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Technology and Economic Assessment of Optoelectronics

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DEPARTMENT OF COMMERCE ★ NATIONAL BUREAU OF STANDARDS ★

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ABSTRACT

Optoelectronics is one of the two major technologies driving the revolution in communications, which will not only have profound effects on the economy but on social and political structures as well. The other technology, optical fibers, is already beginning to mature, but optoelectronics is rapidly catching up, enabling the acceleration of the "information age".

Future productivity advances in optoelectronics will come from integration of the various signal processing functions and from improved manufacturing technologies. Integration may occur in two important stages. The first, referred to "hybrid" integration, is almost at the point of commercialization. Hybrid devices use oxide-based (ceramic) materials and integrate some of the signal processing functions. Total or "monolithic" integration, based on gallium arsenide and related materials may not reach commercialization for another 8-10 years. In both cases, the economic impact will be substantial as information technologies become a critical element of most industries.

As a result, the U.S. and its major competitors, especially Japan, are making major R&D investments in optoelectronics. Worldwide R&D expenditures are expected to reach $1 billion by 1987. In terms of market penetration, fiberoptic systems will attain annual sales of more than $3 billion by 1989. The Japanese have made a national commitment to becoming the world leader in this market, borrowing from their substantial expertise in semiconductor technology.

Competitive positions in world markets will be determined by which countries rapidly advance all elements of the overall technological base. This base includes basic science, generic technology, applications (proprietary product and process technologies), and infratechnology. The last of these consists of measurement-related methods and data and has been shown to have significant effects on productivity growth in other technological areas. Optoelectronics is projected to be equally dependent on this technology element for rapid development and market penetration.

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INTRODUCTION

The economic potential of lightwave technology is vast, and, perhaps even more important, so is the potential for significant social and political impacts.

Light pulses can move through a glass fiber more than 50 percent faster than can electrons through, a copper wire and many times faster than electrons through ordinary semiconductor materials. Moreover, although transistors--the fundamental building block of the electronic computer--can switch on and off 100 million times per second while processing information, researchers have already built experimental light switches that are 10,000 times faster. They can cycle on and off in an incredible 1 trillionth of a second.[1] The optical fiber has equally superior capabilities when compared to copper wire--its counterpart in an electronic system. A strand of optical fiber can carry 500 times the amount of information. In fact, the main limit on further increases in the information-carrying capacity of a lightwave system is the speed of the optoelectronic components, in particular, the laser source.

The demand for optoelectronic components is derived from the demand for lightwave systems that perform functions such as communications, sensing, and control of large industrial plants. One indicator of the rate at which this system demand is mushrooming is the fact that the U.S. demand for optical fiber is expected to reach 2.0 million km in 1986, almost seven times the amount installed as recently as 1983.[2] Audio, video, and huge volumes of data will be transmitted simultaneously. This will make possible video phones, working at home, and potentially a more participatory political process. The technology also has important military applications.

The competition for commercial markets will be fierce. The Japanese believe that fiber and optoelectronic technologies are the keys to their goal of becoming the world leader in information industries. Nowhere is their characteristic aggressiveness more apparent than in this critical technology. The United States must remain competitive in all aspects of optoelectronics, not only to reap the substantial economic rewards, but to have control over the directions that the socially and politically important applications take.

This report analyzes technological and economic trends in the markets for optoelectronics technology. The primary objectives are to provide analyses and quantitative estimates of the economic benefits to the U.S. economy from the emergence of this technology and to identify and assess major technological barriers to the realization of these benefits. An analysis of measurement-related barriers and the associated economic costs is included in order to provide a basis for designing future research programs at the National Bureau of Standards.

Reports such as this one are important for planning in both industry and government because the estimates of the magnitude of various technical barriers can be used to help design private and public research programs with the highest payoff to U.S. industry. If, in fact, these programs lead to the accelerated removal of technical barriers, several major categories of economic benefits can be realized. First, <u>commercial introduction</u> may be accelerated if product-related problems such as optical damage can be overcome.

Second, initial commercial acceptance may be accelerated if problems such as life-time testing are solved, so that users have adequate data on the expected life times and reliability of optoelectronic devices. Third, diffusion can be accelerated if improved process monitoring and control leads to lower costs, or if improved material consistency leads to better, more consistent devices.

Sensitivity analyses performed by Charles River Associates [1984] indicated that relatively small shifts in the time profile of commercial introduction, initial commercial acceptance, and/or market diffusion for optoelectronic devices can have substantial leverage on sales of these products and hence on the cost savings and performance benefits that result from their use. Relatively small shifts in the timing of commercial introduction may also be important determinants of which country gains the competitive advantage in this technology and hence achieves the largest market share. The implication is that research programs which accelerate the removal of these barriers or problems can provide substantial economic leverage.

The concept of optical technology derives from the invention of the laser and also includes new applications of conventional optical techniques, such as lenses in high output lasers and LEDs (light emitting diodes) in optical communications and printers. The idea of transmitting information on a beam of light became practical about 1970, when Corning Glass demonstrated new high silica fibers having relatively low attenuation (signal loss). At that time sources of coherent light or lasers were already available and so the rudiments of a working system could be put together. Although research continued over the decade of the '70s, private investment and progress in this field has been accelerating significantly in the 1980s as the commercial potential of this technology has become better understood.

This report focuses on applications of optoelectronics for information-handling systems (excluding optical computing).[3] A revolution is underway in the application of information technology to office, the factory, and the that will continue for several decades. Opportunities will proliferate for developing new products to meet a growing variety of information needs. Similarly, the availability of new and varied sources of information will permit more efficient and productive operations of all kinds. In the area of information applications, the most important characteristics of the optoelectronic technology are those relating to signal processing techniques.

In some specific and very important application areas such as telecommunications, the dominant trend in signal processing technology is integration of the various functions performed directly on an optical wave. Integrated optical circuits are optical guided-wave devices that perform a variety of processing functions on the light beams which they guide, and the degree of integration may turn out to be highly correlated with increases in such performance attributes as processing speed and with declining cost of production.

The main advantages of light wave technology for commercial information-related applications, from which is derived much of the demand for optoelectronic devices, are

* Higher transmission rates and transmission capacities for all types of information (audio, video, data, and combinations of the three)

* Secure communications channels--tampering without detection is virtually impossible

* Immunity from electromagnetic and radio-frequency interference that would otherwise compromise performance (also important for military applications)

* Higher performance sensors, such as optical fiber gyros

Integrated optoelectronic circuits for telecommunications applications can be envisioned as eventually consisting of single semiconductor chips with integrated optoelectronic transmitters, comprising lasers and electronic support circuitry, not only for driving the laser, but also for monitoring, stabilizing, and shaping its light pulses. Similarly, future receiver chips would include amplifiers, equalizers, and pulse reshapers, as well as the photodetectors themselves.

Because lasers are already being used in ranging, printing, and optical disk writing, as well as in such optical fiber sensors as hydrophones, magnetic sensors, and gyroscopes, optoelectronic technology is likely to benefit these applications also.

The economic potential of optoelectronic technology is immense. Collectively, the applications for this technology should grow over the next 15 years at a rate at least as fast as any other area of electronics. Not only will the economic impact be substantial, but the social and political impacts of changes in the way people work and live may be even greater, brought about by as much as a hundred-fold reduction in the cost of accessing information.

PART 2

OPTOELECTRONIC TECHNOLOGY

This new but rapidly emerging technology has been widely discussed in trade publications, technology forecasts, market studies, and government-sponsored competitive assessments. The majority of these analyses have focused on communications applications, in particular, optical fibers. Other application areas with substantial market potential have been given less attention, probably because their development cycles are somewhat behind that of optical fibers. The only comprehensive comparative analysis to date of these other areas is a study of the Japanese optoelectronics industry by the Yano Research Institute [1983] of Tokyo. Although the statistical data are limited to Japan and are only of historical interest (1981 or earlier) in this rapidly changing area, the classification system is comprehensive and still relevant.

An ideal classification system emphasizes applications which are described in the context of the major functions that the technology is being targeted to perform. Classifying applications under an umbrella of market-oriented functions that the new technology and existing competing technologies perform is an important characteristic of Japanese planning.[4] The major functional classifications used in the

Yano report are

<u>Information-Handling</u>

Photo-applied equipment (such as laser printers or optical video disks

Photo-applied sensing (such as laser radar or fiber sensors)

Communications (data, image, voice transmission)

Optical Information Processing (such as space parallel processing or spectrum analyzers)

<u>Energy-Related</u>

Machining techniques

Power generation

Lighting

Heating

Below the market-oriented classification level is a product-oriented level such as the classification scheme adapted from Holman and Wood [1985]:

simple devices:

- fibers
- lasers
- photodetectors
- microelectronic control
- passive connectors
- passive couplers

complex devices:

- electrooptical switches
- modulators
- multiplexers
- repeaters
- signal processors
- optical amplifiers

materials:

- III-V SEMICONDUCTORS[5]
- oxide electrooptics
- organics

glasses

processing:

crystal growth
thin-film deposition
ion-implantation
lithography

manufacturing technology:

microassembly
packaging
process control
reproducibility
automation

The evolution of optoelectronics technology is expected to occur in three phases. In the first phase (current market), optoelectronic systems have been composed of distinctly separate electronic circuits (for signal generation, modulation, amplification, detection, switching, and filtering) and optical components (light sources and detectors). Acoustic components may be used for coupling. These systems resemble electronic circuits prior to integration, when circuits consisted of a number of discrete components such as transistors. "The components are fairly bulky, and can be subject to alignment problems, temperature drifts, vibration, moisture, and dust. In addition, they require that light-encoded signals be converted to electronic ones for switching and other processing".[6]

The second phase is the current state of the art in the sense that progress has moved beyond the research stage into development, with initial commercialization of new products imminent. This phase includes <u>some</u> integration of the electronic and optical components. Basically, such "hybrid" integration consists of semiconductor components, which perform various waveguide functions, deposited on the same substrate. These forthcoming integrated optic devices are expected to be manufactured using monocrystalline (single-crystal) substrate such as lithium niobate because of their acceptable electrooptic properties and relative ease of fabrication.

The third phase will produce totally integrated structures on a single-material substrate of a ternary or quaternary semiconductor (i.e., a semiconductor composed of three or four elements). These substrates will likely be based on gallium arsenide. The important implication is that most of the production requirements of electronic and optical devices can be met by a single material and single basic production process, rather than two or more materials with distinctly different production processes. The expectation is that such total integration will provide greater reliability, circuit density, and speed.

An important advantage of integration is the reduction of interconnection problems that occur during electronic/optical and optical/electronic signal conversion. A single integrated optoelectronic circuit on, say, a gallium arsenide chip might, for example, link electronic equipment and optical fibers, thereby replacing an elaborate interface with several parts. Moreover, because integration reduces unwanted path delays and other effects of electrical interconnections, the integrated device would be speedier and less noisy. In addition to processing light itself without conversion to electricity, the eventual integration of several components on a single substrate or chip will provide the substantial advantage of increased stability. This is the key to achieving circuits that can handle coherent optical waves in small, densely-packed, and highly versatile configurations.[7]

DESCRIPTION OF THE TECHNOLOGY

Although electronic components will interface with optical components at some point in an optoelectronic-based system, the development of optical technology will be the critical driving force in determining the rate and direction of advance of the overall technology and the evolution of market applications.

Particularly important is the interface between fiber optics and microelectronics. Optical fiber technology is well developed at this time. Continued materials and production process advances will likely continue, but radical technological advances in fibers for 1.3 micron and 1.5 micron transmission windows are neither needed nor expected. The "interface" technology is another matter. This technology performs functions such as switching, modulating, control, test, and distribution, which are just as critical to the overall system productivity. The interface requirement derives from the fact that microelectronics is based on electrons and optical fibers is based on photons. Interaction between the two requires an "optoelectronic" function that provides a transition between the two domains. Optoelectronic technology therefore encompasses "the broad range of materials and devices that generate light (lasers and light emitting diodes), amplify light (optical amplifiers), detect light (photodiodes), and control light (electrooptic circuits)".[8] Each of these functions requires electrical energy to operate and depends on electronic devices to sense and control this energy.

One exception to the requirement for electrical energy is a group of optical materials whose refractive indices depend in a nonlinear way on the intensity of the light passing through them. Potential applications of this property are configurations known as optical bistable devices (OBD), in which the optical signal itself biases the optical device without electrons or conversion to the electronic domain.[9]

Four major areas of optoelectronic technology appear to be pivotal in determining which competitors dominate the emerging markets:

(1) monolithic optoelectronic integration. The objective of monolithic integration is to combine on a semiconductor wafer or chip the high-speed microelectronic functions, laser signal sources, aligned optoelectronic switching circuits, and photodetectors. This technical achievement promises to simplify, improve the quality, and increase the performance of the interface between microprocessors and the optical fibers that will interconnect them in all future high-performance systems applications.

The importance of technical and commercial developments in monolithic integration cannot be overemphasized. Japan is attempting to direct its impressive skills in III-V semiconductor lasers toward full wafer-scale monolithic optoelectronic integration technology. Achieving practical monolithic optoelectronic integration on a common III-V semiconductor substrate is certainly Japan's primary, if not only, target for the next 15 years.[10] If the Japanese succeed, the reason will be the development of thin-film process technology. Mass production of low-cost circuits will not be possible without significant progress in this area.

Holman and Wood [1985] point to two short-term technical goals that the Japanese may be near achieving:

DBR and DFB lasers[11]--
Tokyo Institute. of Technology,
Hiroshima Univ., KDD, NTT, NEC, Toshiba

Partial monolithic integration--
laser and electronics - Hitachi
detector and electronics - Fujitsu
laser and FET[12] - Fujitsu
detector and electronics - NEC

(2) In-line optoelectronic amplifiers. These devices may replace the conventional repeaters currently being used in long-haul telecommunications systems. No signs of commercialization are yet evident. Japan's R&D efforts are primarily at NTT's Electrical Communications Laboratory. In the United States

no significant R&D effort has been identified. Some R&D is apparently underway at British Telecom.

(3) Bistable materials and devices. An important application could be a bistable optical switch in which the switching state can be controlled directly and rapidly by the very optical signal to be switched. Development of such a switch would eliminate the expensive optical-to-electrical conversion necessary in first-generation electrooptical switching technology. Optical bistability would allow response to a destination pulse in the incoming optical signal to correctly bias or position the switch for subsequent data pulses.[13]

No commercialization seems possible in the near future. The United States appears to be as far along as Japan and European countries in the development of bistable optical switching science and technology. However, the Japanese appear to be building a "very strong theoretical, experimental, and materials base". Bistable switching is also the subject of a major international research initiative in Europe.[14]

(4) Optoelectronic Couplers and Switches. These devices are essential for cost-effective single-mode optical fiber systems. Among the types of practical components needed are isolators, polarization filters, intensity modulators, phase shifters, switches, multiplexers, and demultiplexers.

Three primary obstacles exist to cost-effective, high-volume manufacturing of such components: process control, package development, and automated asssembly. The Japanese appear to be in the strongest position to integrate these key technologies, as all three areas are major strengths of their electronic firms both at the R&D and production stages.

Of the above four areas of optoelectronic technology, monolithic integration has the greatest potential impact. However, this is a "next generation" technology. Ahead of it and just now entering the market place is hybrid integration. Thus, the general topic of integrated optics requires considerable discussion.

Integrated Optics Technology

As summarized by Alferness [1981], the acceleration of interest and progress in integrated optics in the United States "is no doubt a result of the rapid progress in low-loss, high bandwidth single-mode fibers and semiconductor lasers, as well as the interest in integrated optic devices for use in noncommunication applications such as the spectrum analyzer and fiber sensors." Sever-' years later, Alferness [1984] observed that integrated optics has "the potential to provide efficient, low-power, compact, mass producible electrooptic waveguide devices for a number of years, [and] appears to have imminent applications in three primary areas: telecommunications, high-speed signal processing, and fiber sensor processing."

As a result, U. S. firms have dramatically increased their investment in integrated optics research and development (R&D). Many firms, which were not visibly in optoelectronics as recently as 1983, now have major dedicated research efforts underway. The same pattern of increased investment in optical technology R&D is being observed in Japan. The Yano Research Institute [1983] observes that "most of Japan's leading companies have organized special departments called 'Optical Systems Divisions', and the actual pace of the commercialization of optical technology has proved more accelerated than expected several years ago."

The name integrated optics encompasses all optical or guided-wave devices used to perform functions directly on an optical wave. The basic fiber optic system consists of a light source to initiate the light beam, a glass fiber waveguide (optical fiber) to guide the light beam, and a receiver or detector to decode the information and transform it back to electricity. The light source is either a laser or a light-emitting diode, and the receiver has a light detector made from a semiconductor material. For transmitting over long distances, repeators are required to amplify the signal.

Hybrid Integrated Optics

Hybrid integrated optic waveguide devices are usually made from a single crystal wafer designed to confine the wave in a narrow channel a few microns wide and deep. The device has specific paths or channels of higher refractive index than the surrounding medium, and this enables it to contain and conduct the wave. Some such devices employ a physical property possessed by certain materials called the electrooptic effect. This effect is characterized by a change of the optical index of refraction when an electric field is applied to the material. [15]

In the generation of integrated optic devices currently reaching the commercialization stage, oxide-based materials such as lithium niobate, lithium tantalate, and other related materials are being used. These substances provide waveguide functions (switching, modulating, multiplexing or filtering, and coupling) but not signal generation or reception functions, i.e., they do not serve as sources or detectors. In a "hybrid" optical system, therefore, other components must perform these functions and be physically attached to the substrate.

Ceramic-based (oxide-based) substrates such as lithium niobate have relatively strong electrooptic effects (measured by the electrooptic coefficients along the crystallographic directions), so that modest voltages are required to produce an effect strong enough to serve as the basis for practical devices. "Active devices" employ an electric field to induce a change in refractive index which forms the basis for a switch, a modulator, or a (de)multiplexer. "Passive devices" do not require the use of an electric field. Rather, waveguide channels are positioned in a configuration that allows the device to perform a coupling or filtering, but not a switching function.

Lithium niobate is currently the preferred material for making optoelectronic devices for two reasons. It has relatively similar values of the electrooptic coefficient in the different crystallographic directions, making it nearly insensitive to the plane of polarization of the incoming light signal. This ceramic material also has the potential to yield large single, homogeneous crystals of reasonably high quality. For switching and modulation applications, lithium niobate has an advantage along one performance dimension over III-V semiconductors because of its considerably larger electrooptic effect.

Several oxide materials possess electrooptic "figures of merit" larger than that of lithium niobate: barium strontium niobate, barium sodium niobate, and barium titanate. However, lithium niobate is expected to remain the material of choice for some time because it should soon be readily available as large-diameter single crystals of optical quality higher than that of other materials with comparable electrooptic coefficients. This compound also offers excellent chemical and adequate physical ruggedness, is a superb electrical insulator, and is well suited to the formation of guided-wave circuits. None of these other materials possesses all these advantages.[16]

Lithium niobate does, however, have two performance limitations that could lead to its eventual replacement in optoelectronic applications. Its optical properties are not sufficiently nonlinear to allow the development of monolithic bistable optical switches. And even more important, lithium niobate does not have the potential to perform as a practical laser source, photodiode, or electronic circuit.[17] These functions must therefore be integrated with lithium niobate circuits in a hybrid manner. While this is not impractical, the potential cost is high unless automated microassembly and packaging methods can be developed.

Lithium niobate crystals are grown from a melt by the Czochralski method, a standard crystal-pulling technology used widely in the semiconductor industry for making semiconductor-grade silicon. The crystals can be grown in three-inch-diameter by two-foot-long dimensions from the melt.[18]

There are three competing methods for forming waveguide devices from lithium niobate. Of these, the most extensively practiced is the in-diffusion of titanium because of the ease with which three-dimensional or channel-type waveguide structures can be formed. The steps in the process for producing lithium niobate waveguides using titanium in-diffusion are

(1) lithium carbonate, which is a relatively cheap material, and niobium pentoxide, which is more expensive, are mixed and melted in a crucible. A single crystal of lithium niobate is grown by the Czochralski technique, which involves slowly drawing a starting seed crystal out of the melt contained in a crucible, with the crystal continually solidifying as it is drawn out. The Czochralski technique is the only commercial technique known to be currently in used for making lithium niobate crystals.

(2) The finished single crystal is cut into one millimeter thick wafers; during the cutting step a sizable portion of the lithium niobate is lost in the form of dust. The wafer is then polished and prepared for actual waveguide production.

(3) In order to produce a waveguide, channels of higher refractive index (to contain the light) must be formed in the wafer. The channels are only a few microns in diameter. Different kinds of devices from couplers to switches and modulators are formed by changing the design of the channel patterns and the modulating electrode configuration. The favored technique is to in-diffuse evaporated titanium onto the surface of the lithium niobate in the presence of oxygen. Before in-diffusion, the desired channel pattern is delineated by photolithographic techniques similar to those used in integrated circuit technology.

(4) A layer of photoresist is deposited on the wafer. The photoresist is exposed to ultraviolet light through a mask with the desired channel pattern in it; a solvent is then used to dissolve the photoresist, either where the channels are desired or on the remainder of the wafer (depending on the process used).

(5) Titanium is then evaporated onto the surface to the desired thickness.

(6) The wafer is placed in a second chemical bath which removes the titanium except in the regions of the channels. This leaves very fine strips of titanium across the surface in the desired channel pattern.

(7) The titanium is then diffused a few microns into the wafer surface at high temperature in the presence of oxygen.

<u>Technical Barriers</u>. In spite of the significant research advances in recent years, the Charles River Associates report and additional industry interviews have identified a number of technical barriers that are currently inhibiting further technical development and subsequent commercialization of ceramic-based integrated optic devices. These barriers are related to both material limitations and to limitations inherent in the physics of the devices themselves:

<u>Optical damage</u>. the currently preferred optical device production technique, titanium in-diffusion of lithium niobate, yields waveguides which suffer from significant photorefractive sensitivity (or susceptibility to optical damage) in the visible region of the spectrum compared to other production techniques. (The optical damage is a change in refractive index of the waveguide during exposure to visible light and is characterized by a loss of transmitted power.)

The effect can be minimized to a large extent by heating crystals or waveguides above 300 degrees Centigrade, by using a longer wavelength light (such as in the infrared region), or by using a light beam with very low power densities. However, the propensity for optical damage remains a problem in designing systems, even though over the last few years a partial understanding of mechanisms causing optical damage has been achieved.

Factors facilitating long-term resistance to optical damage at the long wavelengths have not yet been adequately characterized. Accelerated life-time testing is not deemed adequate for lithium niobate devices and long-term tests (of at least one-year duration) in the infrared region are needed.[19]

Availability of consistent material. Lithium niobate is often found in a nonstoichiometric state.[20] That is, the ratio of Li_2O to Nb_2O_5 is not always one-to-one and the optical properties vary significantly with the stoichiometric change. Variations in starting compositions for material used in waveguides can cause significant and intolerable variation in waveguide performance. First, uniform formation of the waveguide is strongly affected by the stoichiometry. Second, such variations imply that the refractive index will vary and the electrooptic effect induced by the externally applied field will also vary across devices. If variations occur across a wafer, switches in a set have different properties. Variation along the boule leads to wafer differences and with the result that one set of switches varies from another.[21]

Over the long term, optical properties appear to change. This phenomenon is called "driftback". The source of driftback is unknown, although a suspected cause is the existence of traps in the material or the presence of fields that affect trapping.

The control of stoichiometry and impurity levels will be critical for quality control and the achievement of high yields in the production of devices which exhibit a standard, uniform response.

Electrooptical Coefficient and Implications for Device Configuration. Basic problems remain related to the inherent bulkiness and size of waveguide devices relative to electronic devices that perform similar functions. The length of a single switch made from lithium niobate can be up to one-half centimeter. A larger switching array (for example, a 16-by-16 array) would be quite large compared to an electronic integrated circuit chip designed to perform switching applications. The lithography to downsize is available, but in order to obtain tolerably small switching voltages the device must be several millimeters long. The change in the index of refraction must be large enough to result in a sufficient phase change in the light signal to effect switching. The index change must be integrated over a sufficient length in the waveguide to achieve the phase change necessary to switch, and this therefore requires the waveguide to be relatively long.

Materials with higher electrooptic coefficients are highly desirable as these would allow the development of more compact devices. Alternatively, to make the proper index change over a shorter distance, the applied field would have to be larger, which is less desirable. Materials with higher electrooptic coefficients than lithium niobate include strontium niobate and sodium barium niobate. However, the crystals of these two materials are defect-prone. More work is needed on the basic engineering of growing defect-free crystals of these types of materials.[22] To this end, development of potassium niobate has been advocated.

These barriers to the commercialization of hybrid integrated optic devices have important <u>measurement-related</u> components. The most important areas of deficiency are

<u>Optical Material Characterization</u>. A need exists to define and qualify an <u>optical grade</u> of lithium niobate. Characterization of <u>required impurity</u> levels, their distribution, and the permissible level of nonstoichiometry in lithium niobate are needed.

An ability to achieve greater consistency in material quality from one production run to another is required. Lithium niobate wafers are very expensive because customers are asking for extreme <u>control</u> of all properties. The demands result from lack of knowledge of the purity needed and what impurities are significant. If suppliers knew what to control and to what degree, production costs could be significantly lowered.

Meeting such requirements will necessitate greater control and monitoring of processing, which will, in turn, require standards as to what constitutes an optical grade of lithium niobate as a function of system requirements and device performance.

Such standards would also need to take into account the effects of variations in lithium niobate stoichiometry on device performance.

Phase Equilibria. Research on the phase equilibria of melting relations in lithium niobate containing additives such as magnesia and titania would be of considerable help to industry. Availability of these phase equilibria data would enable better control of the crystal growth process and allow improved characterization of the final crystalline product.

Waveguide Fabrication Monitoring Techniques. Researchers at a leading laboratory have stated that measurements of lightwave guide properties have been found to vary significantly for properties such as insertion loss and coupling loss. They have found 20 to 30 percent differences in the measurement of coupling loss. Examples exist of one group seeing phenomena such as "double moding" using the same measurement methods as another group which did not observe it.

As development nears the pilot production stage prior to commercialization, measurement techniques to monitor the operations involved in making waveguide devices will be needed. This would include developing techniques to monitor the channel size of the waveguide and a rapid technique for monitoring the titanium diffusion profile in the in-diffused waveguides without having to process the device all the way. Measurement of these index profiles is important, as smooth profiles are not necessarily expected due to variations in dislocation density, scattering, etc. No fully acceptable technique exists for determining the radial index profile of a light guide.

Lifetime Testing. Performing extended lifetime testing of waveguide devices for times of one year or more. Apparently no one has done such test using infrared light. Accelerated life tests have been performed but are considered inadequate in giving true assessments of long-term performance. Industry needs methods to obtain the test data to accurately assess long-term performance and resistance to optical damage in the infrared.

In summary, significant progress has been made in waveguide device research (primarily titanium-doped lithium niobate), but significant development is still needed to make this a practical technology for mass-produced components. According to Alferness [1984], "if very high bandwidths are desired, integrated optic components may prove useful and economical. For such large volume applications, the thin film manufacture of integrated optic devices like taps, switches or wavelength demultiplexers would provide a tremendous economical benefit over bulk components."

With respect to measurement technology and related data, the state of the art is at the same stage of development as measurements for fiber optics were seven to ten years ago. Currently lacking suitable measurement methods, users cannot tell if suppliers' materials meet specifications. Failure or inability to to measure and control each process step results in low yield rates or overdesign, either of which adds significantly to cost. Trying for zero percent error in each process step because the significance of each step is not known is currently characteristic but very impractical. Given the rapid progress of foreign competitors, particularly the Japanese, failure to close these gaps will impose significant economic costs on U.S. industry and result in reduced shares of world markets.

Monolithic Integrated Optics

Combining lasers, detectors, and active electronic devices for modulating light signals on a single-crystal chip was first suggested 13 years ago by Amnon Yariv. Advances in the fabrication of electronic and optical devices--transistors as well as lasers and photodetectors--have confirmed the feasibility of combining the two types of devices into one circuit to create a new, powerful class of monolithically integrated circuits for a number of applications.

The current view is that such circuits, made from gallium arsenide (GaAs) and other elements (such as aluminum or indium and phosphorous) will not only be smaller than electrically connected discrete devices (including hybrid integrated circuits), but more rugged and reliable. They should also cost less.[23] Ceramic materials provide only the functions of a substrate for the other circuit elements and as a waveguide for the light beam--hence, the label "hybrid" integrated circuits. The degree of integration is therefore limited to the waveguide-related functions such as switching, modulating, multiplexing or filtering, and coupling. Gallium arsenide circuits are also capable of being used for signal generation and reception, i. e., as sources, repeaters, detectors, etc., and hence have been characterized as providing "monolithic" integration. Typical lasers formed in these structures will generate light in the near infrared and infrared regions of the spectrum, from 0.75 to 1.6 micron wavelengths.

Note must be taken, however, of recent research at Stanford by T. Y. Fan and R. L. Byer [1985] which may eventually upset the three-stage evolution of integrated technology discussed above. Fan and Byer have demonstrated an optically-excited lithium niobate laser at 1.09 microns. If subsequent research can adjust the dopants to lengthen the operating wavelength, the predicted evolutionary transition to gallium arsenide may become subject to challenge. At this time, however, most researchers remain adamant that oxide materials like lithium niobate cannot be made into a viable laser in which the lasing is stimulated by an electric current as opposed to a light source.

Farther into the future, II-VI semiconductors may become the materials of choice at longer wavelengths. Research in this direction would benefit from existing technology developed for infrared detectors.

R&D investment in monolithic integration of waveguide devices, active components (lasers and detectors) and the associated microelectronics will continue to increase. According to Alferness [1984], this increased investment is due to encouraging progress in reducing semiconductor waveguide losses, improved epitaxial growth techniques, and a maturing laser technology. Nevertheless, although achieving practical and cost-competitive monolithic integration in III-V materials is a promising goal, a commercially successful outcome is not inevitable. A number of nontrivial obstacles must be overcome. These obstacles are discussed below. Because of the experimental nature of gallium arsenide-based optoelectronics, a discussion of specific product and process technologies is postponed to Part 3, which examines R&D trends.

Technical Barriers. Some of the significant barriers to eventual commercialization, organized by major category, are

Materials-related barriers:

(1) The most suitable III-V substrate material depends on the particular device application. According to Holman and Wood [1985], high-speed electronic circuits, semiconductor lasers, photodetector arrays, and guided-wave electrooptic circuits may each have their own unique substrate and active layer requirements. Significant technical developments will be required before these performance requirements can be attained with a common substrate.

(2) For some applications, the power and frequency requirements are leading researchers to materials which have shorter lifetimes; but, lifetime testing methods are inadequate for effective research.[24]

(3) Heat dissipation problems and the larger optical losses inherent in GaAs may be characteristics intrinsic to this material and not removable or mitigated by further processing improvements.

(4) GaAs also has a much lower electrooptic coefficient than lithium niobate, so a higher driving voltage is likely to be required.

Process-related barriers:

(1) Production yields. Perhaps the ultimate limitation with respect to yield in the production of GaAs devices will be the quality and uniformity of the substrate material. The defect density is still quite high, although the Japanese have made

substantial progress. The high-yield production of very high-quality, low-dislocation density, III-V substrates requires the minimization of extended crystal defects (dislocations).

The multilayer III-V optoelectronic fabrication process yields must be increased significantly over their present levels if wafer-scale integration is to become commercially successful. For example, infrared laser diode sources are now commercially available, but lack of effective production technology is still a serious problem. Yields of 10 percent were being reported until recently. Within the past two years, yields of laser production have risen to 50 to 70 percent, but this is still not acceptable. The laser diode light sources have multiple-layered structures, the production of which is difficult.

Even more important is the total yield of the monolithic integrated chip which is the yield of the laser, multiplied by the yield of the electronics, multiplied by the yield of the waveguide circuit, multiplied by the yield of the detector array.[25]

(2) Wafer-scale integration. Difficult substrate compatibility problems must be overcome before high-speed electronic circuits, photodiode arrays, distributed Bragg reflector (DBR) lasers, and optical waveguide circuits can be integrated onto a common substrate. For example, the monolithic integration of a semiconductor laser and an electrooptical guided-wave circuit requires that the laser cavity be formed by distributed feedback, distributed Bragg reflection, or some similar process that puts the output beam directly in the waveguide plane.

According to Holman and Wood [1985], excellent progress in this area recently has been made in Japan, particularly at the Tokyo Institute of Technology and at NEC, but commercial laser sources are still formed with cleaved facets as no major effort has been made to bring to a commercially viable level the somewhat intricate grating etching processes.

(3) Thin-film technologies. This general approach seems to hold the key to competitive advantage through low-cost production. However, promising thin-film processing techniques (such as MBE and MOCVD) currently require the use of toxic

chemicals and complicated control electronics.[26] The complexity of process control plus slow deposition rates are barriers to cost-effective production. Mass production at competitive cost will not be possible without significant progress in developing new process concepts and control techniques.

(4) Microassembly. The assembly of cost-effective optoelectronic components requires that the various elements (the lasers, fibers, optical circuits, electronic circuits, and photodetectors) be packaged quickly and in an automated manner.

According to Holman and Wood [1985], the most critical aspect is that optoelectronic elements have to be positioned precisely with respect to each other. The alignment tolerance needed is usually measured in fractions of a micron. Proper design of packaging materials and substrates, automated micromanipulation, automated microbonding, and feedback control are the characteristics of a successful approach.

Industry sources interviewed by Charles River Associates [1984] indicated that ten years will likely be required for this technology to reach the stage which lithium niobate has achieved today (that is, early in the development stage as opposed to the research stage). Thus, monolithic integrated devices may not begin to substitute for ceramic integrated optic devices until the mid 1990s, assuming the current projected productivity differentials remain intact over the next ten years. Nevertheless, the astonishingly total commitment by the Japanese to monolithic integration based on III-V semiconductor materials means that future U.S. competitiveness demands a sustained and intensive R&D response.

Part 3

RESEARCH & DEVELOPMENT TRENDS IN OPTOELECTRONIC TECHNOLOGY

No integrated-optic devices are commercially available today, with the exception of one relatively simple device recently introduced by Toshiba. However, as evidenced by the market projections in the following sections, the growth rates for devices based on integrated-optic technology will be exceptionally high. Moreover, the demand for integrated-optic devices is derived from the demand for systems or final user applications which have orders-of-magnitude greater markets as measured in terms of sales (although not necessarily in terms of value added).

An increasingly large and diverse number of firms have become convinced of the economic gains from this technology to the point of taking results of their applied research to the considerably more expensive development stage. This commitment is based on the belief that at least communications markets and likely others will grow extremely fast over the next 10 years.

However, before optoelectronic devices reach their target markets in communications and other areas, the functions to be performed or the level at which they will be performed will have to be more accurately defined. High-speed optical switches, modulators, wavelength filters, and polarization manipulators have been made in the laboratory, but in the simple systems currently being developed these devices are not yet utilized. Existing systems consist of three separate (non-integrated) components: a laser, a fiber, and a detector. Current commercial lasers are capable of being turned off and on for such applications as switching at speeds of over 1 Gigahertz (1 billion times per second). This speed equals the current maximum for a electronic switch, but higher data transmission capacity will be required. Optical switches can potentially be turned on and off in an incredible one trillionth of a second. Integrated optics will be needed to perform these more sophisticated, high-speed functions.

The following sections discuss R&D investment trends and emerging commercial markets for optoelectronic technology.

RESEARCH & DEVELOPMENT INVESTMENT TRENDS

Besides the United States, Japan is a major factor in world markets for optoelectronic technology. A number of European firms have also made major commitments to this technology. In the United States, AT&T has been the dominant performer of generic technology research, at least for communications applications. Its counterpart in Japan, NTT (Nippon Telegraph & Telephone), has played a similar dominant role in that country. Many other firms in both countries have radically increased their R&D investments in recent years, with the result that the amount of applied research and development has increased significantly. A reasonably comprehensive list of market participants is given in Table 1.

The United Sates may actually be the world leader in basic and generic III-V microelectronic technology research, but the Japanese are ahead in the all-important applied R&D. The Japanese have made a strong national commitment to achieving world leadership in

Table 1

U.S. and Foreign Companies Involved in Optoelectronic R&D

U.S. Companies	Japanese Companies	European Companies
Allied	Canon	British Telecom (U.K.)
AMP	Denki	CNET (France)
ASA	Fujitsu	Ericsson (Sweden)
AT&T	Furukawa	Philips (Holland)
Battelle Laboratories	Hitachi	Plessey (U.K.)
Crystal Technology	KDD R&D Labs	Siemens (Germany)
Cyberoptics	Matsushita	Thompson CSF (France)
Dukane	Mitsubishi	
Dupont	NEC	
General Optronics	NTT	
GTE	Oki	
Hewlett-Packard	Omron Tateisi	
Honeywell	Shin-Etsu Handotai	
Hughes	Sony	
IBM	Sumitomo	
ITT	Toshiba	
Kodak		
Lasertron		
Litton		
Lytel		
McDonnell-Douglas		
MMM		
Motorola		
Optovision		
Optron		
Ortel		
Polaroid		
RCA		
Rockwell		
TRW		
Westinghouse		

optoelectronics technology. Although they actually entered this field in earnest after the United States and Western Europe, Japan currently is the world leader in the cost-effective production of semiconductor lasers, and their optical fiber technology is second to none. Japanese private-sector R&D investment in optoelectronics is growing at a rapid rate. The total European R&D effort in this area is estimated to be about one-half the total U.S. investment. The technology leader in Europe is believed to be France.

Table 2 provides some rough estimates of worldwide private and public R&D expenditures for optoelectronic technology. These estimates were compiled by surveying domestic and foreign industry officials and U.S. observers of this industry, some of whom have recently visited foreign research facilities. Respondents were asked to estimate the the number of full-time equivalent scientists and engineers engaged in optoelectronic R&D for firms actively pursuing this technology. An attempt was made to focus the estimates on dedicated optoelectronic research. A substantial additional investment in III-V (gallium arsenide) semiconductors is being made for microelectronic applications as well as for optoelectronics. Where possible, a portion of these funds was added to the estimates in Table 2.[27] Average annual expenditure rates per employee were then applied to estimate R&D expenditures. These rates varied depending on the sophistication of the research and the country in which the firm's R&D facility is located. The data collection was not comprehensive or highly structured, and the estimates and trends should be considered quite rough.

The estimated year-to-year increases are substantial due to increased investments by firms already committed to optoelectronics and to the entry of new participants. For example, Japan's NTT increased its total R&D expenditures between 1983 and 1984 by 35 percent. During this same time, a number of U.S. firms such as Dupont, Kodak, and Polaroid formed dedicated R&D programs. In just two years (1987), total worldwide R&D expenditures for optoelectronics

Table 2

Estimates of
Optoelectronic R&D Expenditures
(in $millions)

	1981	1982	1983	1984	1985	1986	1987
United States							
Industry	65	98	122	192	250	312	375
Government	4	5	6	18	27	27	38
Total	69	103	128	210	277	339	413
Japan							
Industry	106	132	160	206	258	322	386
Government	6	15	21	24	26	22	19
Total	112	147	181	230	284	344	405
Europe							
Industry							
Government							
Total	30	45	65	90	140	165	190
World Total	211	295	374	530	701	848	1008

Sources: industry and government interviews, MITI documents

Note: U.S. R&D expenditures estimated by obtaining estimates of full-time equivalent scientists and engineers currently engaged in optoelectronic R&D in the United States at levels from $150,000 to $250,000 per scientist year, with the level depending on the type of research; similarly, estimates for Japanese industry research expenditures were obtained by multiplying estimated full-time equivalents by $125,000 to $200,000.

are expected to reach an annual rate of approximately $1 billion. Government funding will be a small, although critical, percentage of total R&D expenditures.[28]

In terms of U.S. industry structure, a survey by Kessler Marketing Intelligence (KMI) yielded an average estimate of 233 systems firms and 200 to 300 components manufacturers.[29] But, as pointed out by KMI, the industry structure in 10 years will likely parallel the electronics industries in which the number of systems manufacturers is orders of magnitude greater than the number of component suppliers.

Finally, although telecommunications is the dominant application area today (58 percent), the KMI survey indicated that in 10 years the portion of the market represented by telecommunications will have fallen below 50 percent.[30]

R&D TRENDS IN COMMUNICATIONS

"What Marshall McLuhan called the 'Global Village' will come about through advanced technology in fiberoptics and electrooptics in the future. All communications will be digitized and integrated onto a single system. The main transmission portion of that system will use optical technology."[31] The integration process is already underway. For example the distinction between voice and data is disappearing. Fiber optic systems are increasingly using telephone hierarchies, originally designed for voice channels, for both voice and data. In the future, "the amount of information transfer will become so vast that only optical communications will have the capacity to handle the traffic." In the not-too-distant future, architects designing buildings and houses will assume that the contractors that install lighting, heating, and air conditioning systems will also have the expertise to install fiberoptic systems for centralized communications. The centralized systems will include telephone, data, videotex-type services, along with the control systems for these services and communications.[32]

With respect to major R&D strategies, both the United States and Japan are pursuing the development of currently more successful oxide-based electrooptics such as lithium niobate and the more distant but currently more versatile III-V semiconductors such as gallium arsenide and indium phosphide. Based on the published literature, Japan appears to be allocating most of its optoelectronic R&D to III-V semiconductors. The main reason is the desire to draw upon their existing comparative advantage as the world's leader in manufacturing III-V semiconductor laser diodes. They thus have the requisite process technology well developed and should have an advantage in developing the process technology for integrating laser, electronics, detectors, and optical switches on large III-V chips or wafers (i.e., the optoelectronic integrated circuit).[33]

However, Japan is not ignoring hybrid integrated optics based on oxides such as lithium niobate. As pointed out by Holman and Wood [1985], a few more assembly steps are required, but Japan is "skilled in working cost effectively with small parts and in automating complex assembly." Holman and Wood also argue that the "Japanese can take the best III-V laser sources, and separate detector chips (either or both monolithically integrated with electronic circuits), and use them with electrooptical switches and circuits made from oxide electrooptics such as lithium niobate".

Japan is, in fact, still pursuing lithium niobate and related oxide-based electrooptics. On the one hand, NTT's research labs appear to be doing "very little work on lithium niobate", if the scientific literature is used as an indicator. On the other hand, lithium niobate technology may simply be in the process of transfer to development at NTT. Moreover, "niobate technology appears to be spreading into a number of industrial laboratories that were either minimally involved (NEC and Mitsubishi) or previously uninvolved

(Fujitsu and Canon).[34]

AT&T seems to be following a pattern similar to that of NTT by downgrading long-term (generic) lithium niobate research. AT&T's current R&D in this area appears to be quite applied in content (device-oriented) and thus is located in the development oriented divisions.

With respect to process technology, Japan has made significant progress in developing techniques critical to the high-yield integration of high-density electronic circuits with optical circuits based on gallium arsenide. The focus of this progress has been on producing defect-free crystalline gallium arsenide wafers as starting material for the subsequent production of optoelectronic integrated circuits (OEICs). The production technology is liquid-encapsulated crystal growth (LEC). LEC is a modification of the Czochralski crystal-pulling techniques which has become the standard process in all countries for growing large-diameter boules for III-V materials.[35]

NTT developed the major improvements to the LEC process over the past several years, and the improvements are being incorporated into commercial-scale production technologies by both Japanese and U.S. firms. Four main approaches are currently being investigated for enhancing the uniformity of bulk LEC-grown gallium arsenide: (1) reducing the thermal gradient from the center to the outside of the crystal; (2) doping the melt with indium; (3) growing the crystal in a magnetic field; and (4) automatically controlling the diameter of the crystal under computer control.[36] The Japanese are also experimenting with the injection of arsenic during crystal growth to provide more homogeneous crystals. Most of the laboratories in both the United States and Japan are investigating two or more of these approaches in the same crystal puller. However, although R&D progress in LEC bulk crystal growth in the United States and Japan is believed to be about even, some U.S. industry officials think that Japan will be the first to commercialize the improved technology. Currently, Japanese firms seem to be the only commercial sources for GaAs substrates.[37]

Recently, a new process under development by Bellcore (Bell Communications Research) has shown the potential to give the United States a process technology lead. The technology, called vapor levitation epitaxy (VLE), may prove to produce high-quality optoelectronic wafers at a fraction of the cost of existing epitaxial processes--and in a fraction of the time. VLE may also turn out to be more flexible in terms of its suitability for a wide range of applications.[38]

The VLE process works in the following way. The raw wafer moves along a conveyor belt on a cushion of vapor and is positioned over a porous disk. Then a blast of vaporized semiconductor elements is sprayed through holes in the disk. The vapor condenses as a thin, ultrasmooth crystal layer which, because of the uniformity of the condensation, is largely defect-free. The possible composition and number of layers are large, as the wafer can easily be moved over different disks to deposit different vapors. This flexibility offers the possibility of custom-designed chips.

Claims have been made that VLE will offer substantial processing cost reductions for the manufacture of semiconductor lasers. Such a development would likely bring the cost of multimedia communication systems down to market penetrating levels.

Once defect-free wafers are produced, a second process technology is needed to actually produce the OEICs. At Japan's Optoelectronic Joint Research Laboratory (OJRL), such a process is under development in which a combination of molecular-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) is used to build up thin layers on the gallium arsenide substrate.[39] A process called reactive ion beam etching (RIBE), using chlorine, is being developed for etching the chips. Physical etching is done with chlorine ions accelerated in an electric field, and the chlorine radical is used for chemical etching. This dry process produces a sharp profile, whereas the unfocused ion beam previously used tended to undercut the channels in the resist masks. Wafers are moved from station to station within linked vacuum chambers while these processes are performed in sequence.[40]

R&D TRENDS IN TELECOMMUNICATIONS

The two major performance attributes in telecommunications systems are transmission speed and capacity. Devices which can exhibit these attributes at higher and stable levels of performance over extended periods of time at lower unit costs will rapidly penetrate telecommunications markets.

In the area of semiconductor waveguides, the two currently most promising applications, according to Alferness [1984], are optical switching and high-speed optical modulation. Other classes of devices promise applications in multiplexing or filtering, and coupling.[41] With respect to waveguides, the rapid emergence of single-mode fiber technology has been a primary factor in the increased interest in integrated-optic devices, which are single-mode.[42] Titanium-diffused lithium niobate ($Ti{:}LiNbO_3$) waveguide technology is currently the most developed. A variety of telecommunication devices have been demonstrated using this material. However, the reduction of propagation losses in gallium aluminum arsenide (GaAlAs) semiconductor waveguides to approximately 1 dB/cm has rejuvenated research activity in this material.

Stable emission of the light pulse at a single frequency gives less dispersion. Dispersion or pulse broadening can occur from two separate causes. First, signals of the same wavelength which follow different paths through a multimode optical fiber become separated by virtue of having traveled different distances. Dispersion from this source is eliminated by the use of "single-mode" fiber. Single-mode fibers have very narrow cores clad in an outer layer of glass of lower index of refraction. The 4-micron diameter glass core transmits only a single mode of light down the fiber and thereby eliminates the dispersion that would otherwise be caused by the presence of other modes. A very short light pulse can propagate great distances (10 to 100 km) without suffering pulse shape degradation. The result is higher transmission speed and thus greater information capacity or "bandwidth". Also, because of the elimination of dispersion, single-mode fiber systems require fewer repeaters than do multimode fibers. The spacing is important because repeaters can cost $40,000 to $60,000 each.[43]

Second, even single-mode fibers display some dispersion of the index of refraction across the range of wavelengths in the light signal. However, single-mode lasers minimize the effects of this dispersion. They also offer the small emitting area desirable for coupling output into monomode fibers.

However, even with single-mode lasers such as distributed feedback and C^3 lasers, direct current <u>modulation</u> can affect temperature and the laser wavelength, thereby creating pulse broadening (a phenomenon called "chirping"). This results in a serious penalty for data rates above about one Gbit/s. For such long-haul, very high bandwidth systems, dispersion limitations due to chirping can be avoided by using a CW single-frequency laser, and an external integrated optic modulator.[44] In 1983, a significant R&D milestone was reached toward producing a cost-effective very high-speed switching and modulating device. A team of scientists at Bell Labs developed a lithium niobate device called a high-speed traveling-wave directional coupler switch/modulator that operates at a wavelength of 1.32 microns.[45] The device is significant because it can operate at this desirable wavelength, where optical fiber losses are optimally low, without the previous undesirable requirement of substantially increasing the drive voltage. The new coupler switch/modulator device allows the laser diode to be left running continuously, with the switch being used to perform intensity modulation. This is expected to eliminate modal noise. The 58 picosecond pulses so generated may permit modulation rates up to 16 Gbit/s, according to the Bell researchers. Some researchers have speculated that continuous laser operation rather than off-on switching may also prolong a laser's operating life.

Because the use of single-mode fibers requires injection of a light beam into a much narrower fiber (a few microns across compared to approximately 50 micron diameters for multimode fibers), which is necessary to restrict propagation to a single wavelength mode, difficult alignment problems remain to be solved. For long-distance transmissions, low fiber-coupled insertion loss is essential. Much research over the last several years has been aimed at increasing the fiber waveguide <u>coupling</u> efficiency, and at reducing the propagation loss in Ti:$LiNbO_3$ waveguide devices. Fiber-coupled insertion losses as low as 1.5 dB have been achieved. Generally, there must be tradeoffs between insertion loss, and modulation bandwidth and drive voltage. Detached focusing optics can collimate the light beam, although with added bulk and cost. Also, too much power extraction from an emitting region can damage the facet. However, some laboratories have demonstrated modulators that appear to satisfy practical requirements--they operate at low voltages (less than 5 V), have a broad bandwidth of 5 GHz, and a lower insertion loss of less than 2.5 dB.[46]

Toshiba has demonstrated a "multiplex transmitter" based on the world's first integrated five-element semiconductor laser array. The system transmits five optical signals simultaneously through a single optical fiber, each at a different wavelength, compared with one signal per fiber for most conventional optical transmission systems. Five DFB lasers are connected to an optical multiplexer that bundles signals for transmission. Development and testing of the multiplex transmitter is underway at Japan's MITI-sponsored Optoelectronics Joint Research Laboratory (OJRL) and is expected to be completed in 1986. Toshiba sees applications in telemetering and telecontrol systems for large manufacturing units and in long-distance telecommunications.[47]

An equally active area of integrated optics research, and one which has been emphasized since the early days of fiberoptic communications is optical switching for signal routing and time division multiplexing. As single-mode fiber technology advances, the need for high-speed optical switches has become apparent. Mechanical switches are useful only for speeds of a few milliseconds, so integrated optic switches will be required for optical signal routing at medium and high speeds.

Laboratories around the world, including AT&T's Bell Laboratories, CNET in France, and NEC and Fujitsu in Japan, are actively pursuing research on single-mode switching elements. NEC researchers have reported a time-division optical switch for video switching. High-speed optical switching is important for time-division multiplexing and demultiplexing, since it may enable communications systems to take advantage of single-mode fiber's very large bandwidth without requiring comparable broadband electronics. Researchers at Bell Laboratories have recently demonstrated multiplexing and demultiplexing optical pulses separated by as little as 100 picoseconds.[48]

The increased complexity of proposed future coherent lightwave systems will require correspondingly sophisticated optical components including polarization controllers, phase modulators, or frequency shifters. Researchers at British Telecom Research Laboratories in England have used titanium-diffused lithium niobate ($Ti:LiNbO_3$) waveguide phase modulators in their coherent detection systems experiments. Very broadband (approximately 18 GHz) integrated optic modulators have been used by researchers at Hughes Aircraft to demonstrate a 0.8 micron fiberoptic microwave link. Arrays of independently modulated lasers can send several signals through an optical fiber simultaneously (multiplexing), thereby saving on the number of fibers while still allowing redundancy should any one device fail.[49]

Single-mode systems now operate at 1.3 microns compared with shorter wavelengths (0.8 to 0.9 microns) of first generation systems. At this wavelength, dispersion in doped silica fibers can be eliminated. However, such systems can potentially function best at the 1.55 micron wavelength where the fiber has its lowest signal loss (attenuation). Operating at the 1.55 micron wavelength with fibers optimized for 1.3 micron transmission results in undesirable levels of dispersion. Ideally, one would like to move the zero-dispersion wavelength to 1.55 microns.

This can be achieved by doping the optical fiber, but this significantly increases the cost of the fiber (which accounts for about 75 percent of total system cost). Another approach is to use a very narrow emission bandwidth (i.e., a single-mode laser). This requires a long-wavelength laser made from a quaternary semiconductor material (InGaAsP). Such a semiconductor has a longer lifetime than GaAs and the emission wavelength can be "tailored" or "tuned". However, threshold currents are very sensitive to temperature, so output power must be limited to several milliwatts to avoid potentially destructive thermal runaway.[50]

Single-mode 1.3 micron lasers are currently commercially available. They can be classified into two groups: index-guided and gain-guided lasers. The gain-guided type is easier to manufacture but produces a less stable and uniform beam. However, production methods for any class of long-wavelength laser are still in the development stages. Production yields for 1.3 micron lasers have recently been increased from 10 percent to over 50 percent, but this is far from satisfactory for commercial-scale production. 1.55 micron lasers are even more difficult to make. Only a few small U.S. companies currently produce them.

For commercial trend analyses, a distinction must be made between trends in technological advances in the laboratory, as indicated by periodic announcements of the results of "hero experiments" (so-called because they keep breaking performance records), and levels of performance that can be achieved at acceptable life-cycle costs (production costs plus costs of use, including those costs related to failure rates). For example, at the Conference on Optical Fiber Communication '85, AT&T researchers announced new records for the speed at which light signals can be modulated. Using both direct modulation and indirect modulation approaches, they have demonstrated maximum rates of modulation of 2 gigabits (2 billion bits) per second and 4 gigabits per second, respectively.[51] These experiments represent state-of-the-art research which has focused on lasers and optical fiber systems using single mode (wavelength) light signals.[52] One AT&T researcher estimates that the system would be competitive for modulation applications at a cost of about $300, but production requirements, let alone production costs, are undefined.

More recently, NTT has developed an ultra high speed distributed feedback-type (DFB) laser diode capable of converting the equivalent of 144,000 lines of telephone information into optical signals in one second. This is equivalent to an optical signal conversion capacity of 10 gigabits per second, compared with 400 megabit modulation rates of recently installed fiberoptic systems! NTT researchers have managed to reduce the parasitic capacitance markedly by shaving off 90% of the buried layers sandwiching the active layer and by changing the crystal substrate from N-type to P-type, thereby allowing efficient flow of current to the active layer. Also, the active layer has been impregnated with zinc dopants to enhance the efficiency of the substrate. A prototype DFB laser developed under the new method featured a high output of 10 milliwatts.[53]

As these lasers are difficult and expensive to make, the marketplace may see multimode lasers for a while. Researchers at Plessey Research Ltd. in England have used a buried heterostructure (multimode) laser emitting at 1.556 microns to send 1.3 gigabits per second over 103 kilometers of fiber. The fiber was engineered by Corning Glass Works to have minimum signal dispersion for the laser's wavelength. The multiple wavelengths emitted by the source travel at approximately the same velocity in such a fiber, making the use of multimode sources feasible for long-haul applications. Plessey claims this approach yields the highest value yet recorded of the bit-rate-times-distance figure, 139 gigabit-km per second for a multimode laser. Plessey views this technology as a practical route to long-haul, high-speed systems in short-term.[54]

Laser-generated light signals, even under optimal transmission conditions, will periodically require regeneration. The current technical approach is to detect an incoming optical signal, reform it electronically, and then regenerate the signal with a laser. The cost of a repeater is in the $40,000 to $60,000 range.

A much simpler method obviates the need to convert from the optical to the electrical domain and back again. This approach uses a single laser amplifier. The incoming laser signal passes through the laser cavity and is strengthened with the gain of the amplifier. In the case of a local power failure, the device is transparent to the incoming light signal. However, a disadvantage of the amplifier is that any dispersion that has occurred in the course of transmission is not treated. Such <u>in-line optoelectronic amplifiers</u> may be used mainly in high-performance long-haul systems, in spite of the fact that dispersion is not treated. The lack of a need for an electrical interface simplifies the design of long-haul telecommunications systems. For local area networks, the dispersion property is not a concern, although the transparency property is important.[55]

NTT achieved the first demonstration of an in-line optoelectronic amplifier. A major obstacle to the attainment of a commercial device is the difficulty of producing a device with sufficient gain. Little U.S. R&D activity is apparent at this time. AT&T currently has no systems under design that include in-line amplifiers. However, British Telecom has an R&D program for in-line amplifiers operating at 1.5 microns, which is part of a significant R&D effort aimed at the development of coherent communication systems.[56]

According to Holman and Wood [1985], <u>optical bistable devices</u> are "fast becoming one of the most popular long-range research topics in many laboratories throughout the world." Such devices would allow high-speed optical switching without leaving the optical domain. Currently available electrooptical switches, such as those made of lithium niobate or gallium arsenide, require a control voltage pulse to switch from one switch state one to another. For the switch controller to know whether to apply a voltage to the switch or not, the incoming optical signal (or part of it) must be detected to receive proper destination instructions. The time required to detect the destination signal, and then activate the switch, limits the bandwidth of the optical network within which the switch can operate.

An optically bistable switch would avoid this limitation. The incoming optical signal itself would cause the switch to enter the desired state. The signal's destination pulse, in passing through the switch, would program it directly by altering the switching material's refractive index. Switching speeds of a few picoseconds are believed feasible. Such speeds would be very difficult to achieve with conventional electrooptical or magnetooptical techniques.

No one country has an identifiable technological lead, although many are pursuing research in this potentially important area.

LOCAL AREA NETWORKS (LANs)

Because these networks operate over distances of no more than 5 to 10 kilometers, designers are considering wavelengths of about 0.8 microns because sources and detectors for this wavelength are more developed. However, enough demand should appear for the long distance systems at 1.3 or 1.5 microns that the technology for such lasers and detectors will develop.

In addition to the laser, another possible light source for optical signals is the light-emitting diode (LED). At present, using LEDs seems to be the desirable approach, particularly in LAN applications, because of their low cost and high reliability compared with lasers, but potential users have feared that LEDs put too little power into the fiber. Moreover, the most efficient switching technology may depend on single-mode laser sources. However, Fujitsu has recently announced the development of an edge-emitter LED which, unlike conventional surface-emitter types, greatly enhances the coupling efficiency between the LED and single-mode optical fibers. Compared with surface-emitter LEDs, which have a tendency to disperse the light produced, the edge-emitter produces light in a narrow beam with a spot diameter of less than one micron. The coupling efficiency with single mode fibers is improved 10-fold over surface-emitter LEDs. The Fujitsu device operates at 1.3 microns and has a transmission speed of 300 megabits per second, a 50 percent improvement over conventional LEDs. Price of this indium gallium arsenide LED is only slightly higher than that of other LEDs.[57]

However, researchers at AT&T Bell Labs have recently shown that LEDs of both the surface-emitting and edge-emitting variety can produce enough power to send a signal of 140 million bits per second over several kilometers of fiber. This, AT&T says, is sufficient for use in local loops.[58]

At a recent conference, BellCore announced an edge-emitting LED which can transmit with a bandwidth 560 Mbps over 15 km. At the same conference, BellCore also announced a super-radiant LED which can send with the same bandwidth over a distance of 25 km.[59] With these and other recently announced hero experiments, LEDs seem to be creating at least as much excitement as the laser and offering the potential for applications beyond the LAN.

At the systems level, the telephone companies regard local area network service as critical to their survival in the communications marketplace. About two years ago, computer companies were thought to be the future developers of LANs, but now the telephone companies have clearly established themselves as the dominant providers.

LANs will soon become an important market. Roger Blantz, President of Mountain Bell, is quoted in Kessler Marketing Intelligence [1984] as saying that 60 percent of the total information that moves electronically--voice, data, and video--moves less than two miles, and an additional 25 percent of information moves within the local exchanges. Thus, 85 percent of information moves within the telephone LATAs (local access and transport areas).

With the move toward higher information transfer rates, which includes a concurrent need for video and image transmission, fiberoptic systems have begun to move into buildings and industrial and university campuses. By 1986, fiberoptics will have moved into the subscriber loop.[60]

CONCLUSION

This section has attempted to group optoelectronic devices by function and underlying technology, and to discuss trends in the technology's evolution. However, as the development of the Toshiba "multiplex transmitter" and the AT&T traveling wave "switch modulator" indicate, any classification scheme which separates functions on some presumed technological basis is tenuous at best and raises questions about the market projections made at this level of disaggregation in the next section.

With respect to technological leadership, the current status is a mixed picture. The Japanese are ahead in the development and commercialization of sources (lasers and LEDs) while the United States has the lead in advanced optoelectronic detectors. The United States may still have the lead at the systems level, with the Japanese in hot pursuit.

AT&T Bell Laboratories and NTT are the dominant research leaders. They both account for 28 percent of the published papers in their respective countries.[61] However, an observation with implications for the future is that a number of other large Japanese firms (such as NEC) are appearing with greater frequency on the lists of hero experiments. This trend is likely a cause for concern for the U.S. optoelectronics industry as a whole. No one will push AT&T out of the technology race, but most other aspiring U.S. participants have only recently established research facilities which puts them at least several years behind their Japanese counterparts.

Part 4

PROJECTIONS OF MARKET GROWTH AND ECONOMIC BENEFITS

The following sections present projections of growth rates for optoelectronic devices and the product systems of which they are components. These projections are then used to estimate aggregate benefits to the economy from the diffusion of this technology into the marketplace. The rate of market penetration will be influenced by the rates at which various classes of technical barriers are overcome. In optoelectronic technology, measurement-related barriers are particularly important, and estimates are presented of the economic benefits to be realized from the removal of this class of technical barriers.

MARKET GROWTH PROJECTIONS

The demand for optoelectronic devices is a derived demand. That is, the demand depends to a large extent on the demand for the final system (in this case, a communication system) of which the devices are components. Sales of communications equipment of all types are projected to grow to 90 billion dollars annually by 1990.[62] For current generation optical technology, actual and projected worldwide sales for the major categories of components in a fiber optic communication system are presented in Table 3. These data are for markets which involve systems based on optical fibers, such as communications and sensors.

In communications technologies, the trend is towards integration of optical signal processing functions. The projected explosive growth in sales of integrated optical devices for communications applications is expected to be the result of a number of factors. First, the overall demand for fiber optics is expected to continue to grow rapidly as the ratio of performance to price continues to improve. Second, the share of single-mode fiber in total fiber sales will grow rapidly due both to improvements in the single-mode performance-to-price ratio and to an increase in the demand for high bandwidth and/or high data-rate transmission. Single-mode fiber will depend relatively more on integrated optics to achieve its superior productivity potential. Third, integrated optics will gain greater market acceptance once initial commercial applications demonstrate that target performance levels can be realized in a reliable manner. Fourth, diffusion into the marketplace of products based on integrated optic technology will depend greatly on learning economies in production. Thus, as with other technologies, costs will decline rapidly once initial market penetration occurs and the growth of sales will accelerate.[63]

Other markets are also emerging for optoelectronic devices which do not involve optical fibers. Although not treated in this report, these markets will contribute significantly to the aggregated demand for optoelectronic technology. Actual and projected worldwide sales data for optoelectronic devices for all markets are presented in Table 4. Extrapolations to 1992 of these projections from Dataquest are

Table 3

WORLDWIDE FIBEROPTIC MARKET BY COMPONENT SEGMENT, 1981-1989
(current $ millions)

	1981	1982	1983	1984	1985	1986	1987	1988	1989
Fiber/cable	109.7	217.8	370.8	542.7	766.6	1048.7	1390.6	1810.8	2251.4
Trans/rec.	56.8	92.5	150.4	179.8	239.3	313.5	419.0	519.0	665.2
Connectors	10.9	16.6	28.7	38.4	51.0	66.5	81.0	102.2	127.6
TOTAL	177.4	326.9	549.8	760.9	1056.9	1428.7	1890.5	2432.0	3044.2

Source: Kessler Marketing Intelligence [1983]

Table 4

WORLDWIDE MARKET FOR OPTOELECTRONIC DEVICES, 1980-1990
(current $ millions)

Year	Sales
1980	689
1981	797
1982	820
1983	1102
1984	1350
1985	1330
1986	1454
1987	1716
1988	1981
1989	2059
1990	2335

Source: Dataquest

substantially lower than those from Japan's MITI, which forecast an aggregate 1992 world market for all optoelectronics applications of $4 to $8 billion. Using the broadest feasible set of markets potentially affected by optoelectronics technology, a recent report by International Resource Development estimates that in 1985 the total value of shipments in these markets will be more than $9 billion. IRD predicts that these markets will collectively growth an annual rate of 27 percent for the next few years, "outpacing computers, telecommunications and just about all of the other high-tech markets".[64]

The importance of optoelectronic devices in determining the competitiveness of products containing these devices is evidenced not only by the mushrooming R&D investment aimed at increasing the productivity, and hence the price/performance ratio, but by the fact that other major components such as optical fibers have already experienced their more radical advances and hence price declines.

Projections of U.S. sales for particular ceramic (oxide-based) integrated optical devices were prepared by Charles River Associates for two groups or classes of products. Worldwide sales projections were extrapolated from the CRA numbers for Japan and Europe using sales projections from Kessler Marketing Intelligence. These projections are presented in Table 5. The first device grouping includes modulators and filters to be used in multiplexing applications. These devices were grouped together because their use will be closely connected with the use of sources, repeaters, and detectors. Sales of modulators and filters were therefore projected based on projections of sales of sources, detectors, and repeaters. In contrast, optical switches are expected to be used primarily in communications switching systems. The projections of integrated optical switches were based on projections for sales of telecommunications switching systems.

The sales of lightwave sources, detectors, and repeaters used to derive the projections of modulator and filter sales are themselves

Table 5

PROJECTED WORLDWIDE SALES OF INTEGRATED OPTIC DEVICES FOR COMMUNICATIONS
(millions of current dollars)

	Ceramic Modulators/ Filters	Ceramic Switches	In-Line Amplifiers	Total Ceramic Devices
1990				
Europe	4.7			4.7
Japan	1.4			1.4
U. S.	7.0	____	____	7.0
Total	13.1			13.1
1995				
Europe	57.6	22.1		79.7
Japan	17.4	6.7		24.1
U. S.	85.6	32.8	____	118.4
Total	160.6	61.6		222.2
2000				
Europe	434.7	177.8		612.5
Japan	131.5	53.8		185.3
U. S.	646.3	264.3	____	910.6
Total	1212.5	495.9		1708.4

Sources: Charles River Associates [1984], Kessler Marketing Intelligence [1983] projected based on forecasts that total U.S. fiber optic equipment sales will reach $2 billion per year in 1990. This number represents an approximate mean of the range of forecasts by credible sources. Nevertheless, the range of forecasts is still wide in spite of several years of significant sales on which to base trend projections. The upper and lower bounds of the range of estimates ($1.5 to $2.5 billion) vary by 25 percent from the mean value. Consequently, the derived estimates of device sales, such as modulators and filters, have an equally wide variance.

Another problem with estimates of the markets for individual optoelectronic devices is the uncertainty about the directions that integration will take. The CRA report makes separate estimates for modulators/filters and switches. However, current research is combining (integrating) functions in different ways. For example, with respect to hybrid integration, the previously described high-speed switching and modulating device demonstrated in 1983 by Bell Labs casts doubt over the usefulness of developing separate market estimates for "individual" integrated optic devices which may not exist beyond the very early stages of market development. And if, as projected in this report, monolithic integration arrives in the marketplace earlier than current forecasts indicate, the question of separate markets for many "devices" is moot.

The projections of fiber optic systems sales used to derive the projections of ceramic integrated optic device sales imply an annual growth rate of 20 percent, which is moderately conservative for an advanced technology in the early and middle portions of its life cycle.

Assumptions Underlying Optical Modulator/Filter Projections

Following Charles River Associates, sales of sources, detectors, and repeaters are assumed to constitute 37 percent of total sales of fiber optic equipment in all years after 1990. This assumed share used by CRA was in turn based on published estimates by Gunderson and Keck [1983]. Technology and market factors will both continue to change and thus could easily shift this estimated share of sales over time. For example, the increasing use of single-mode technology with greater distance between repeaters should decrease the share of these devices in total sales. On the other hand, as fiber optics penetrates further into subscriber loops, local area networks, and other shorter distance applications the share of sources and detectors may increase. The effect of these trends may be to cancel one another.

In fact, in a survey of fiberoptics marketing executives by Kessler Marketing Intelligence, the respondents estimated that 40 percent of equipment sales are currently accounted for by all components other than cable and fiber (i.e., connectors, splicers, sources and detectors, couplers, and test equipment).

CRA assumed that when full diffusion of integrated optic devices is reached, sales of modulators and filters will be about half the size (in dollar terms) of sales of sources, detectors, and repeators. CRA arrived at this assumption by constructing a number of scenarios of feasible trends in the prices of devices and the percentages of sources, detectors, and repeators which would be attached to modulators and/or filters once full diffusion of integrated optics is reached. CRA concluded that 50 percent is a reasonable assumption as to the eventual maximum ratio of the value of integrated optic modulator and filter sales to sales of sources, detectors, and repeaters.[65] However, CRA estimated that ratios varying about 10 percentage points (i.e., 20 percent) higher or lower could reasonably be assumed. Changing the assumption by such an amount changes the sales of modulators and filters by 20 percent in the same

Table 6

ASSUMPTIONS UNDERLYING PROJECTIONS OF U.S. SALES OF INTEGRATED OPTIC DEVICES: MODULATORS AND FILTERS

Category	Year	Value	Assumption
Total U.S. Fiber Optic System Sales	1990	$2,000M	Consensus forecast
	1995	$5,000M	20% annual growth from 1990
	2000	$10,000M	15% annual growth from 1995
U.S. Sales of Sources, Detectors, & Repeaters	1990	$700M	
	1995	$1,800M	37% of total fiber optic sales
	2000	$3,700M	
Maximum (full diffusion) U.S. Sales of Modulators & Filters	1990	$400M	50% of source, detector, and repeater sales
	1995	$900M	
	2000		
Market Share (of maximum sales) of Modulators & Filters	1990	1.9%	1% market share achieved in 1988; commercial diffusion follows a logistic curve
	1995	9.3%	
	2000	34.9%	
U.S. Sales of Integrated Optic Modulators & Filters	1990	$7M	
	1995	$86M	(market share)x(maximum sales)
	2000	$646M	

Source: Charles River Associates [1984]

direction.

The final set of assumptions relates to the diffusion path that modulators and filters will follow. First, these devices are assumed to be introduced commercially by the late 1980s and to achieve a 1 percent share of potential applications by 1988. CRA based this assumption on the results of industry interviews indicating commercial introduction of such devices was probably three to five years away in 1983. Second, the diffusion of integrated optic devices is assumed to likely follow a logistic (or s-shaped) market-penetration curve.[66] A number of studies have found that such curves represent many market diffusion patterns of new technologies.[67] A further assumption is that the speed of diffusion in this case will be about the average determined in past studies of diffusion. The implication is that nearly 9 years will be required for market penetration to increase from 5 percent to 50 percent. Based on these assumptions, ceramic integrated optic signal modulators and filters will be used in about 35 percent of their potential applications by 2000.

The above assumptions, used in constructing the projections, are summarized in Table 6. These sales projections are relatively sensitive to the assumptions underlying them for several reasons.

First, while these devices are currently in the development stage, problems must still be overcome before they can be produced reliably, with high reproducibility, and at a cost that makes them competitive with existing technologies. Second, even once these products are commercialized, barriers to diffusion will have to be overcome. For example, the section of this report on technical barriers pointed out that existing lifetime testing methods have not proved useful for testing these devices. Thus, even if conventional lifetime testing methods were available and tests begun today, only several years of data could be accumulated by the time of projected commercial introduction. The result will be considerable uncertainty on the part of users with respect to the reliability and useful lifetimes of these devices. The consequent "transactions" costs shared between buyer and seller will significantly slow market penetration. Only if the infratechnology (measurement technology) advances to the point of providing accelerated test methods, will this retarding effect on market penetration likely be removed.

Moreover, as CRA points out, the projections of integrated optic sales in 2000 are very sensitive to the year in which 1 percent diffusion is assumed to be attained. For example, a change in this assumption by one year (to 1987 or 1989) results in a change in the projected market share in 2000 of approximately 20 percent (to 43 percent or 28 percent, respectively). This adjustment will, in turn, produce a change in the projected 2000 sales of modulator and filter sales by approximately 20 percent (if all other assumptions remain unchanged).

The implication of this finding is very important. The leverage on the stream of future sales of moving the point at which 1 percent diffusion is reached forward in time (i.e., closer to the present) can be quite significant, even if the rate of diffusion beyond 1 percent is unaffected. Moving this point forward in time can be accomplished by moving up the point at which commercial introduction takes place or by accelerating initial commercial acceptance and diffusion. Thus, any strategy by industry or by industry and government cooperatively which accelerates initial commercialization and subsequent diffusion throughout U.S. industry will have net economic benefits, especially for strategically important technologies such as this one.

For example, device reliability and lifetimes are of critical importance to system designers; rapid initial diffusion requires reliability in use and acceptable operational lifetimes. The implication is that <u>the payoff to the economy from the timely availability of measurement techniques which improve and demonstrate integrated optic device reliability and lifetime can be significant</u>.

The projected sales of integrated optic devices are very sensitive to the rate of diffusion assumed. CRA assumed an average diffusion pattern of 9 years for market penetration to move from 5 percent to 50 percent. Decreasing the assumed diffusion time between 5 and 50 percent by one year while maintaining all other assumptions would result in a 35 percent increase in the projected market share of integrated optic modulators and filters in 2000 to 47 percent. The projected level of sales of these devices would correspondingly increase by 35 percent. A one-year increase in the assumed time required for a 5-to-50 percent increase in diffusion would result in a 25 percent reduction in the projected market share in 2000 to 25 percent.[68]

Assumptions Underlying Optical Switch Projections

The market projections for ceramic integrated optic switches were derived in a similar but slightly different manner from those for modulators and filters. The assumptions underlying these projections are presented in Table 7.

Because optical switches are likely to find application in central office and private branch exchange (PBX) switching systems, these projections are based on projections of U.S. sales of commercial telecommunications switching systems. Electronics (January 13, 1983) projects that total U.S. sales of telecommunications switching systems will reach $3.9 billion in 1986. According to Electronics data, reaching this level will require an average annual growth rate of about 22 percent from 1982 levels. Sales of switching systems to the end of the century were projected by assuming average annual growth rates of sales of 20, 15, and 10 percent for the periods 1986 to 1990, 1990 to 1995, and 1995 to 2000, respectively.

Table 7

ASSUMPTIONS UNDERLYING PROJECTIONS OF U.S. SALES OF INTEGRATED OPTIC DEVICES: OPTICAL SWITCHES

Category	Year	Value	Assumption
Total U.S. Sales of Communications Switching Systems	1986	$3,934 M	Projection from Electronics (January 13, 1983)
	1990	$8,158 M	20% growth from 1986
	1995	$16,408 M	15% growth from 1990
	2000	$26,425 M	10% growth from 1995
Market Share of Optical Communications Switching Systems	1990	--	1% market share achieved in 1995; commercial diffusion follows a logistic curve
	1995	1.0 %	
	2000	5.0 %	
U.S. Sales of Optical Communications Switching Devices	1990	--	Optical market share x total sales
	1995	$164 M	
	2000	$1,321 M	
U.S. Sales of Integrated Optic Switches	1990	--	20% of value of switching systems
	1995	$33 M	
	2000	$264 M	

Source: Charles River Associates [1984].

The diffusion of optical switching systems was projected based on the assumption that 1 percent diffusion is achieved by 1995. While integrated optic switches may be technically developed prior to this time their large scale commercial application in switching systems will probably be paced by the commercial development of a direct (in-line) optical amplifier. The existence of a derived demand for integrated optic switches is due to the fact that switching is usually performed in conjunction with signal amplification. If conversion to electricity is required for amplification, the advantages of optical as opposed to electrical switching (i.e., increased data rates) will be nullified. Industry interviews by CRA indicated that commercial introduction of optical signal amplifiers is probably on the order of 10 years away.[69] The reason for this projection of relatively distant commercialization and diffusion is that in-line amplifiers will be based on the more difficult gallium arsenide technology.

The diffusion path for optical switching systems was projected based on the same assumptions as was the diffusion path for modulators and filters. Diffusion is assumed to be characterized by a logistic curve calibrated so as to yield 1 percent diffusion in 1995 and to predict a gap of about nine years between 5 and 50 percent diffusion. These assumptions yield the projection that optical switching systems will gain a 5 percent share of total U. S. sales of optical switching systems and could reach an annual sales rate of $1.3 billion by 2000. As was the case for the modulator and filter sales projections, if diffusion were more rapid or if commercial introduction were to occur sooner, the leverage on sales in year 2000 would be significant.

CRA predicts that optical switches will make up only a fraction of the value of optical switching systems. This fraction is expected to be about 20 percent.[70] Accordingly, sales of integrated optical switching devices are projected to be about $260 million in 2000.

BENEFITS TO THE ECONOMY FROM OPTOELECTRONICS TECHNOLOGY

Nature of Expected Benefits

Some of the productivity increases in information-handling functions are:

(1) multiplexing. Integrated optics can be used to lower the cost of multiplexing applications which enable more information to move along an optical fiber per unit of time. For example, wavelength division multiplexing (WDM) allows light signals generated by several sources to move simultaneously along a single fiber by shifting the wavelength of one or more of the light waves. This approach has the effect of creating several information-carrying channels on a single fiber. The number and thus the cost of fibers in a communication system are reduced, while preserving redundancy should one of the signal sources fail.

Multiplexing is presently accomplished with bulk crystal technology. However, as pointed out by Charles River Associates [1984], the use of integrated optic devices on a single crystal substrate offers several potential advantages over existing technology. First, the use of integrated optic multiplexers is expected to increase the number of channels per single-mode fiber from one or two to a total of four or five. Second, integrated optic devices are expected to provide qualitatively better multiplexing at higher data rates than does bulk crystal technology on single-mode fibers. Third, with the realization of substantial learning economies, the cost of single-crystal, ceramic-based multiplexers may fall to as low as one-quarter to one-half the cost of bulk crystal multiplexers.

(2) Modulation. Modulation or the encoding of information in the light ray is presently performed directly by switching the light on and off. This method is acceptable at shorter

wavelengths and lower data transmission rates. However, external modulation using a separate (integrated optic) device may well be required to achieve data transmission rates substantially above one gigabit per second at longer wavelengths without sacrificing distance between repeaters.[71] Moreover, researchers interviewed by CRA speculated that the use of external modulation will result in improvements in the reliability of the light sources.

(3) Switching. Integrated optic devices represent the only feasible way to directly switch light beams at high speeds (i.e., in the megabits or gigabits per second range). Industry personnel interviewed by CRA indicated that the cost of an integrated optic switch based on single-crystal ceramic materials may eventually go as low as one-tenth the cost of an equivalent electromechanical switch.[72] Large-scale optical switching will become cost-effective only through integrated optic technology.

(4) In-line amplification. The reduction in the required number of repeaters is a major objective of optical fiber research. Repeaters are costly and when they are needed their operation is inefficient due to optical/electronic conversions. These conversions can be eliminated with the result that not only are costs reduced but reliability is increased. Holman and Wood [1985] rank in-line amplification as one of the four most important future application areas of optoelectronic technology.

Estimated Benefits from the Generic Technology

As integrated optic technology diffuses into the marketplace following the typical diffusion pattern of performance and process improvements along with other "learning curve" effects, the average annual cost savings (productivity gains) realized by the economy will increase until some point of maturity is reached. For example, CRA estimates that by the year 2000 the average cost savings resulting from the installation of ceramic integrated optic modulators and filters will be more than 1.5 times the value of the sales of these integrated optic devices themselves.[73] Using the CRA U.S. market forecasts for modulators and filters discussed above, the total economy-wide cost savings due to the use of integrated optics in communications applications is projected to exceed $1 billion per year by 2000. The CRA estimate is probably quite conservative, given that a second calculation by CRA using plausible assumptions yielded an estimated annual cost savings at least twice this amount. Thus, a projected range of annual cost savings by 2000 would be $1 to $2 billion. Adding the projected cost savings from integrated optic switches yields a total projected annual cost savings gain from these two classes of optoelectronic devices of $1.4 to $2.8 billion by 2000.

The above projections do not include the potentially substantial future economic benefits from performance enhancements projected for optoelectronic technology. For example, integrated optic switching will allow many times higher data rates in switching than are possible with existing technology. The use of integrated optic filters for multiplexing may result in better quality multiplexing as well as cheaper modulation. The projections of productivity gains are based only on the latter category of benefits (i.e., cost savings). Moreover, industry participants believe that external modulation with integrated optic devices may increase the reliability and lifetimes of light sources. Again, these types of benefits will be substantial but are not included in the above estimates.

Estimated Benefits from Measurement Research and Standards

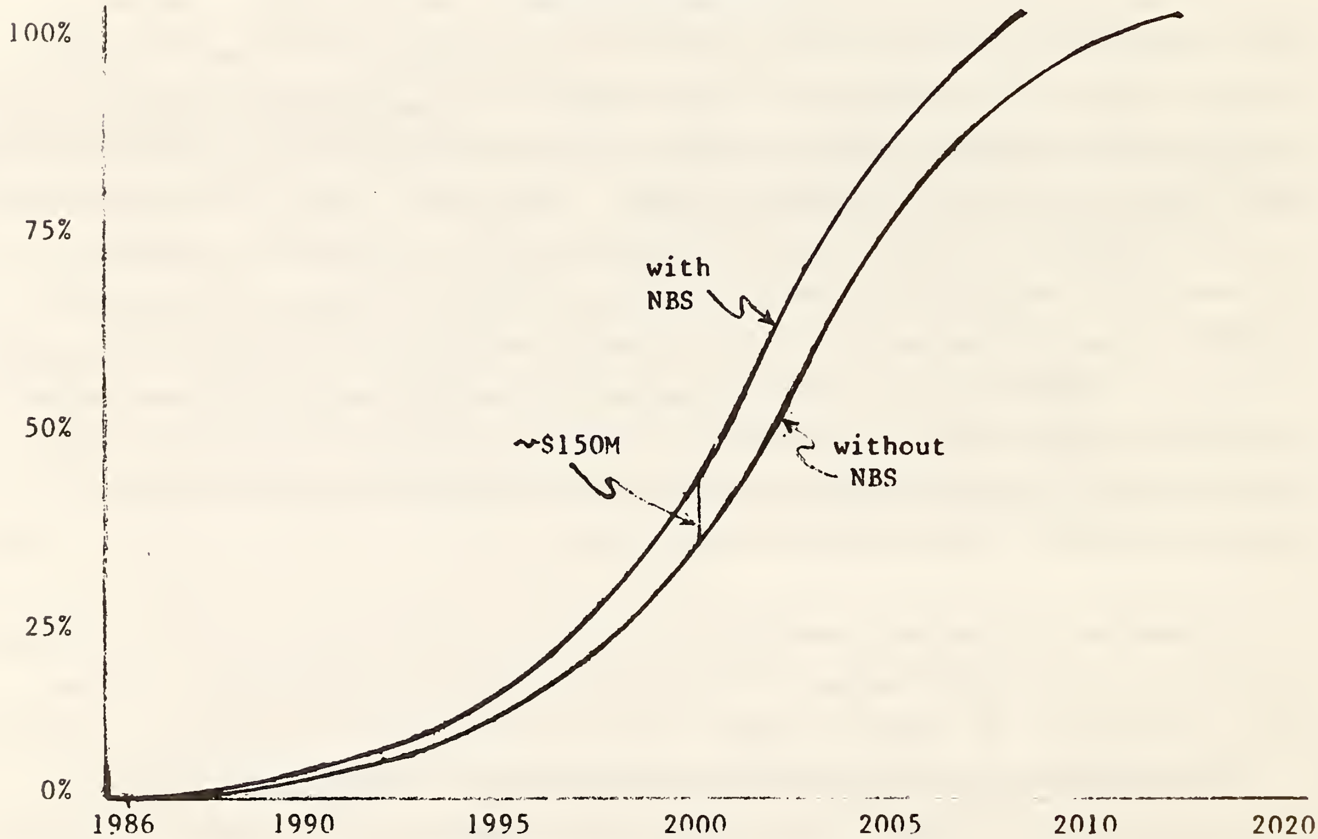
These estimates can be used to project the benefits from measurement research conducted by the National Bureau of Standards. Earlier discussion noted that product and process technologies and thus research content and methods in optoelectronics are very similar to those in semiconductor technology. Therefore, a reasonable assumption is that the projected contribution by measurement-related technology to the optoelectronic industry is proportional to the documented NBS contribution to productivity growth in the semiconductor industry.[74]

Using the projections developed by CRA for the cost savings from assumed market penetrations in 2000 by integrated optic modulators/filters and switches and assuming an NBS research program similar in relative scope and depth to the one which has supported the semiconductor industry, the NBS contribution to the productivity growth (measured in terms of cost savings) of U.S. suppliers of these two classes of optoelectronics devices is projected to reach a level (in current dollars) of $35-70 million per year by 2000. Because these two device classes represent only a fraction of the 11 device classes identified earlier in this report, <u>a reasonable projection of the aggregate annual cost savings to the optoelectronics industry from NBS research is $100 to $200 million</u>. Moreover, these estimates are biased downward because they are derived from the above industry estimates of certain categories of cost savings, which, as noted, exclude likely substantial productivity benefits from other categories of impact. Assuming a fairly comprehensive NBS metrology research program in this area, funded at an average annual level of $5-$10 million and applying appropriate present value calculation will clearly yield a high a benefit-cost ratio.

Examples of market penetration curves approximating the previous projections for components of integrated optics technology and the above estimates of possible NBS contributions are diagrammed in Figure 1. The productivity benefits of NBS-supplied technologies and services appear to shift the penetration curve only slightly to the left. However, as the sensitivity analyses performed by Charles River Associates indicate, quite small forward shifts in time of market penetration can result in sizable economic benefits. For example, attaining 50 percent market penetration only one year earlier would result in a 35 percent increase in the projected market share in the year 2000. Conversely, a slower diffusion pattern would have large negative effects on projected market shares. In Figure 1, the area between the two curves represents the cumulative benefits to the economy from NBS support. That these aggregate benefits would be substantial is clear from the estimate of benefits of $100-200 million for one year (2000). Of course, the distribution of benefits occurs farther out in time than the distribution of research costs, so that, even with substantial overlap, the application of an appropriate discount rate lowers somewhat the nominal benefit-cost ratio. But, as

Figure 1

Examples of Possible Market Penetration Curves for Integrated Optics



the estimate of the NBS contribution was based on the assumption of a moderate size research program, which would not exceed $5-7 million annually in the peak years, the discounted benefit-cost ratio will be quite large.

Relationship Between Component and System Productivity

A final point relates to factors affecting productivity and hence economic benefits. As with other technologies that exhibit a "systems" character (i.e., a number of components/devices combined in some way to perform a specific function), the productivity of communications systems is a combination of the productivities of the components/devices of which they are composed plus an additional increment due to the specific way in which the various devices are "organized" into the system. The individual devices exert "leverage" on the overall system productivity; conversely, a failure to advance the productivity of a particular device will result in a lower system productivity level. In fact, the KMI survey, referenced at several earlier points in this report, indicated that systems manufacturers added 76 cents of value for every dollar added by component manufacturers.

In cases of particularly critical devices, insufficient productivity gains can cause a "bottleneck" to overall productivity growth and result in greatly reduced rates of diffusion of the system technology and thus slower market penetration. As will be discussed shortly, both industry and government strategic planning must take steps in their respective areas of responsibility to remove these bottlenecks in a timely manner. Timing is particularly important to attain a competitive position in increasingly contested world markets.

Part 5

COMPETITIVE STRATEGIES AND GOVERNMENT POLICIES

In this section, an analysis is undertaken of the competitive positions of the United States and other countries which have made a commitment to participate in the emerging markets for optoelectronic devices. From a variety of domestic and international sources, this report concludes that the Japanese are ahead in the critical race to commercialize optoelectronic products and rapidly penetrate the target markets.

ADVANCING GENERIC TECHNOLOGIES

Much has been written about Japanese economic strategies and their continuing success. At the most general level, Japan's success in commercializing advanced technologies stems from two overriding factors--determination and policy/institutional flexibility:

(1) One aspect of these strengths with important implications for the potentially enormous optoelectronics markets is the well-known Japanese propensity for pushing the technology towards the market early in the technology's life cycle.

> While commercial enterprises in other countries are waiting and evaluating potential market directions and rates of growth, the Japanese seem to be able to reach a consensus decision as to a technology's economic value and set up the institutional apparatus and funding to cooperatively advance the generic technology.[75]
>
> In the past, the Japanese have acquired technology from other countries and rapidly accomplished the applied R&D, thereby reaching the market first or at least being a "fast second". More and more, the Japanese are cooperatively conducting the nonproprietary and high-risk generic technology themselves in order to accelerate the timing of the proprietary R&D and subsequent commercialization.
>
> (2) The Japanese are also willing to assume the risks of early commercialization. They use the advantage of early market participation to gain production and marketing experience.
>
> (3) After the initial market entry, the determination of Japanese industry to succeed becomes especially evident by their emphasis on continual improvements in production efficiency in addition to improvements in product performance.

In optoelectronics, the Japanese Government through its Ministry of International Trade and Industry (MITI) has organized an 8-year, $75 million program to advance the generic technology in this area. The research is being conducted at a dedicated facility called the Optoelectronic Joint Research Laboratory (OJRL). Although ostensibly focused on optoelectronics applications for monitoring and control systems, the publicly available literature from MITI as well as firsthand accounts of American visitors indicate that the content of the research follows the typical Japanese pattern of developing broadly applicable generic technology. A MITI brochure states the following:

> "This system [of R&D financing] has been established to conduct large-scale research and development which is urgently required but requires a large amount of risk and money over a long [time] period and cannot be borne by the private sector alone."

The Japanese apply a philosophy of "appropriate competition" in which the nonproprietary character of generic technology as well as its frequent lengthy gestation period are recognized as important factors in determining the timing of commercial entry and subsequent market penetration. Japanese firms in concert in with their government cooperatively advance the generic technology and throw the game open to intense competition among themselves as well as with the rest of the world. Holman and Wood [1985] offer the possibility that the Japanese are also more adept than are U.S. firms in finding their appropriate market niches and product lines without more competition than any one firm can comfortably handle.

However, the often used simple model of the Japanese taking American technology and adding value through improved production efficiencies does not apply to optoelectronics. A major reason for the projected Japanese success in this technology is the relevance of semiconductor product and process technology in which the Japanese are the world's best. Not only do they have the technology lead but the Japanese economy's financial structure and their industry's financial health provide the cash flow needed to fund major applied R&D programs and then to make the required capital investment to tool up for production.

This assessment does not mean that U.S. industry is out of the running any more than the Japanese were out of the running in the mid-1970s when they quickly caught up with and passed U.S. firms through their cooperative VLSI program. The United States is on par with the Japanese in the advancement of generic optoelectronic technology and the U.S. university system appears to have a decided edge over the rest of world in the general capacity to conduct basic and generic technology research.

However, neither U.S. industry nor the U.S. university system appears to be accumulating the necessary R&D equipment and research funds. Neither are the National laboratories being funded to provide the threshold levels of research funds required to support a U.S. industry commitment to the development of this technology. Specifically, no dedicated U.S. research program in optoelectronics currently exists comparable to that at Japan's Electrotechnical Laboratory. Moreover, not only are national laboratories such as Japan's OJRL efficient mechanisms for achieving the economies of scale and scope inherent in generic and infratechnology research, but they provide an efficient means for transferring the results of the research to industry in a timely manner compatible with industry's competitive strategies. In Japan, this research at national or industry cooperative laboratories appears to leverage industry R&D investment at levels "several times that of MITI".[76] Having efficiently accomplished the generic and infratechnology research together, the Japanese firms then plunge into intense competition with each other.

Until recently, the United States had nothing underway to compare with OJRL in Japan. However, Battelle's Columbus Laboratories has initiated a cooperative research program, funded entirely by industry, which will closely parallel the Japanese effort in organization, although the research objectives are more focused on process techniques. Unfortunately, the Battelle consortium will operate with half the funding and is beginning seven years later than the government-funded Japanese OJRL. The new Battelle program began in 1985 with six firms (Allied, AMP, Dukane, Hewlett-Packard, ITT, and Litton Systems). Battelle hopes to expand to 14-20 firms in 1986. The target funding level is $12 million for the first three years.[77] The proposed program has three major objectives: developing automated microassembly and packaging technologies; developing manufacturing processes for fabricating optical circuits; and, developing processes for producing optical-grade crystals for guided wave optics. These objectives include not only the development of new generic technologies and materials, but also infratechnologies such as testing procedures and other standards.[78]

In following the Japanese model, this cooperative research program is a distinct departure from the typical Battelle multiclient arrangement in which industry "participates" only as a subscriber; that is, the industry supporters receive the results of the research but are not direct participants. The new optoelectronics research program will utilize scientists and engineers from the participating U.S. firms, whose financial contributions will pay for the material and equipment costs as well, while Battelle will absorb the overhead costs. As previously discussed, one of the advantages of this form of research consortium is that the direct participation of scientists and engineers from member firms significantly speeds up the technology transfer process--an increasingly important factor in determining competitive advantage.

A noteworthy aspect of the proposed consortium is the substantial effort required by Battelle to obtain the participation of a significant number of U.S. firms. Battelle is in effect playing the role of MITI, but without MITI's advantage of research funds. In fact, Battelle must ask participants for operating funds. However, funding is not the only factor in determining whether a consortium is created. Competitive motivation is, as previously discussed, an essential determinant.

But perhaps the most overlooked factor is the coordination requirement. Participating firms do not simply reach a decision to join a consortium through some push-button internal decision process. Instead, the divisions within a firm, which have a stake in the new technology and which often operate at least semiautonomously within the corporate structure in order to promote internal competition, must collectively reach a decision on participation. No one division wants to fund the firm's participation in the consortium with the cost counting against their measured rate of return, while other divisions benefit from the funded research as "free riders". Often a champion or facilitator is needed to organize and coalesce support within the firm. This need is especially apparent in firms without central R&D functions. The facilitator role is frequently played by MITI in Japan, and Battelle has had to do the same for their optoelectronics cooperative.

THE ROLE OF INFRATECHNOLOGIES

In addition to generic technologies, individual firms systematically underinvest in "infratechnologies" which are techniques and methods (such as measurement methods) that must be uniformly used by all firms in the market for a particular technology.[79] The National Bureau of Standards is the primary supplier of nonproprietary measurement and test methods as well as critically evaluated scientific and engineering data used by industry in research, production control, and market transactions. As evidenced by the analysis of technical barriers facing U.S. firms investing in optoelectronics technology, measurement methods and data will play critical and pervasive roles in the evolution of this emerging technology. Yet, for the reasons cited in the referenced literature, industry will underinvest in these infratechnologies.

These methods and data provide the technical basis for voluntary industry standards which increase the efficiency of the entire technology-based economic process: (1) they allow the results of experimental research to be determined, thereby permitting state-of-the-art research to advance; (2) standards provide assurance that specified production processes will yield the required levels of quality and reliability; (3) standardized acceptance test methods reduce transactions costs associated with custody transfer in the marketplace. Thus, standards improve the efficiency of R&D, production, and marketing so that the overall price of a new product is reduced, thereby accelerating market penetration.

The timing as well as the provision of these infratechnologies are critical factors in helping industry achieve competitiveness in technology-based markets. Thus, NBS must interact closely with U.S.

firms individually and collectively (through industry associations and research cooperatives) to effectively plan its own complementary research programs.

Part 6

CONCLUSION

Optoelectronics technology is in the "takeoff" stage in its life cycle. The crude hybrid integrated optic circuits currently emerging from the laboratory will quickly be replaced by much more powerful versions and later on by totally integrated circuits. This technology along with the more developed optical fiber technology will be the driving forces behind communications, sensing, storage and retrieval, printing, and other information-handling applications which will have major economic impacts over the next several decades.

The economic impacts of optoelectronic technology will be substantial. Markets potentially penetrated by optoelectronic technology are estimated to collectively have current (1985) sales of $9 billion with an average projected growth rate of 27 percent. Japan's NTT alone plans to spend an astounding $80 billion over the next 15 years to completely replace the national communication system. One estimate of the cost savings to the U.S. economy from the use of only two categories of integrated optic devices in communications applications is $1.4 to $2.8 billion annually by 2000. In terms of the Government's contribution of infratechnology, the cost savings to the economy from the timely development of measurement technologies which support industrial R&D, production, and marketing are estimated to reach an annual rate of $100 to $200 million by 2000.

Decisions made right now by companies will greatly affect their future competitiveness. These companies, collectively as an industry, will determine their country's competitiveness in world markets. The estimated worldwide expenditures in 1985 for optoelectronics R&D of approximately $700 million represents a dramatic 40 percent increase over the previous year and reflects the entry of a number of large firms. R&D investment is expected to increase another 40 percent over the next two years. New would-be competitors are joining in the race to develop and market optoelectronic components, optical fibers, and information-handling systems based on these two technologies. Annual sales of such systems are estimated to be $3 billion in 1989--triple the level for 1985.

One of the most important considerations in planning industry, government, and joint industry/government R&D programs is timing. Sensitivity analyses have shown the dramatic impact of only a year's difference in the timing of commercialization. Given the long lead times required to set up and carry out major research programs, appropriate planning and implementation of R&D strategies are essential to achieving competitiveness in world markets. At this point in time, the United States and Japan are approximately equal in terms of generic research aimed at product development. The Japanese seem to have the lead, however, in the development of production technology. This lead is not insurmountable if the appropriate industry and government programs are carried out in the time frame required to achieve early market entry. The window in time during which strategies can be formulated and successfully carried out is not large, given the formidable competition faced by U.S. firms. No better testimony to the severity of this competition exists than the fact that in 1984 the U.S. electronics industry experienced a negative balance of trade for the first time in its history.

The appropriate strategies seem to be a continuation of the buildup of private-sector R&D capabilities coupled with increased cooperative research at the generic technology stage and accelerated infratechnology research to enable competitive timing of industry's product and process development as well rapid market penetration. Cooperative research should include combinations of private firms, universities, and government laboratories. Infratechnology research will be focused at the National Bureau of Standards. A complete understanding of the required steps in the development of optoelectronics and identification of the most efficient performers (from both private and public sectors) of each step are essential for success in the intense international competition which is already underway.

The importance to the United States economy of being competitive in world markets for optoelectronic products cannot be overemphasized. The projected sizes of the markets understate the importance of the productivity-leveraging effects of these technologies on the information systems which are the engine of the "information age". Not only economic effects, but social and political effects will result from orders of magnitude reduction in the cost of accessing information in the home and the workplace. Work styles and, in fact, life styles will change significantly.

The nations whose economies are competitive in information services will be the ones with the highest rates of growth over the next several decades. Most important for industry and policymakers to recognize is the fact that although much of final demand for information is in the form of services, the underlying manufacturing base will be the major determining factor in the future rates of productivity growth and hence international competitiveness in this arena. Thus, because of the increasing pervasiveness of information technologies in society, competitiveness in the production and sale of computers, optical fibers, and optoelectronic components will be critical to achieving increases in the standard of living in the decades ahead.

REFERENCES

1. See Business Week, May 21, 1984.

2. See Fiberoptic Marketing Intelligence [December 1984].

3. The other major area consists of energy-related applications.

4. Japan's Optoelectronic Industry and Technology Development Association defines optoelectronics in similar applications-oriented and functional contexts. Such an approach may help explain why the Japanese tend to be quick to identify and achieve market applications of new technologies.

5. III and V refer to the third and fifth "groups" of the periodic chart of the elements. Gallium arsenide is the most commonly researched compound from the elements found in these two groups. The shorthand "III-V semiconductors" is used to distinguish that group of materials from silicon-based semiconductors.

6. Tien and Giordmaine [1980].

7. See, for example, Bar-Chaim, Ury, and Yariv [1982] and Kao [1983].

8. Holman and Wood [1985].

9. Holman and Wood [1985].

10. Holman and Wood [1985].

11. DBR = Distributed Bragg Reflector and DFB = Distributed Feedback.

12. FET = Field Effect Transistor

13. Holman and Wood [1985].

14. Holman and Wood [1985].

15. The index of refraction (n) is the ratio of the velocity of light in a vacuum to the velocity of light in the material and is always greater than or equal to one (because in a vacuum, n = 1, and in materials light always has a lower velocity).

16. Holman and Wood [1985].

17. Holman and Wood [1985]. However, as discussed in another part of this report, very recent research has claimed the potential of

developing a lasing function for certain doped forms of lithium niobate.

18. See Charles River Associates [1984].

19. Charles River Associates [1984, pp. 20-22].

20. Stoichiometry is the atomic proportion or ratio of the different elements that make up a compound (eg., in lithium niobate, $LiNbO_3$ the stoichiometry is one lithium to one niobium to three oxygen atoms).

21. Charles River Associates [1984, pp. 22-23].

22. Charles River Associates [1984, p. 23].

23. For a technical description of monolithic integrated circuits, see Bar-Chaim, Ury, and Yariv [1982].

24. The problem of shorter lifetimes inherent in these materials may be mitigated somewhat by the possibility of using smaller geometries (compared to lithium niobate), which may reduce the need for higher drive voltages.

25. Holman and Smyth [1984].

26. MBE stands for molecular beam epitaxy and MOCVD for metal-organic chemical vapor deposition. The highest quality optoelectronic films have been made recently by these processes.

27. For example, MITI is allocating approximately $15 million per year for such horizon technologies as superlattices and superstructures which have applications in optoelectronics.

28. Japanese government funding shows a declining trend because of the winding down of MITI's support for OJRL. Any plans for future funding other than support for programs at the Electrotechnical Laboratory are not known at this time.

29. See <u>Fiberoptic Marketing Intelligence</u>, November 1984.

30. The remaining 42 percent of the current market is divided among video, computer connect, and military applications.

31. Kessler [1984]

32. Kessler [1984].

33. Holman and Wood [1985].

34. Holman and Wood [1985].

35. Holman and Wood [1985]. The Czochralski method is described on pages 15-16 of this report.

36. See the Japanese Technology Evaluation (JTECH) Program Panel report [1985].

37. See Bell [1985], p. 48.

38. See Breakthrough [August 1, 1985].

39. MBE, developed in the 1960s at Bell Laboratories, is based on the epitaxial growth of thin layers from a few nanometers to hundreds of nanometers thick. Molecular beams are directed toward a heated substrate, where they condense in the form of a single crystal. Growth proceeds at approximately one atomic layer per second. MOCVD introduces the gaseous constituents of a semiconducting compound into a reaction chamber, where they combine on a heated substrate. (See Bell [1985]).

40. Haavind [1985].

41. Switches allow the light to be moved from one channel to another, i.e., from one fiber to another. Modulators change the frequency, amplitude, or phase of the optical signal to encode information. Wavelength division multiplexers (WDMs) combine several optical signals of different wavelength from separate fibers. A multiplexer is also used to filter a specific wavelength from laser light sources. The filter can be tuned to maintain a signal of unvarying wavelength. Couplers transfer the light from one input channel to another channel for transmission through a fiber.

42. There are two main types of optical fibers. One type, known as "multimode fibers", propagate light of a single frequency in discrete optical paths called modes. Modes are characterized by the distribution and direction of magnetic and electrical fields. These paths or modes are determined by waveguide parameters such as refractive index and geometry. Fiber waveguides of larger diameter (i.e., 50-100 microns) typically support hundreds of modes simultaneously--hence, the name "multimode" fiber. When the waveguide's diameter is made sufficiently small (4-5 microns), only a single optical mode can be transmitted at the designed wavelength. Such a "single-mode" waveguide does not display the modal interference (dispersion) of multimode fiber.

43. Hecht [1984] provided these estimates, although more recently the cost seems to have dropped by around 20 percent.

44. Alferness [1984].

45. Alferness [1983].

46. Alferness [1984].

47. See Davidson [1985].

48. Alferness [1984].

49. Alferness [1984].

50. Hecht [1984].

51. This rate is equivalent to 14,000 telephone conversations or 100 average novels per second.

52. In the internal modulation experiment, the Bell Labs researchers used a specially designed distributed-feedback laser and showed that they could turn it on and off 2 billion times a second to produce pulses with extremely stable wavelength. They transmitted these signals over 103 kilometers of fiber without needing a repeater to boost the power and restore the signal.

In the external modulation experiment, an optical switch was used made of a titanium-diffused lithium niobate waveguide element that shifted the light signal in and out of the fiber in response to an electrical signal pulsed 4 billion times a second. With the external modulation device, a somewhat higher-powered laser could be used, and the researchers were able to send the signal without repeaters over 117 km of fiber (Thompson [1985]).

53. See Japan Electronics [November 15, 1985].

54. The bit-rate-times-distance figure is obtained by multiplying the bandwidth (maximum modulation rate) times distance to get a basis for comparing the results of different experiments. For example, the external modulation experiment at AT&T established a record for single fiber systems of 470 billion bit kilometers per second.

55. Holman and Wood [1985].

56. Holman and Wood [1985].

57. See Japan Electronics [September 1, 1985].

58. Thompson [1985].

59. See Fiberoptic Marketing Intelligence, October 1985.

60. See Kessler Marketing Intelligence [1984], p. 23.

61. Bell [1985].

62. See Business Conditions Reports [January 1985].
63. Charles River Associates [1984].

64. International Resource Development [1985].

65. Charles River Associates [1984, pp. 39-40]. CRA arrived at this assumption in the following way. They assumed that modulators and filters will eventually cost approximately twice as much as detectors. Repeaters are more complex and might cost as much as four to five

times as much as sources (as estimated by Montgomery and Dixon [1981]). CRA also assumed that modulators have the potential to be used with 25 to 50 percent of all light sources (and repeaters) once full diffusion is reached. This assumption reflects the fact that the benefits of external modulators will be realized primarily in high data-rate, long-wavelength transmission and that not all applications will require long-wavelength systems or even perhaps the data rates offered by external modulation. Filters have the potential to achieve more universal usage than modulators because they provide benefits even at shorter wavelengths and data rates. Multiplexers are assumed to have the potential to be used with 75 to 100 percent of all fiber optic sources, detectors, and repeaters, once full diffusion is reached. Thus, a rough average use rate for the two classes of devices is 50 percent.

66. A number of related curves of the general "s" shape have been proposed and tested empirically. See Martino [1983].

67. See, for example, Charles River Associates [1983] for a partial review of the relevant literature.

68. Charles River Associates [1984, p. 42].

69. Charles River Associates [1984, p. 44].

70. Based on data in Integrated Circuit Engineering [1980] and Electronics [January 13, 1983], CRA estimated that the ratio of the value of integrated circuits used in communications switching systems to total systems value was approximately 20 percent in 1980.

71. At such speeds internal modulation causes instability problems in the light signals generated by the laser. Instability causes higher signal losses which decrease the required distance between repeaters.

72. The alternative to integrated optic switching is more likely to be digital electronic switching rather than electromechanical optical switching.

73. CRA [1984, p. 47] also characterized the potential savings in the following way. Industry interviews indicate that integrated optic filters used in wavelength division multiplexing applications on single-mode fibers are expected to have the capacity to handle 33 to 67 percent more channels while costing 50 to 75 percent less than existing multiplexers. The implication is that the cost savings from substituting integrated optic filters for existing multiplexers will be 1.67 to 5.67 times the value of filters installed. That is, on a per channel basis, the cost of the existing approach to multiplexing is 2.67 to 6.67 times greater than the expected ultimate cost of multiplexing with integrated optics.

74. See Charles River Associates [1981].

75. See Tassey [1985] for a discussion of the nature of generic technology and the possible roles for government in supporting its

development.

76. Spicer [1983].

77. Note that the MITI-funded program is at an average annual rate of about $10 million compared to the proposed Battelle program for which proposed funding is at an average annual rate of $4 million. Spicer [1983] estimated that the total eight-year MITI program, estimated at $75 million, could not be duplicated in the United States for less than $100 million.

78. See Inside R&D [October 23, 1985].

79. See Tassey [1985].

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Optoelectronics is one of the two major technologies driving the revolution in communications, which will not only have profound effects on the economy but on social and political structures as well. Future productivity advances in optoelectronics will come from integration of the various signal processing functions and from improved manufacturing technologies. "Hybrid" integration, which uses oxide-based materials and integrates some of the signal processing functions, is close to commercialization. Total or "monolithic" integration, based on gallium arsenide, may not reach commercialization for another 8-10 years. In both cases, the economic impact will be substantial.

As a result, the U.S. and its major competitors, especially Japan, are making major R&D investments in optoelectronics. Worldwide R&D expenditures are expected to reach $1 billion by 1987. In terms of market penetration, fiberoptic systems will attain annual sales of more than $3 billion by 1989. The Japanese have made a national commitment to becoming the world leader in this market.

Competitive positions in world markets will be determined by which countries rapidly advance all elements of the overall technological base. This base includes measurement-related methods and data which have been shown to have significant effects on productivity growth in other technological areas. Optoelectronics is projected to be equally dependent on this technology element for rapid development and market penetration.

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