s. The "chirping" behavior of semiconductor lasers is determined in part by the internal structure of the laser. Buried heterostructure (BH) lasers have generally low chirp and are favored, despite their complexity in manufacture, for high-bit-rate systems. As one goes to the 10-Gbits/s regime, it is likely that external modulation will be necessary for high-bit-rate, error-free transmission. The use of external modulators, however, results in additional power loss, and the system designers would need high-power (~ 50 mW) lasers for practical high-bit-rate systems. In applications where optical interconnection distances are relatively short (e.g., internal equipment interconnects), and laser output power is therefore not critical, lasers with very low-threshold currents (<1 mA) based on single-quantum well structures represent an important emerging technology.

Fiber and Cables

The two main characteristics of a fiber waveguide are its attenuation and bandwidth. Attenuation in present silica materials has been reduced to almost the theoretical lower limit. Research is currently under way to fabricate fibers using fluoride glasses, which may have attenuations a hundred times lower than present fibers. There are enormous problems to overcome in making practical waveguides from these new materials, but the research warrants continuation because the potential benefits are immense. Conceivably, transoceanic cables could be constructed without underwater repeaters, as an example of one benefit.

The maximum data rate (bandwidth) of an optical signal that can be supported in a fiber is presently limited by fiber material and waveguide dispersion, interacting with the spectral width of the optical sources. With emerging single-frequency sources, this shows no sign of becoming a limiting factor. Further, carefully tailored waveguide designs have been used to make fibers that can provide for flexibility in the choice of light source (the dispersion-shifted and the dispersion-flattened fibers, for example). This fiber design work is an important research effort that should proceed simultaneously with other activities to facilitate alternative system designs.

Beyond attenuation and bandwidth are a number of environmental requirements defining fiber degradation in use. These requirements have become increasingly important as the desire has evolved to both reduce fiber protection and submit fibers to more hostile environments. This has led to complex materials studies aimed at the improvement of materials properties. One such large effort is in hermetic coatings for strength. A second involves studies of atomic defects generated (or activated) by hydrogen diffusion into the glass, leading to optical absorption at system wavelengths being used. While this phenomenon is generally understood and empirical results show that the attenuation increase is usually negligible, there remains concern about adverse environments with high hydrogen content or high temperature. Continuing research to understand this problem at the atomic level will help provide reassurance to fiber users and will assist manufacturers in expanding the environmental durability.

The function of cabling is primarily to protect the fiber from mechanical stress, both lateral and longitudinal. The latter is conceptually the most straightforward and is accomplished by adding strength members to the cable, as well as by incorporating excess fiber length so that some cable elongation can occur before the fibers are strained. Progress in this area has been adequate and continues as higher-specific-strength materials become available.

Lateral stresses on the fibers are more complex and actually are generated during the cabling process. These minute cabling stresses result in "microbends" that increase the fiber attenuation. Advances in cabling techniques and the increased use of single-mode fibers have diminished the importance of this problem at present attenuation levels. However, increased understanding is helpful in advancing present technology and will become essential if the lower-attenuation fluoride fibers are to become commercially available. Microbends from cabling have an added dimension of complexity when multimode fibers are used, since the mode stripping (removal of higher-order propagating modes) they cause also increases the fiber bandwidth (reduces pulse spreading because of the smaller spread of propagation speeds amongst the modes that are not stripped).

System designers desire a length-bandwidth relation that optimizes fiber performance. Since pulse spreading in multimode fiber depends on a large number of fiber and excitation parameters, so far it has not been possible to provide a satisfactory analytical expression for the length-bandwidth relation. While the importance of the multimode fiber length-bandwidth relationship has diminished with increasing single-mode fiber usage, multimode fibers are being considered for future applications, which would again increase the importance of research in this area.

Aside from these specific technical areas, research and development in cable technology is gradually advancing with corresponding progress in cabled fiber cost reduction. This cost-performance improvement work should continue to be supported.

Passive Components

The cost and performance of passive components are major impediments to the advance of a number of applications of optical communications, e.g., local area networks. An exception to this may be fibers and cables that have benefited from a great deal of research and development over the years. The other components (discussed here) have not received as much attention and are not improving at the same rate as fibers and cables. For example, almost all the commercial passive components of today were designed and built in the laboratory over 10 years ago—the incorporation of new ideas has been rare. The obstacles these components present can be illustrated by the performance of demountable connectors, perhaps the most commonly used device, which typically can have insertion losses of up to about 1 dB. The power loss a system can tolerate is typically 20 to 30 dB. Therefore at the 1-dB-per-connector loss level, no more than about 20 connectors can be incorporated between a source and detector. Contrasting this with the negligible loss of present coaxial connectors shows that major design compromises have to be made in optical fiber system design.

The basic reason for this difficulty is the small cross-sectional size of the optical beam—which is, at the same time, a major advantage in terms of miniaturizing complex systems. There is a lack of sufficiently precise, three-dimensional forming techniques for manufacture of optical fiber system components. The two-dimensional solution, photolithography, has been used to some advantage when the third dimension is small; but it is generally inadequate. The forming problem has led to cost-performance trade-offs in component insertion loss. This problem becomes particularly vexing with the increasing incorporation of single-mode (i.e., small-core) fibers that require tighter tolerances. It is generally conceded that systems of the future will utilize single-mode fibers, so that this problem will assume increasing importance.

These general considerations, and some more specific ones, will become more evident in the following discussion of individual components.

Connectors

Single-fiber connectors are classified into two types, contact or butt-joint and expanded beam. The expanded-beam connector is more stringent in angular alignment tolerances, whereas the contact method is more stringent in lateral positional tolerances. The practical compromise between these two needs further investigation, including the necessity for optically polishing fiber ends. Single-fiber connectors typically cost $10 to $100 for multimode fiber and $20 to $200 for single-mode fiber, depending on performance. In general, assembly in the field needs simplification.

Multifiber connectors generally accommodate only a few fibers and employ some type of circular geometry. As in all connectors, craftspersons also have difficulty assembling these in an adverse environment.

Array connectivity seeks the advantage of easily joining cables with large numbers of fibers. Presently, a flat grooved plate holding the array of fibers is the basic element. The difficulty of obtaining uniform results for all fibers is apparent, and no attempt is made to fabricate such connectors in the field. Instead, cables are terminated in the factory, with attendant lack of flexibility in deployment.

Connectors with low reflection coefficients are increasingly important in high-data-rate and coherent communications systems because reflections returned to the lasers used in those applications can cause instabilities in the laser output that are harmful to system performance. Reflections at connectors placed in series along a fiber can also cause fluctuations in the output power at the end of the fiber due to interference effects.

Wavelength-Division Multiplexing (WDM) Components for Filtering, Multiplexing, and Demultiplexing

Wavelength-division multiplexing (WDM), optical communication in the wavelength multiplex mode, allows modulated radiation from several laser sources of clearly distinct wavelengths to be transmitted simultaneously over a single fiber. Spectrally selective optical multiplexers or demultiplexers are used at the start and end of the transmission route to ensure low-loss combination and separation of light of the various wavelengths. WDM technology is a key to the utilization of the full bandwidth capability of optical fibers. Commercial communication systems in operation today utilize wavelengths that are widely separated (0.8 microns, 1.3 microns, and 1.5 microns), but future systems are expected to utilize single frequency lasers in the 1.5- to 1.6-micron low-loss band, spaced a nanometer or less apart in wavelength.

Integrated optics is expected to play an important role in developing the necessary active and passive WDM components required for high-capacity WDM. These will require arrays of stable, single-frequency lasers of well-defined wavelength, low-loss waveguides, narrow-band gratings, filters, and multi-wavelength photodetectors.

Realization of practical WDM components for closely spaced wavelength applications hinges greatly on the development of new materials technology.

Vapor-phase growth techniques for fabrication of arrays of InP-based lasers and detectors of high uniformity need to be developed. New materials combinations with large electrical field effects for switching of optical signals in waveguides need to be explored. The possibility of using the mature silicon materials and processing technology for fabrication of low-loss waveguides and gratings on a silicon chip is particularly attractive.

Fiber Backplane and Other Optical Interconnects

As data rates increase, interconnections inside equipment become increasingly difficult to implement with conventional copper traces on circuit boards and backplanes, twisted pairs, and coaxial cables. Recently very short-distance fiber-optic interconnects have been used in place of copper wires and cables. However, there is research in progress to implement both the photonic equivalent of printed-circuit interconnects and also optical free-space interconnects.

The challenges associated with optical circuit-board and backplane traces are twofold. First, appropriate materials and processing technologies must be created to form light-guiding regions on circuit boards and backplanes of sufficiently low loss, of sufficient dimensional tolerance, and sufficient reliability—all at an acceptable cost. Second, optoelectronic interfaces are needed to economically couple light into these light-guiding traces and to remove the light at the other end (or possibly at several places along a light-guiding trace). It is desirable that these fight-launching and light-receiving optoelectronic interfaces be integrated into electronic circuits, so that packaged electronic circuits with these optoelectronic interfaces can be fabricated as components that can be mounted directly on circuit boards containing the optical traces they will access.

Free-space interconnects offer the possibility that arrays of optical transmitters can be connected to arrays of optical receivers with relatively simple and rugged lenses to define the optical paths. Such free-space optical interfaces offer certain advantages over fiber and optical traces on circuit boards, such as propagation delays that can be identical for a large number of connections that are not exactly parallel. Free-space interconnects eliminate the need for connectors and may improve reliability of interconnections. Realization of practical free-space interconnects awaits the development of arrays of reliable optoelectronic transmitter and receiver modules and appropriate lens and physical design technologies to achieve the desired alignments. Research in interconnect topologies is also needed to obtain a synergy between the capabilities of free-space interconnects and interconnection applications that can use those capabilities.

Other Passive Components

As higher data rates and coherent techniques are employed in fiber-optic systems, the lasers used to meet the requirements of these applications are increasingly sensitive to reflections that cause various instabilities. Optical isolators are needed to reduce reflection effects. Miniature opto-isolators are being employed in high-performance laser packages today. Further improvements in packaging and integration are desirable to reduce cost and increase reliability.

Optical directional couplers with low insertion losses and predictable coupling ratios are needed for removing and adding light in passive bus configurations. Although various directional coupler designs have been demonstrated and manufactured (e.g., fused tapered couplers), improvements in cost, performance, and reliability are still needed for many applications. Similar remarks apply to star couplers, which are used in networking configurations that are alternatives to passive bus configurations.

Some couplers are incorporated in flat substrates and therefore suffer from geometrical mismatch in going from fibers to rectangular waveguides. Planar structures by themselves do not have a bright future but will become very important when combined with active devices in the emerging technology of optoelectronic integrated circuits.

Photonic Switches

A number of technologies have been demonstrated for switching an optical signal between two or more outgoing paths. These include mechanical devices that physically move fibers or that physically move lenses or mirrors directing an optical beam; optoelectronic devices where an applied voltage across two or more electrodes causes a field within an electro-optic material, which in turn changes the coupling of waveguides within the material or otherwise modifies the optical characteristics of an optical circuit within the material; electrically, acoustically, or optically controlled gratings created within a material to cause diffraction of an optical beam; and electrically or optically controlled non-linear optical devices.

Of the variety of optical switching devices demonstrated or proposed, some are more practical than others, and some have near-term applications (e.g., simple mechanical switches for remotely controlled optical cross connects). However, optical switching devices are in general larger and more power consuming than their electronic counterparts; and many of these devices have numerous practical limitations such as temperature sensitivity, polarization dependence, wavelength dependence, requirements for high voltages, and high loss. Materials improvements and device-design improvements are the two key dimensions of current research on these devices. While these device limitations are being actively addressed, much systems research is also needed to achieve large-scale application of optical switching devices in systems as a replacement for electrical-to-optical conversion accompanied by electronic switching.

Optical Amplifiers

Optical amplifiers are potentially important building blocks of all optical communication systems. In present optical communication systems the amplification function is accomplished by converting the optical signal to electronic form (detection), amplifying the electronic signal with an electronic amplifier, and then reconverting the amplified electronic signal to optical form. There are two main types of optical amplifiers: (1) fiber-based amplifiers, and (2) semiconductor laser-based amplifiers. The main uses of optical amplifiers are in (1) pre-amplifier applications where amplification of low-level signals is performed and there is no intentional loss between the output of the amplifier and the receiver and (2) in-line applications where relatively large optical signals are amplified and loss is expected between the output of the amplifier and the receiver. The former are likely to be important in high-bit-rate (>2 Gbits/s) systems if good APDs do not exist. In-line amplifiers are believed to be useful in both long haul (to compensate for fiber losses), in the local loop (to compensate for split-off and coupling losses), and in optical switching to compensate for losses in the switches.

Over the last few years, there has been considerable worldwide activity in developing amplifiers with large available gain, low insertion loss, low noise, large bandwidth, and saturation output power. To date, no practical semiconductor laser amplifier has been developed. The main potential advantages are the ease of manufacturing, high gain, and the tunability of the bandpass used for noise filtering and channel selection. However, semiconductor laser amplifiers have polarization-dependent gain that needs to be controlled through development of better optical isolators.

Fiber amplifiers, especially Raman amplifiers, suffer from the high pump power required for amplification. Research needs to be performed on special fibers with low loss and high Raman cross-section as well as special dopants for optically pumped fiber amplifiers. This is a promising field that needs increased attention.

Integration And Packaging

The interfacing of optical components with electronic ones is a key element for all future information transmission systems where one envisages the merger of optical signal processing with purely electronic media such as high-speed computers. One can imagine that in the interest of low cost and circuit simplicity, the terminal sources and receivers in the optical link may take on electronic processing involved with the communication link. One can fabricate, for example, a heterojunction bipolar transistor driver and a laser on a single chip or a pin photodiode and a field-effect transistor on the same chip. More complex integrated devices involving arrays of lasers, detectors, amplifiers, transistors, and modulators can be imagined. One of the main motivations for optoelectronic integration besides cost is performance. As speed increases, the interconnection of integrated circuits and subsystems becomes more critical and cannot be easily implemented with technologies available today. Compound semiconductor-based transistors are intrinsically faster than Si ones, and the monolithic approach provides significant additional improvements through reduction of undesirable parasitics associated with packaging discrete devices.

A key stumbling block in the exploitation of optoelectronic integrated devices has been the materials and processing technology. With high levels of integration, large-area compound semiconductor substrates of exceptional quality (low defect and dislocation density) and a vapor-phase crystal growth technique for growing uniform, epitaxial layers on the surface are required. Recent progress with hybrid MOCVD and MBE techniques suggests that this may be close at hand. However, because of the many conflicting processing requirements for optical and electronic devices, the ability to grow patterned structures in situ in a multichamber MBE machine will ultimately be extremely important if one is to exploit the full benefits of optoelectronic integrated devices. Major emphasis should be placed on developing further the materials and processing technology based on hybrid MBE/chemical-vapor deposition multiwafer, multichamber machines.

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Receiver Subsystems

The key elements of a receiver subsystem are the optical detector and the low-noise amplifier that couples the optical detector to conventional electronics. In telecommunications applications two types of optical detectors are typically used. These are the PIN photodiode and the avalanche photodiode (APD). Both types of devices can be fabricated from silicon material for 800- to 900-nm wavelength systems. Both types of detectors can also be fabricated from indium-gallium arsenide phosphorus material compositions for 1300- and 1500-nm wavelength systems. At these longer wavelengths, however, the APD is just beginning to emerge from the research laboratory as a practical device. Leakage is in the wide bandgap InP layer to avoid excessive tunneling dark currents. Hence the name SAM APD is given to this structure. The response speed of SAM APDs is limited by trapping of holes at the heterojunction interface. This can be greatly improved by placing a graded InGaAsP layer between the absorbing and multiplication regions. Such separate absorption and graded multiplication (SAGM) APDs have exceptional response speeds and high sensitivity. For example, with a receiver operating at 8 Gbits/s, at a wavelength of 1.5 microns, and using a GaAs FET front-end amplifier, a sensitivity of- 26 dbm. has been obtained for a 10^{-10} bit error rate. Typical APDs of this type yield receiver sensitivities that are 5 to 10 db better than those achieved with non-multiplying PIN detectors.

The sensitivity of a receiver employing an APD is determined by the relative impact ionization rates of electrons and holes and by dark current. Recently, several advanced APDs have been proposed that rely on superlattice band-structure engineering to modify the relative impact ionization rates. Such APDs are in early stages of research and require exceptional control of materials both in terms of doping as well as composition for their practical realization. They, however, hold the promise for achieving receivers with a performance dictated by the laws of quantum mechanics.

Appendix E

Fiber-Optic Sensor Performance

This appendix describes the properties and performance of representative fiber sensors, as well as uses and potential markets for these sensors.

High-Performance Devices

In their 8 years of development, the fiber-optic hydrophone, gyro, and magnetometer have attracted much attention and are arguably the most advanced of the high-performance devices. Performance parameters of these sensors are shown in Table 5.1. In the case of the hydrophone, various configurations of packaged interferometer hydrophones have routinely achieved detection levels equal to or better than conventional piezoelectric devices. These sensors have also demonstrated a flat frequency response in the band of interest as well as insensitivity to environmental parameters such as pressure and temperature. The technology is that of the fiber-optic interferometer (typically a Mach-Zender), in which the incident acoustic field, either through a compliant mandrel design or by a compressible coating, strains the optical fiber. The reference fiber either is isolated or has a coating that is relatively insensitive to pressure. The resulting phase shift in the interferometer is then demodulated (or converted to an amplitude modulation) to give a stable output.

The fiber gyroscope is a single fiber arrangement for a fiber interferometer. The output of the optical source is split and launched as two counter-rotating beams in a fiber coil of length L and radius R. Under ideal conditions the two counter-propagating beams should see the same optical path (i.e., reciprocity).

However, when the fiber coil is rotated, there is an optical phase shift (known as the Sagnac effect) between the beams traveling in opposite directions. This phase shift is proportional to the product of the angular rotation rate, the total length of fiber in the loop, and the radius of the fiber loop. For a fiber length of 500 m wound on a 10-cm radius coil, a rotation rate of 0.1° /h corresponds to a Sagnac phase shift of 1 microrad, which is readily measurable. To obtain stability over the long fiber lengths involved, polarization-preserving fiber is used. This approach has led to the development of a number of in-line fiber-optic components such as polarizers, depolarizers, and polarization-preserving couplers. Measurements have shown that polarization-preserving fiber systems can achieve a sensitivity of $10^{-3\circ}$ /h and a random drift of $5 \times 10^{-4\circ}$ /h (see Table 5.1) for other performance parameters). These and other experiments have shown, at least in a laboratory environment, that the fiber-optic gyro can operate at the level required for navigation-quality, strapdown inertial systems.

Control Sensors

Fiber-optic pressure sensors (see Table 5.1) have been developed to a level almost equivalent to that of position sensors. This lag in development is due to the fact that conventional pressure sensors, which offer low cost and adequate resolution, are readily available for most commercial and military applications; furthermore, the quantity of pressure sensors required is surprisingly small compared to other sensor types such as those used for temperature, liquid level, and flow. In spite of an excellent research base, the commercialization of fiber-optic pressure sensors requires the identification of unique applications where their total dielectric nature provides a significant advantage over conventional technology. Pressure-sensor development will result from either hazardous/explosive environment applications or from a gradual evolution towards all-fiber sensor systems following the development of other more frequently used sensor types.

Similarly, the development of fiber-optic vibration sensors depends on specific applications where their dielectric nature has distinct advantages. Two important vibration-measurement applications have such requirements. The first application, vibration monitoring in generators, could provide assurance against costly equipment damage. Generator high-voltage levels produce an EMI environment that in many cases prevents use of conventional piezoelectric accelerometers. The second application involves measuring acceleration in the presence of explosive gases, such as those in an offshore oil platform and in mines, where electrically based measurements are hazardous.

Temperature sensors have been commercially available for many years. The most common sensor types use fiber to transmit infrared radiation from a high-temperature process and are limited on the lower end to a range of about

300°C to 2000°C. More recently, sensors based on fluorescence of materials placed at the end of a fiber-optic probe and fiber-optic-based temperature switches have become available. In addition, laboratory demonstration of temperature sensing has been completed utilizing a great variety of techniques. Recently the development of fire-resistant fiber cable capable of operation to at least 650°C has been reported. Since it does not incorporate any polymeric materials, it does not give off toxic fumes or smoke at high temperatures. Temperature sensors are also used to monitor excessive temperature increases. Fiber temperature sensors, because of their EMI immunity and small size, may be placed directly within the windings of electrical equipment or other electrically noisy, confined areas. As an additional example, fiber-optic temperature sensors have been successfully used in chlorine production plants. In this application, galvanic cells are used to separate chlorine from sodium chloride and require 62 kiloamperes per cell. The processing environment is electrically noisy and contains explosive hydrogen and corrosive gases and liquids. For optimum efficiency the baths are temperature controlled to a few degrees Celsius. The optical temperature sensors provide the performance and reliability required, and expanded use is envisioned.

Several types of fiber-optic flow meters have been developed for control applications. Most are simple adaptations of conventional technology. In general, the following four approaches are used: (1) orifice plates (differential pressure), (2) turbines (frequency), (3) vortice shedding (frequency), and (4) laser doppler velocimetry-direct optical interrogation. Laser doppler velocimetry may be considered the most advanced technique; it is offered as a commercial product by several vendors. The advantages of this technique include an all-optical sensing head as well as wide dynamic range. The device works as a conventional laser doppler velocimeter, which measures particle velocities; however, fibers are used to transmit the light to and from the flow region. Work on the other three approaches has been limited to laboratory demonstrations, and the performance of these approaches is typical of the conventional technique from which they are derived.

Liquid-level sensors based on several different principles have been demonstrated. Sensors based on refractive index variations have received the most attention to date. These devices typically fall into two categories. Either fiber termination senses the liquid level through a coupling of guided optical modes to radiated optical modes in a region where the core of the fiber is exposed to the liquid, or the fiber is terminated in a prism where total internal reflection is used to couple the guided energy into a return fiber. In the presence of the liquid, the internal reflection in the prism is frustrated, resulting in optical power coupling into the liquid. Such devices are available commercially. Another type of sensor is based on measuring the differential absorption between two wavelengths. The absorption type sensor, like sensors based on an exposed fiber core, can in principle be extended to continuous level sensing.

Appendix F

APD	avalanche photodiode
BH laser	buried heterostructure laser
BISDN	broadband integrated services digital network
Bragg cell	acousto-optic cell
C^3	cleaved-coupled cavity laser
CCD	charge-coupled device
chirping	change of frequency during a pulse interval
CID	charge-injection device
CMOS	capacity-coupled metal-oxide silicon devices
CRT	cathode-ray tube
DFB	distributed feedback (laser)
DRAM	dynamic random access memory
EL	electroluminescent
EMI	electromagnetic interference
FPA	focal plane array
GaAs FET	gallium arsenide field effect transistor
GaAs/AlGaAs	gallium arsenide/aluminum gallium arsenide
GHz	gigahertz
HgCdTe	mercury-cadmium telluride
InP	indium phosphide
InSb	indium antimonide
IR	infrared radiation
IRST	IR search and track (radar)
LED	light-emitting diode

$LiNbO_3$	lithium niobate
MBE	molecular-beam epitaxy
MOCVD	metallo-organic chemical vapor deposition
MOS	metal-oxide semiconductor
Nd-YAG	neodymium-yttrium-aluminum garnet (laser)
OEIC	optoelectronic integrated circuit
PIN	photodiode made using three layers composed of p-type, intrinsic, and n-type semiconductors
SAGM APD	separate absorption and graded multiplication avalanche photodiode
SAM APD	separate absorption multiplication avalanche photodiode
SAR	synthetic aperture radar
SCBR	silicon chip Bragg reflector (laser)
SNR	signal-to-noise ratio
TDI	time-delay integration
VLSI	very large-scale integrated (circuit)
WDM	wavelength-division multiplexing