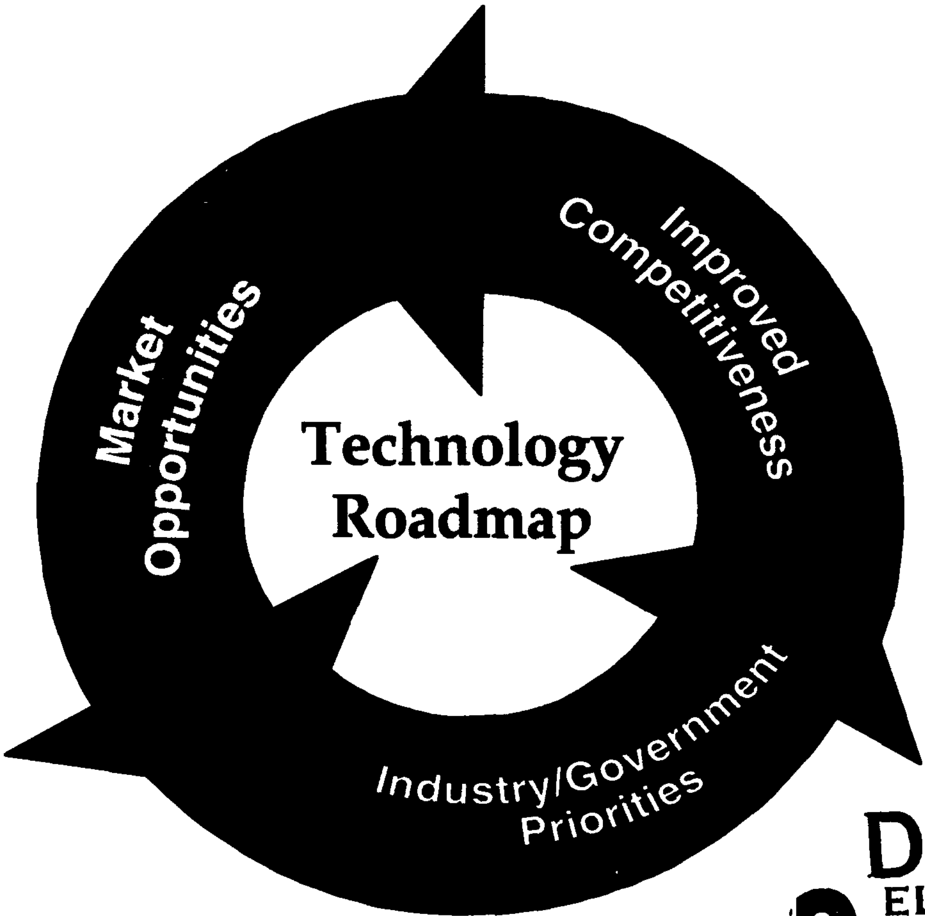
Optoelectronic Technology Roadmap



Conclusions & Recommendations

OIDA Optoelectronics Industry Development Association

Mission —

OIDA's mission is to advance the worldwide competitiveness of the North American Optoelectronics Industry.

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This report sets forth the major recommendations of the Optoelectronics Industry Development Association (OIDA) to improve the competitiveness of North American optoelectronics industry. The report summarizes an effort to determine the greatest market opportunities and key technical barriers, and to identify the highest priorities for improving the competitiveness of the industry.

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FOREWORD

This report sets forth the major recommendations of the Optoelectronics Industry Development Association (OIDA) to improve the competitiveness of the North American optoelectronics industry. This represents the first time that the North American optoelectronics industry has developed a consensus on the future of optoelectronics markets and technologies, and on the steps needed to improve the competitiveness of the industry.

Optoelectronics may be the most significant set of new technologies since semiconductors. It is the new frontier of the information age, making possible enormous advances in the collection, movement, and display of information. Optoelectronics is the enabling technology for equipment with markets that will reach into the hundreds of billions of dollars in the next decade and for industries that will employ over a million people.

Although the North American optoelectronics industry is competitive in many high-performance technologies, it has faltered in many of the largest markets. In key segments of the industry, including flat panel displays, optical storage equipment, and consumer optoelectronics, the domestic industry is weak. One reason is that the North American industry, unlike its counterpart in Japan, has not had a mechanism to guide private and government investment to the areas of greatest opportunity.

This report -- and the technology roadmap on which it is based -- provides such a mechanism. It is the result of the work of over 500 people from industry, academia, and the national laboratories who participated in a two-year process to determine the greatest market opportunities and key technical barriers, and to identify the highest priorities for improving the competitiveness of the industry.

We believe the recommendations presented here will make a substantial difference to the competitiveness of the industry. Their value can be measured by the change in share of the global market the domestic industry experiences. Progress can also be measured against the milestones established in the full technology roadmap. In the first analysis, the recommendations require not new funds, but a refocusing of existing funds. The programs we propose call for matching contributions from industry and a commitment to commercialize the technologies.

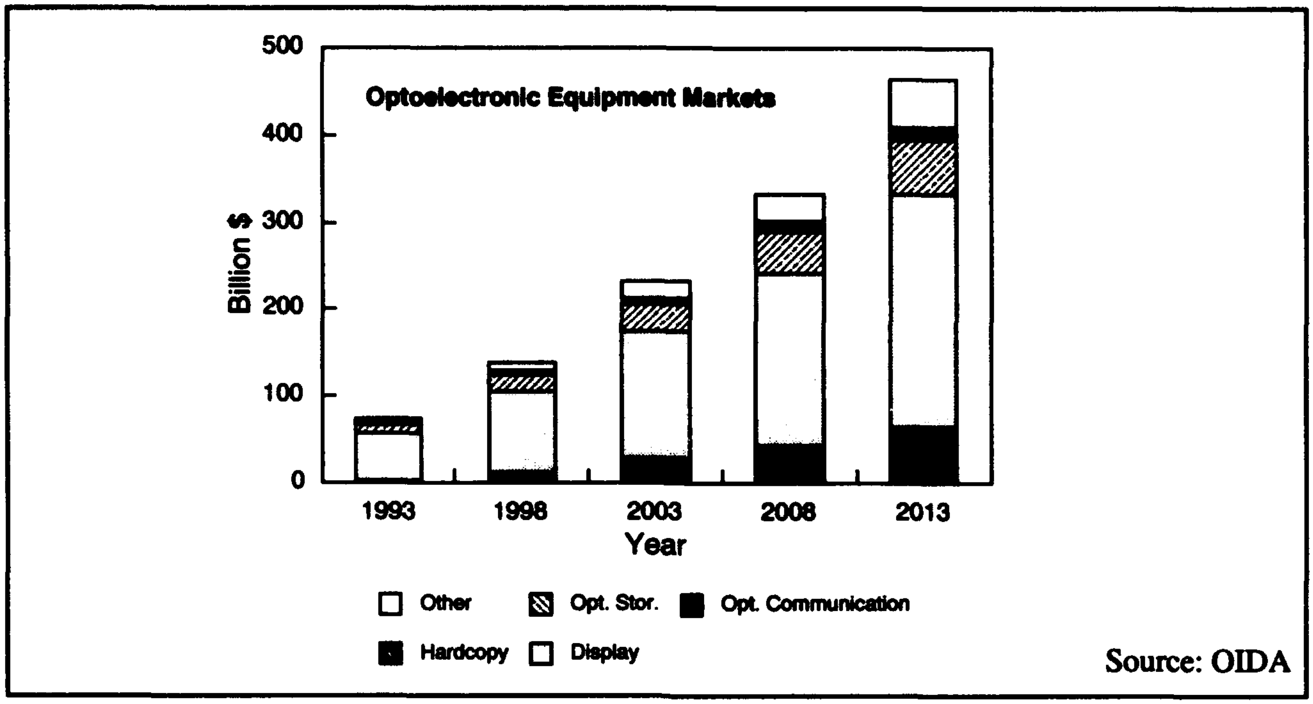
The challenge facing the North American industry has been difficult, and will become more difficult with time if changes are not made. The opportunity to be gained or lost now, in terms of jobs and economic growth, is enormous. We look forward to working with all segments of industry, government, and academia to make the changes needed.

Paul Pankow
Chairman, OIDA
Vice President, 3M

William Braun
Former Chairman, OIDA
Sr. Vice President, Motorola

Arpad Bergh
President, OIDA
Executive Director, Bellcore

Executive Summary



Note: Values are world market for equipment enabled by optoelectronics. Figures for display include CRTs and flat panel displays. Equipment enabled by displays includes computer monitors, televisions, and laptop computers. Figures do not include the values for services and software enabled by optoelectronics, which are substantial for optical communications and optical storage.

Optoelectronic technologies are key enablers for the information age. They underlie such burgeoning information age technologies as flat panel computer displays, fiber optic communications systems, optical storage, and laser printers. Based on a two-year, industry-wide program to identify the markets for optoelectronics and the key technical advances needed to exploit those markets, this report presents OIDA's recommendations to improve the competitiveness of the industry.

The markets identified for equipment enabled by optoelectronics are large and are expected to grow rapidly, from over $50 billion today to over $400 billion in twenty years (in constant dollars), as shown in the figure above. This is due both to the growth in the overall electronics markets and the expanding role of optoelectronics within electronics.

Recommendations

OIDA has developed recommendations to improve the competitiveness of the North American industry in displays, optical communications, optical storage, and hardcopy technologies. The key competitive challenges and highest priority recommendations differ from area to area, but in all areas, the OIDA recommendations will make critical improvements. The recommended program should improve U.S. market share.

The following table summarizes the key areas of recommendations and highlights the areas where new programs or increased efforts are needed. Most of the recommendations can be funded through refocusing existing optoelectronics programs, or through the planned budgets of the industry-driven technology programs, such as the Advanced Technology Program, the Technology Reinvestment Program, or Federal laboratory technology transfer programs.

OIDA RECOMMENDATIONS SUMMARY

- ● new initiative
- ◍ increase effort
- ○ maintain effort
- □ no action

"FOOD CHAIN"	DISPLAY	OPT COMM*	OPT STORAGE	HARD COPY
Market Development	□	●●●	□	□
U.S. Manufacturing	●●●	□	□	□
Manufacturing Technology	◍◍◍	◍◍◍	◍◍◍	□
Metrology/ Standards	●	◍	●	●
R&D	○○	○○	◍◍	○○

*Optical Communications includes telecommunication, data communications, and optical switching and computing

Displays

Flat panel displays have an enormous market and are a critical component for many electronics products. The U.S. currently has less than five percent of the world market, but has significant technical strengths. OIDA believes that the top priority is to establish a domestic, high-volume manufacturing industry. Although U.S. manufacturers are interested and have strong technical capabilities, the barriers to entry are high. The barriers to manufacturing must be reduced by reducing the technical and financial risk. This can be achieved by supporting R&D tied directly to high-volume manufacturing ventures and by developing infrastructure for manufacturing. Continued support for a strong precompetitive R&D program in display technology is also essential.

Optical Communications

Optical communications technologies are key enablers for a national broadband communications network. They are already the technology of choice for long distance communications, and are being used increasingly for shorter distance communications. Much of the market growth is expected to be in shorter distance communications that will require lower cost components.

OIDA is proposing a two-part strategy for strengthening the domestic industry in these markets. First, it is essential to help expand U.S. markets to enable U.S. firms to produce in higher volumes and at lower costs. OIDA strongly supports the efforts by the Administration and private sector groups to develop a national information infrastructure through regulatory reform and demonstration projects. OIDA particularly supports projects that demonstrate the feasability and cost-effectiveness of bringing broadband communications, data processing, and storage systems into hospitals, schools, factories, and other locations. Second, it is essential to support an R&D program that focuses on reducing the cost of optoelectronics, both through improvements in manufacturing technologies and through the development of new inherently low-cost components and devices.

Optical Storage

Optical data storage is a key enabler for multimedia software, digital libraries, and paperless offices. It is currently a large and growing business, and is expected to reach $30 billion by the year 2003. Japanese companies currently dominate the optical storage equipment industry, while the North American industry is competitive in media (optical disks and tapes). The coming shift to optical storage based on green and then blue light (which will enable higher density storage) will present a significant opportunity for the U.S. industry to reenter the business.

To take advantage of this opportunity, OIDA recommends two cooperative industry-government R&D programs: one focused on lasers and the other focused on substrates, media, and recording systems. These programs must address the feasibility of low-cost manufacturing and the ability of the private sector to rapidly develop competitive, commercial products.

Hardcopy

Hardcopy output includes not only common office printing and copying, but also printing of photographs, newspapers, magazines, medical images, and printing on packaging. It also includes three-dimensional solid imaging for rapid prototyping and tooling of products. Optoelectronics, in the form of laser printers, laser imagers, copiers, and scanners, is an enabling technology for hardcopy.

OIDA has identified the need for a single color standard to support all color scanning, display, and hardcopy as a critical issue for the future of hardcopy. It is essential to be able to predict in advance how electronic images will appear in hardcopy. OIDA supports NIST initiating a program to bring together the diverse elements of the industry and appropriate standards organizations to develop agreed-upon and broadly applicable color standards,and also supports research by NIST into related metrology issues and algorithms.

INTRODUCTION

Optoelectronic technologies, which use both light and electronics, are key enablers for the information age. Used in such technologies as flat panel computer displays, fiber optic communication systems, optical disc information storage, and laser printers, optoelectronics are vital for the collection, transmission, processing, storage, and display of information.

The use of light gives optoelectronic technologies several unique advantages. First, it is possible to store or move vastly greater quantities of information than is possible with electronics. Second, the use of light makes optoelectronic technologies uniquely suited for gathering and displaying visual information, the form people use most effectively. As information is increasingly communicated and presented in the form of images, these advantages become increasingly important. Images require high communication and storage capabilities that can best be met with optoelectronics; they also require optoelectronics for display and generating hardcopy.

The optoelectronics industry is sizable and substantial, with markets in communications, computing, defense, motor vehicles, aerospace, industrial equipment, and consumer electronics. A recent Department of Commerce survey[1] of the U.S. industry found, based on partial returns, that it produced shipments of nearly $6 billion in 1991 and conducted R&D worth over $880 million. Of this, 74 percent was funded by industry, with 23 percent coming from the Federal government.

However, in the early 1990s, North American optoelectronics manufacturers and users became concerned over the erosion of their share of the growing world market. In particular, North American competitiveness was faltering in many of the highest volume segments of the industry. Part of the problem was that the North American industry did not have a mechanism through which to identify the key markets and to channel both private and government investment to the areas of greatest opportunity. To remedy this situation, the Optoelectronic Industry Development Association (OIDA) began a two-year program to identify the main markets for the next 20 years and to determine what was needed to be competitive in those markets.

Over the course of the program, OIDA conducted 11 workshops and 2 national forums. Over 500 industry representatives attended these meetings to examine the major market needs, to develop a consensus on the evolution of technology, to identify critical enabling technologies and technical barriers, and to develop a strategic vision for the industry for the coming 20 years. The program has produced two major reports:

1. *Market Opportunities in Optoelectronics* (1993); and

2. *Technology Roadmaps for Optoelectronics* –1993 to 2013 (1994)

In the first report, OIDA identified markets for equipment enabled by optoelectronic technologies that would increase from $75 billion in 1993 to $463 billion in 2013, a compound annual growth rate of 9.5% over the 20 year period in constant dollars. Computer products and consumer products represented the largest markets, but there were also substantial markets in communications, the automotive industries, defense, and aerospace. The impact of optoelectronics is anticipated to be even greater considering the growth of broadband information services and software enabled by optoelectronic communications and information storage.

The second report served to develop a consensus view of the evolution of optoelectronic technology over the coming two decades. This technology roadmap report identified major technical barriers to be overcome for the technology to keep pace with growing market demands. The critical policy recommendations from these two reports are summarized in the following pages. These recommendations have been divided into four categories:

- Display
- Optical Communications
- Optical Storage
- Hardcopy

These categories are the technologies with the largest markets. In most cases the markets for these technologies cross several segments; the technologies will enable advances in computers, communications, automotive, aerospace and defense, consumer, and industrial products, and they can help to improve the competitiveness of each of those industries.

The recommendations presented here are those chosen by industry members as making the most significant impact on the competitiveness of the North American industry in each area. Industry is committed to making the recommendations succeed, and we expect industry to contribute matching funds to develop the technologies and to commercialize them once developed. OIDA is also committed to reviewing and seeking improvements in the programs as they evolve. The metric of success for each recommendation is improved market share for the North American optoelectronics industry.

Virtually all of the recommendations can be supported under existing programs, either by redirecting existing optoelectronics R&D, or by support through the planned budgets of industry-government cooperative program, such as the Advanced Technology Program in the National Institute of Standards and Technology, or the Advanced Research Projects Agency's Technology Reinvestment Program, or through cooperative programs with the Federal laboratories.

DISPLAYS

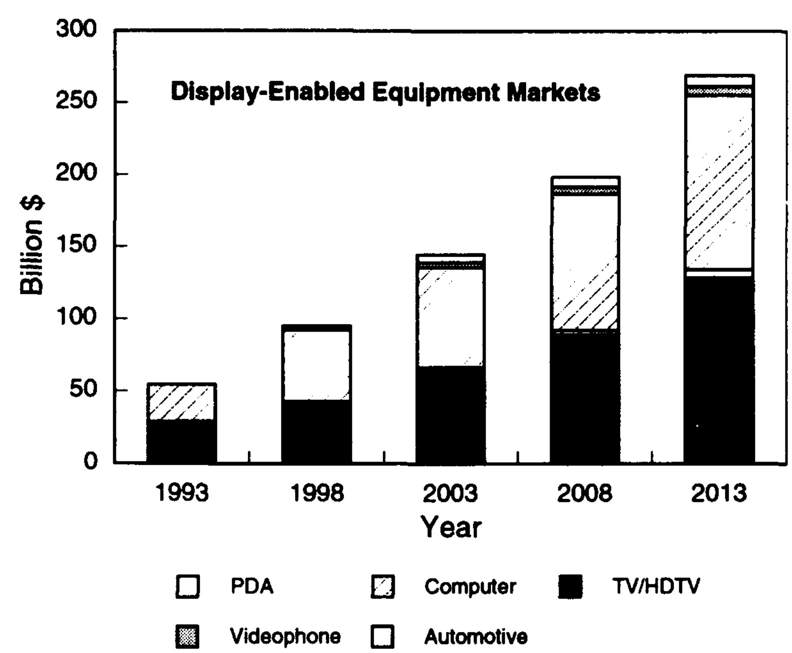
BACKGROUND

Displays are a critical technology for the nation. They are the primary means by which people receive information from machines, converting electronic signals into readily comprehensible visual images. Displays are increasingly ubiquitous in products that use electronics, such as automobiles, telephones, and watches, and are the most critical component in many products, including televisions, laptop computers, and personal digital assistants. Japan currently controls 95 percent of the world market for flat-panel displays. OIDA believes that it is vital that the United States regain a strong competitive position in display technology. OIDA also believes that the opportunity exists to do so today.

It is critical for the United States to have an internationally competitive display industry for four main reasons:

1. **Displays have enormous economic potential.** The current world display market is approximately $20 billion, of which about $5 billion is flat panel displays. By the year 2000, the total is expected to reach almost $40 billion, of which over $20 billion is expected to be flat panel displays. Furthermore, displays are enablers for products with much larger markets, which will grow from $54 billion in 1993 to in excess of $269 billion by the year 2013, an 8.4% compound annual growth rate (see figure below).

   The location of display production will have a strong influence on whether high wage jobs are created in the United States or elsewhere, and will have a significant impact on the U.S. trade balance. For example, assuming one job per $250,000 in sales,[2] $50 billion in sales of display-enabled equipment translates to 200,000



Source: OIDA

Note: Examples of display-enabled equipment include televisions, computer monitors, laptop and notebook computers, and personal digital assistants.

jobs. In addition, there are typically 8 service jobs per manufacturing job. The viability of the U.S. display industry will determine what percentage of those jobs are located in the United States.

2. **A reliable supply of displays is essential for U.S. competitiveness in markets for the equipment that uses displays.** Displays are the most expensive components of many products that use displays, and represent 20-35 percent of the cost of portable computers and over 50 percent of the cost of many personal digital assistants. This percentage is not likely to decrease -- electronics can be shrunk in size and cost, but displays need to remain at a size appropriate for the human eye. In many products, the quality of the display distinguishes the product from its competition. Electronics equipment manufacturers are vulnerable if they do not have access to state-of-the-art displays at the same cost as their competitors. Production rates of many products are currently limited by the availability of displays.

3. **The design and manufacturing of displays is increasingly central to the design and manufacturing of the equipment that uses displays.** For many products, a change in the display supplier requires a redesign of the end product. Moreover, there is likely to be increasing integration between displays and the other electronic functions of products. Semiconductor chips will be first integrated onto displays, and may eventually be coproduced in a single process. As this integration occurs, more and more proprietary technology will be included in the display, and display manufacturers will control an increasing amount of the value of the end product.

4. **Displays are critical components of many defense systems.** Examples range from aircraft cockpits to portable communications gear used by infantry. Having a reliable supply of displays will be increasingly important to the national defense as information technologies become ever more important parts of defense systems. The Department of Defense has supported U.S. manufacturers of displays for defense purposes, and will continue to have to do so at high cost if the United States does not have a competitive commercial industry.

For all of these reasons, OIDA believes it is essential for the United States to develop a competitive display industry. To have a competitive industry means being competitive in the dynamic and important segments of the market.

There are two key market opportunities on which to focus. The first is today's high-volume, high-value market for flat panel displays for laptop computers and other portable information devices. The second is the market likely to emerge later this decade for larger TV/HDTV displays. In the next few years, new projection and flat-screens are expected to replace CRTs in this market, a shift that creates an opportunity for U.S. companies to reenter this market. Consumer video currently accounts for the largest negative balance of trade in the electronics sector, an imbalance so great that it completely offsets the positive balance of trade in all other electronic products combined. In addition, other markets may emerge that are not apparent now, such as head mounted displays for consumer applications

To be competitive in the market for TV/HDTV displays later this decade, it is important for the U.S. industry to develop a strong manufacturing industry in the market for laptop computer displays today. It will be extremely difficult to enter the market for large flat screen displays without manufacturing experience with smaller size displays.

There are good opportunities today for the U.S. to gain a strong position in the flat panel display industry. The market and technology are still growing and evolving rapidly, and the United States has strong capabilities in many of the basic technologies. However, the United States lacks a strong, high-volume manufacturing base. Developing this base is the top priority for the industry.

The private sector faces significant barriers to developing a domestic display manufacturing capability. First, the barriers to entry are high. To build a high volume manufacturing plant for the current leading display technology requires an investment of more than $200 million. Second, the business risk is high. The main competitors--Japanese companies--have made substantial investments, have manufacturing experience, and have a record of selling displays (and other critical technologies) at less than their manufacturing costs in order to keep or increase their market share. Third, the overall business conditions in the United States have not favored manufacturing here. These conditions include factors such as cost of capital, tax environment, presence of specialized suppliers, and others. Display ventures between U.S. and Japanese companies have in the past chosen to manufacture in Japan rather than the United States.

Some conditions have already changed in favor of investing in the United States; the cost of capital differential between Japan and the U.S. has shrunk, and the strong yen now makes investments in the United States relatively more attractive. However, an established manufacturing base and tax[2] provisions still favor manufacturing in Japan. With the recession in Japan, Japanese investments have slowed, creating an opportunity for the U.S. to catch up.

RECOMMENDATIONS

The key roles for the Federal government are to create a business environment in the United States favorable enough to overcome the barriers to domestic manufacturing that were described above and to continue to support precompetitive technology development. OIDA recommends a three-part strategy consisting of: (1) reducing barriers to domestic display manufacturing; (2) supporting the development of a display manufacturing infrastructure; and (3) supporting a strong precompetitive R&D program for display technology. The goal of this strategy is to create a viable, self-supporting, competitive, domestic display industry at the lowest cost to the taxpayer.

REDUCE BARRIERS TO DOMESTIC DISPLAY MANUFACTURING

The Federal government should work to lower the barriers to display manufacturing in the United States. Specifically we recommend support for up to 50 percent of the manufacturing research and development costs associated with flat panel display manufacturing ventures that meet the criteria outlined in the following box. This should significantly lower the cost and shorten the time to profitability of ventures.

Criteria for Support of Flat Panel Display Manufacturing Ventures

1. The private sector should bear most of the cost of the total venture. Although the Federal expenditure can be a large part of the research and engineering costs, it should be a small (e.g. 20 percent) portion of the total venture. Cost sharing with state and local governments should be encouraged.
2. U.S. companies should be significant owners in the venture and should have full access to the venture's technology. Participation by Asian or European companies should be allowed on the condition that they transfer manufacturing technologies. Participation by non-U.S. companies could help to reduce the financial and technical risk, and could allow the establishment of a successful domestic display industry at lower cost to U.S. taxpayers.
3. The venture must commit to working with U.S. materials and equipment suppliers, wherever possible. The goal here is to create a strong infrastructure to make the United States attractive for future display ventures.
4. The venture must produce high information content displays at high volume (tens of thousands/month).
5. Awards should be made on a competitive basis, based on an evaluation of the venture's business plan.

Any display technology venture that meets the above criteria should be able to compete for the awards. No funds should be awarded unless all the criteria are met and industry makes a substantial investment in manufacturing. We recommend that at least three such ventures be supported to create the critical mass needed for a viable industry. A Federal expenditure of $40 million per year for three years could support 3 display ventures (assuming $200 million total cost per venture, spread over three years, with the Federal government share at 20%). The metric of success would be the creation of a viable display industry.

Support the Development of Display Manufacturing Infrastructure

OIDA recommends expanded support for the development of manufacturing infrastructure for displays, including support for technology development in materials, equipment, and component manufacturing. Particular areas where expanded R&D would benefit many types of displays include:

- large-area photolithography,
- high-resolution printing techniques
- packaging/integration of displays and drive electronics
- low-cost drive electronics
- inspection and repair techniques
- in-process measurement techniques.

Details on specific R&D priorities can be found in Appendix 1. In particular, OIDA supports the continued funding of the U.S. Display Consortium. The development of a stronger manufacturing infrastructure is essential to make the United States an attractive site for display manufacturing.

SUPPORT PRECOMPETITIVE R&D

OIDA supports the current diverse technological programs, coordinated by ARPA, DOE, and ATP. These programs should address both advanced and generic technologies. Technological superiority is essential to provide a source of competitive advantage for the U.S. industry. OIDA is concerned, however that unless a high-volume manufacturing capability is established, the major beneficiaries of U.S.-funded technical advances will be offshore producers. A major focus of the supported R&D should be the technologies that are most critical to developing a competitive industry in the U.S. in the high-volume, high-value markets. Details on specific R&D priorities can be found in Appendix 1.

Optical Communications

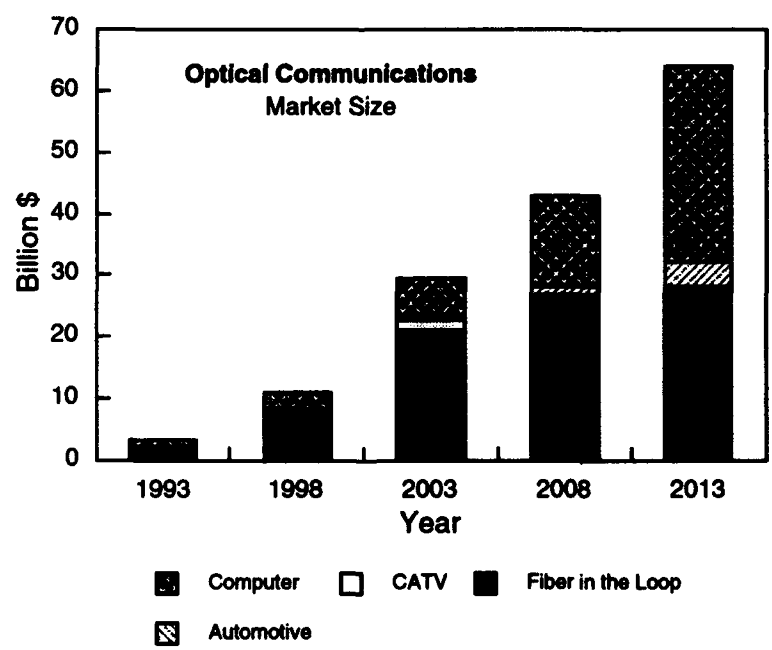
Background

Optical communications technologies are capable of moving vastly greater quantities of information over longer distances than traditional electronic communications technology. As a result, they enable an expanded range of applications and services that have enormous potential benefits to society. Telecommuting and distance learning are among the most promising of these applications.

First applied primarily to long-distance communications, optical communications are becoming cost-effective for shorter distances as costs come down and the demand for greater data flow increases. Optical communications are being used now in telephone and cable-TV distribution networks, data communications networks within office buildings and campuses, and they may eventually be used in computers as well. The light weight and immunity to electromagnetic interference of optical communications also makes them advantageous for many aerospace, industrial, automotive, and defense applications.

The market for optoelectronic communications equipment, including applications in telecommunications, computing, cable television, and automobiles, is expected to grow to over $30 billion by the year 2003, as shown below.

The market for services enabled by optical communications is much larger. Although estimates are somewhat speculative, the Administration's Information Infrastructure Task Force report cites estimates of $190 billion to over $300 billion for the contribution of an advanced National Information Infrastructure (NII) to GDP. A substantial portion of NII services will be enabled by optical communications technologies.



Source: OIDA

The Clinton Administration has recognized the importance of developing an advanced NII. It is equally important to increase U.S. competitiveness in the technologies that underlie the NII to ensure that much of the economic value that comes from designing, developing, and manufacturing equipment and systems related to the NII stays in the United States. It is also critical to keep the United States at the leading edge in the information technologies that are at the nodes of NII networks, such as data processing and storage systems. These technologies also use optoelectronic components in critical subsystems.

There are currently four main market segments for optical communication technologies:

1. **Long distance telecommunications** (trunk and municipal area networks). This is the high performance segment of optical communications, characterized by repeaterless spans of 5-100 km, and high speeds (0.6 to 2.5 gigabits per second). U.S. industry is slipping in this segment. A key need is better epitaxial growth and processing of high performance lasers.

2. **Shorter distance telecommunications** (such as fiber in the loop) This segment is characterized by spans of 1-10 km and speeds of 50-622 megabits per second. This market segment is growing and is highly cost sensitive. U.S. industry lags behind Japan in this segment and needs improvements, primarily in the form of lower cost manufacturing, packaging and alignment technologies, as well as better epitaxial growth and processing of lasers.

3. **High performance data communications.** This segment is character-ized by long distances (for data communi-cations) of 300-2000 meters or relatively high speeds (200-1000 megabits per second). It is cost sensitive. U.S. industry is competitive but improvements, in the form of cost reductions, are needed.

4. **Low cost data communications.** This segment is characterized by short distances (less than 300 meters) or low speed (less than 200 megabits per second). This segment is very cost sensitive. Component costs need to be competitive with wire or small relative to installation costs, and in many cases already are. Individual U.S. suppliers are strong here, but users would like more domestic suppliers. The main barrier for this segment is the lack of familiarity with optical technology on the part of installers and users.

Much of the market growth is expected to be in segments 2,3, and 4, which are all characterized by higher volumes and higher cost sensitivity than the first segment, which has been the largest market to date. All three of these segments will benefit greatly from precompetitive R&D to lower the costs of optoelectronics.

OIDA is proposing a two-part strategy for strengthening the domestic industry in these markets. First, it is essential to help expand U.S. markets in the areas where U.S. firms are strong. Accelerating the development of the national Information Infrastructure is a recommended step towards this goal. Second, it is essential to support and expand cost-shared R&D that focuses on reducing the cost of optoelectronics, both through improvements in manufacturing technologies and through the development of new, inherently low-cost components and devices. This R&D primarily should be for low-cost telecommunication and high-peformance data communication technologies. Support for long-range research also continues to be vital.

Demonstration Example

One example of such a demonstration is an optically connected hospital where the analysis of a patient's condition requires the gathering of multimedia "expertise" from medical centers worldwide (using the optical data highway). This general data would be combined with patient-specific data from the hospital's database (transmitted over the fiber optic storage channel network). The rapid processing of both sets of information on an (optically connected) cluster of the hospital's workstations would generate diagnosis options, which would then be communicated in real time via an infrared connection to the physician's "personal digital assistant" at bedside. Such a demonstration could provide the doctor with previously unavailable diagnosis options rapidly enough to save a patient's life. OIDA member companies are developing the technologies needed for such a demonstration.

RECOMMENDATIONS

ACCELERATE THE DEVELOPMENT OF THE NATIONAL INFORMATION INFRASTRUCTURE

OIDA supports efforts by the Administration and private-sector groups to accelerate the development of the NII through changes in regulatory policy and through demonstration projects. Accelerated development of the NII will help expand the use of advanced information technologies and will enable companies to make greater investments in the underlying technologies.

OIDA particularly supports projects that demonstrate the feasibility and cost-effectiveness of bringing broadband communications, data processing and storage systems to and into hospitals, schools, factories, government services, and other locations. Such demonstrations can illustrate the capabilities of optoelectronic technologies and allow users to determine which capabilities are useful. They can demonstrate the practicality of optoelectronics and can help systems designers and service providers become more comfortable with the robustness of the new technologies. They can also encourage the development of applications that take advantage of the higher performance.

In addition, demonstration projects can help companies integrate a wide range of technologies and can facilitate the emergence of standards and a common infrastructure for both wired and wireless communications. Standards and interoperability will allow increased economies of scale. Demonstration projects can also provide an opportunity to address management and control issues for new high-capability networks. For example, wavelength division multiplexed networks have the potential to simplify both traffic control and resource management.

Demonstrations should be monitored to ensure that a significant fraction of the systems hardware and optoelectronic devices used in the projects come from U.S.-based companies. OIDA members will support and/or participate in such projects.

EXPAND INDUSTRY-DRIVEN, COST-SHARED R&D TO ACCELERATE THE DEVELOPMENT OF LOW-COST OPTOELECTRONIC COMPONENTS AND SYSTEMS

Developing lower-cost optoelectronic manufacturing technologies will enhance the competitiveness of the U.S. industry in the key high-volume segments of the optoelectronics market. Lower costs will allow optoelectronics to be used in lower-speed and shorter-distance networks, including computer and consumer electronics applications. Lowering cost is a two-pronged approach consisting of: (1) developing manufacturing technologies to allow high-performance optoelectronics components to be made less expensively; and (2) developing the inherently low-cost optoelectronic technologies from consumer and industrial sectors into high-performance technologies for a broad range of computer and communications-sector applications.

Companies have independently begun to acquire the necessary manufacturing technologies. The work that is needed, however, spans the development of new components, new manufacturing techniques, and new manufacturing and test equipment, and the industry would be better served by a coordinated team approach. We recommend that team efforts be supported to address the following areas primarily applicable to low cost telecommunications and high-performance data communications:

- automated passive assembly and preci sion alignment
- optoelectronic package platforms that could accommodate both optical and high-speed electronics requirements
- CAD/simulation tools to speed systems engineering of packaged devices
- wafer processing equipment for both InP and GaAs-based technology
- in situ monitoring and control
- flexible batch processing.

A three-year program of $25 million per year to be matched by industry, focused on the above objectives, would provide the needed impetus to accelerate the development of low-cost optoelectronics.

Several Federal agencies and laboratories can play a key role in this area. ARPA has funded some initial work in this area but not at the level needed. Work in this area could also be funded under NIST's Advanced Technology Program, and we recommend this as an ATP focus area. The ARPA-led Technology Reinvestment Program could bring in the experience of the defense industry. Steps should also be taken to strengthen metrology and standards-related work at NIST and the cooperative industrial programs with the DOE national laboratories, especially in areas such as modeling, simulation, materials, process equipment, and reliability assessment and failure analysis.

Continue Support for Long-Range Research

Existing programs that focus on longer range R&D and high-performance applications should continue to be supported. The systems-level implications for optical switching and optical signal processing are only beginning to be understood. Innovations in devices and components should emphasize both low-cost and high-performance issues. Attention is needed on the development of InP optoelectronic integrated circuits and arrays. Existing programs include ARPA's optoelectronics programs; NSF optoelectronics-related centers and support for university researchers; and NIST's core programs in optoelectronics-related metrology. Close interaction between these university and national laboratory research programs and potential industrial users should continue to be a primary focus.

Optical Storage

Background

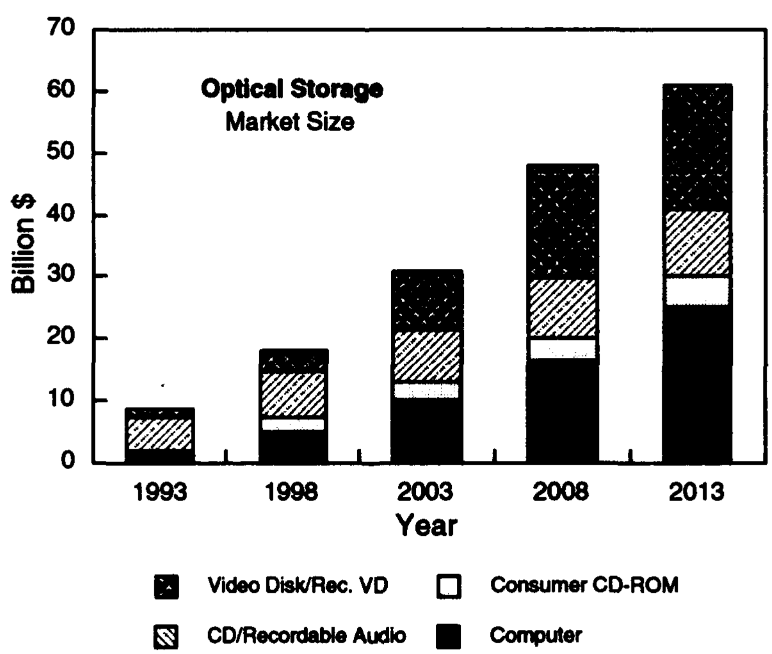
Optical data storage encompasses a wide range of products, media, and applications, ranging from compact discs (CDs) to rewritable magneto-optic drives used in workstations, to optical disk libraries. These technologies are key enablers for multimedia software, digital libraries, and paperless offices.

Optical storage competes with magnetic storage, which has a larger share of the total information storage market, but they each also serve distinctly different markets and customers. In particular, optical storage is uniquely suited for removable, convenient, high-capacity data storage. The performance of both optical and magnetic recording is increasing rapidly, and the costs of both are rapidly declining.

Optical storage is currently a significant business. The market for optical storage equipment, including computing and consumer markets, is expected to reach $30 billion by the year 2003 and is expected to continue to expand, as shown below.

These figures do not include the value of the prerecorded or recordable media, such as optical disks, or the value of the software that is enabled by these technologies. The value of these can be considerably greater than the value of the hardware.

To date, Japanese companies have dominated the optical storage equipment industry, in both consumer and computer-related applications, with European companies in second place. The North American industry is competitive in media (optical disks and tapes) and has signifi-



Source: OIDA

cant technological strengths and some commercial presence in equipment. It is struggling, however, in the face of strong Japanese competition. The challenge for the North American optoelectronics industry is to create a technological edge that will allow the development of superior optical storage devices, and then to translate that technological leadership into products that can be produced in large volumes at competitive cost.

OIDA's recommendations will provide the U.S. industry with this competitive edge. The coming shift to optical storage based on green and blue light will be a major discontinuity in the industry. This shift will greatly increase storage capacities, will neutralize many prior advantages held by competitors, and will present a significant opportunity for the U.S. industry to increase its presence and position in the business. Taking advantage of this opportunity will require not only superior technology, but an early emphasis on manufacturing feasibility. The program proposed focuses on developing products that can be manufactured at low cost and on technologies that the private sector can commercialize rapidly and competitively.

Recommendations

Accelerate the development and commercialization of short-wavelength lasers and suitable high-density optical recording systems and media

Industry-government cooperative programs should focus in two areas: (1) green, blue, and shorter wavelength lasers; and (2) low-cost, manufacturable substrate and media technologies plus complete optical recording systems that exploit both the lasers and the media. Measurement, testing, and standards issues should also be addressed in this program area.

Work in both areas should address manufacturing issues, and should result in documented prototypes that demonstrate manufacturing feasibility. Industry will then be able to rapidly commercialize the products. Work in the two areas must be closely coordinated because advances in both areas are necessary to commercialize the next generation of high-density optical storage. In addition, programs in both areas should be industry-driven, cooperative, and cost-shared with the work conducted by industry and perhaps Federal laboratories. This program, if successful, will result in a competitive North American manufacturing industry in high-density optical storage.

Continue Support for Longer Range Research

The Federal government should continue to support longer range research on 3-D optical memories in universities and federal laboratories. 3-D optical memories have the potential to greatly increase storage capacities per unit volume. Parallel input/output is needed to fully utilize these higher storage capacities. The development of applications that require parallel input/output, as well as low-cost system (CPU) hardware to support parallel processing, would accelerate the development of nonconventional storage technologies.

HARDCOPY

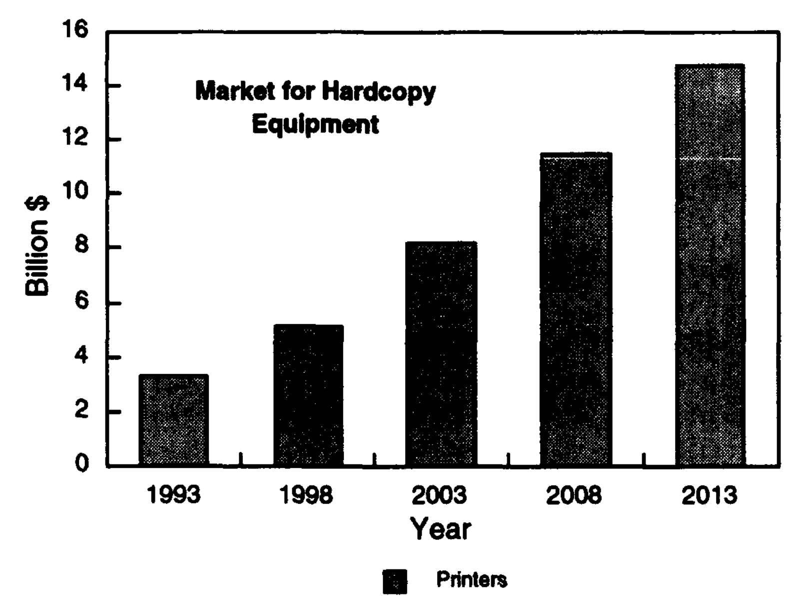
BACKGROUND

Hardcopy output consists of printing and copying images from electronic files onto paper, plastic, metal, film or other material. It includes not only common office printing and copying, but also printing of photographs, newspapers, magazines, medical images, and printing on packaging. It also includes three-dimensional solid imaging for rapid prototyping and tooling of products. Optoelectronics, in the form of laser printers, laser imagers, copiers, and scanners, is an enabling technology for hardcopy.

Hardcopy technologies have a strong synergistic relationship with optical communications. On the one hand, high bandwidth communications enable the movement of images, which in turn drives the need for better hardcopy technologies. On the other hand, the desire to move images (in contrast to text and graphics) is driving the need for higher-bandwidth communications. For example, the publishing industry is a major user of high-bandwidth communications. It has moved to distributed printing around the world because electronic communications are less expensive than shipping paper. Moving medical images will demand even greater bandwidth because of the high resolution required.

With more terminals requiring hardcopy output, the requirement for local printing of color images is forecast to continue to increase in the coming decades. Even the home market may evolve into two printers, one for photographs and one for text.

Optoelectronics-enabled printers for hardcopy output (electrophotographic printers) are forecast to increase from $3.3 billion in 1993 to over $14.8 billion in 2013, a compound annual growth rate of 7.9 percent. This estimate does not include opportunities in the home or in



Note: Includes only electrophotographic printers, not impact, ink-jet, or thermal printers.

Source: OIDA

OIDA has identified the need for a single color standard to support all color scanning, display, and hardcopy as the most critical issue for the future of hardcopy. It is essential to be able to predict in advance how electronic images will appear in hardcopy. This issue involves hardware, software, metrology, data compression, and psychology.

RECOMMENDATION

DEVELOP BROADLY APPLICABLE COLOR STANDARDS.

OIDA supports NIST initiation of a program to bring together the diverse elements of the industry and appropriate standards organizations to develop agreed-upon and broadly applicable color standards. OIDA also supports research by NIST into related metrology issues and algorithms for incorporation into software for color imaging.

ENDNOTES

1 U.S. Department of Commerce, Bureau of Export Administration, *Critical Technology Assessment of the U.S. Optoelectronics Industry*, Washington, February 1994.

2 In the Optoelectronics industry as a whole, based on Department of Commerce and Department of Labor statistics, there is currently 1 electronics industry job for each $160,000 in sales. Displays can be expected to be somewhat more capital intensive.

3 For a discussion of tax incentives for high technology in Japan, see Stern, John (American Electronics Association, Vice President, Asian Operations), *Technotax: How Japan's Tax System Spurs Technology*, Tokyo, 1991.

APPENDIX I
TECHNOLOGY ROADMAP SUMMARY

1. OVERVIEW

This is a summary of the Technology Roadmap completed by the Optoelectronics Industry Development Association (OIDA) during 1993. The Roadmap is intended to be a vision of the evolution of optoelectronics technology over the next 20 years. Its goal is to help bridge the gap between the requirements of future markets and the availability of technology. The program has been funded by OIDA membership dues as well as major contributions from the Advanced Research Projects Agency (ARPA) and the Ballistic Missile Defense Organization (BMDO).

The structure of the Roadmap Program is illustrated in Figure 1.1. The primary activity of the program was a series of six market and five technology workshops that focused on broad market sectors and basic technology categories, respectively. The workshops were attended by a cross-section of experts from industry, academia, and government with specialized knowledge of the workshop subjects. Each workshop had a chairperson, or cochairs, drawn from OIDA member companies, whose function was to identify presenters and attendees and to report on the results.

The market workshops were conducted in the spring and summer of 1992. Preliminary results were presented to OIDA membership at the Forum on Market Opportunities held in September 1992, and a final report (*Market Opportunities in Optoelectronics*) was completed and distributed to the membership in June 1993. The technology workshops were conducted in the spring of 1993, and preliminary results were presented to OIDA membership at the Forum on Technology Roadmaps held in October 1993. This is a summary of the technology roadmap report, *Technology Roadmaps for Optoelectronics* –1993 to 2013.

The technology workshops carried out in Phase II were selected to reflect the technologies that will support the high-growth market opportunities identified in Phase I. The technology workshops carried out in Phase II were selected to reflect the technologies that will support the high-growth market opportunities identified in Phase I. The five technology subjects chosen for workshops in Phase II were as follows:

- Display
- Optical Communications
- Optical Storage
- Optics in Switching and Computing
- Hardcopy

Table 1.1 shows the attendance summary for each workshop. A total of 228 technical experts participated in the five workshops, including 160 (70%) from industry, 42 (18%) from academia, and 26 (11%) from government. These participants represented a wide range of technology activities, ranging from basic research to applied research to product development.

FIGURE 1.1
OIDA TECHNOLOGY ROADMAP
TOTAL PROGRAM

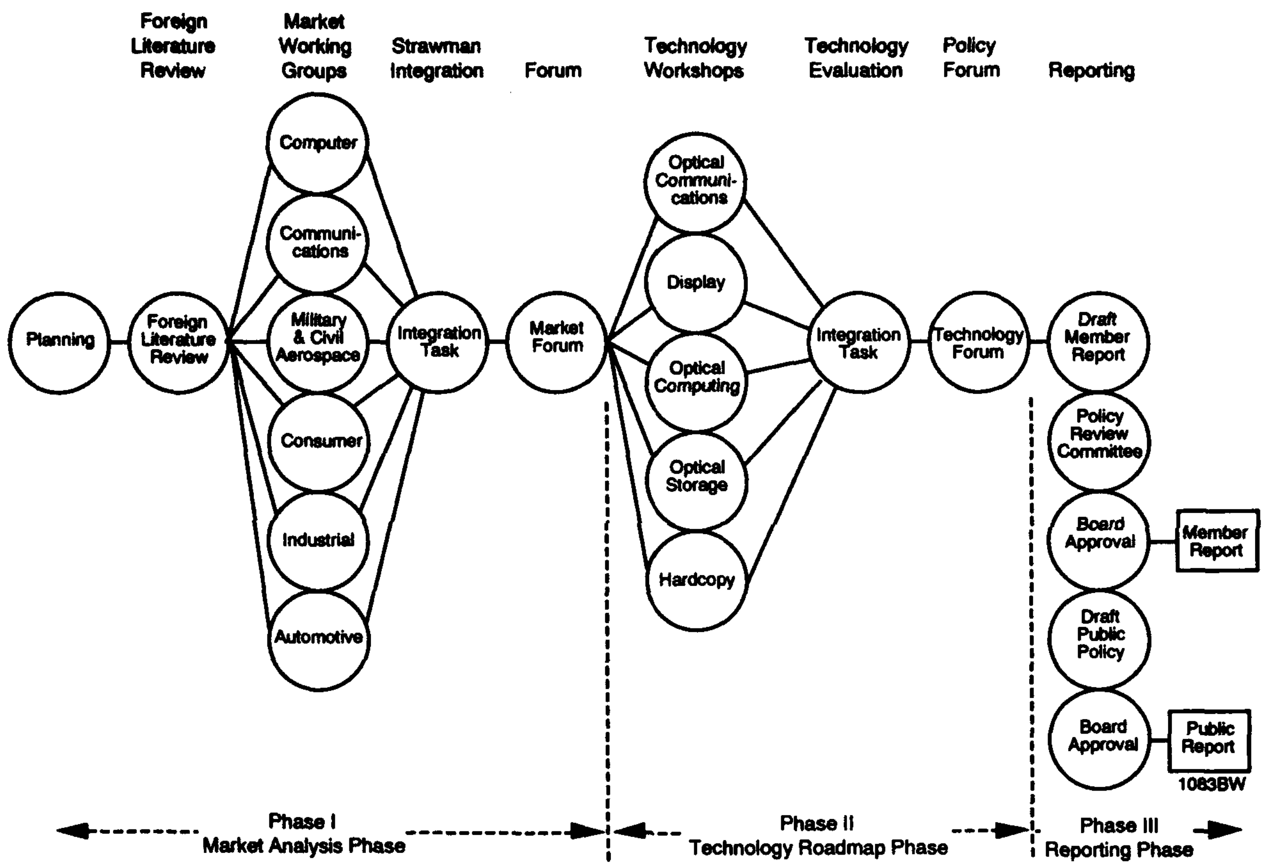


TABLE 1.1
OIDA TECHNOLOGY WORKSHOPS - PHASE II

ATTENDANCE SUMMARY

	Industry	Government	Academic	Total
Display	44	9	5	58
Optical Communications	55	4	5	64
Optical Storage	16	4	11	31
Optics in Switching & Computing	19	8	18	45
Hardcopy	26	1	3	30
Total	160	26	42	228

The five workshops addressed 29 technology areas in discussion groups. These technology areas are listed in Table 1.2.

TABLE 1.2
OIDA TECHNOLOGY ROADMAP WORKSHOPS
BREAK-OUT DISCUSSION GROUPS

Display	Optical Communications	Optical Storage &Computing	Optics in Switching	Hardcopy
A. PMLCD(1)	A. Telecom	A. Media	A. Photonics in Switching	A. Printers — EP(8)
B. AMLCD(2)	B. Datacom	B. Lasers and Optical Heads	B. Intramachine Interconnection	B. Printers — Ink jet
C. EL(3)	C. Package Design & Manufacturing	C. Nonconventional Optical Storage	C. Signal, Neural, Image, and Multidimensional Processing	C. Printers — Thermal
D. PDP(4)	D. Active Semi-con. Device	D. Application-Driven Technology Requirements	D. Optical Memory Access and Data Base Systems	D. Media
E. FED(5)	E. Passive Devices			E. Scanners
F. LED(6)	F. Fiber and Active Fiber Devices			F. Solid Imaging(9)
G. 3D/Holography				
H. Projection				
I. CRT(7)				

(1) Passive Matrix Liquid Crystal Display
(2) Active Matrix Liquid Crystal Display
(3) Electroluminescent Display
(4) Plasma Display Panel
(5) Field Emission Display
(6) Light Emitting Diode
(7) Cathode Ray Tube
(8) Electrophotography
(9) Includes stereolithography, particle fusing, bonding, sheets, filament deposits, and other forms of 3D model building.

The principal objective of the workshops was to prepare detailed technology roadmaps for each technologies that identify the major barriers to success, technology alternatives, and program alternatives that would help to address critical barriers in the future. The tasks for each workshop included the following:

- Review the applications and product drivers for the technology.
- Identify the alternative enabling technologies for the product drivers.
- Identify the barriers which impede both technical and economic viability.
- Assess the sequence and timing of technical developments (a roadmap) needed to bring these technologies to commercial viability.
- Assess the priorities for critical developments.
- Develop a draft roadmap for presentation to the industry.
- Identify priority actions to address the barriers to technical progress.

The workshops addressed issues of both technical and economic feasibility, and considered manufacturing economics as well as technology performance. They also searched for major paradigm shifts in the technologies that could lead to new opportunities.

The workshops provided a technology outlook for the next 20 years to the year 2013. However, the emphasis was on the next five to ten years. This emphasis ensures that technology developments will focus on areas that will contribute to the competitiveness of North American industry within this decade. At the same time, the longer-term perspective helps to identify research programs that can be started now to position North American manufacturers for the following decade.

The roadmaps provide a vision of the future of the industry as of 1993. In some cases, advances are already occuring more quickly than suggested by the roadmaps. OIDA hopes this continues to be the case, especially with regard to the North American Industry.

The technical priorities in the following sections are those identified by the technology roadmap workshop participants and their chairmen. They have not necessarily been endorsed by the OIDA board.

2. DISPLAYS

BACKGROUND

Displays are key enablers for a wide variety of electronic products, including, for example, portable computers, personal digital assistants, and high-definition television. The OIDA report Market Opportunities in Optoelectronics concluded that electronic products enabled by display technology had a worldwide market of over $54 billion in 1993. This market is forecast to grow to $95 billion in 1998 and to $144 billion in 2003.

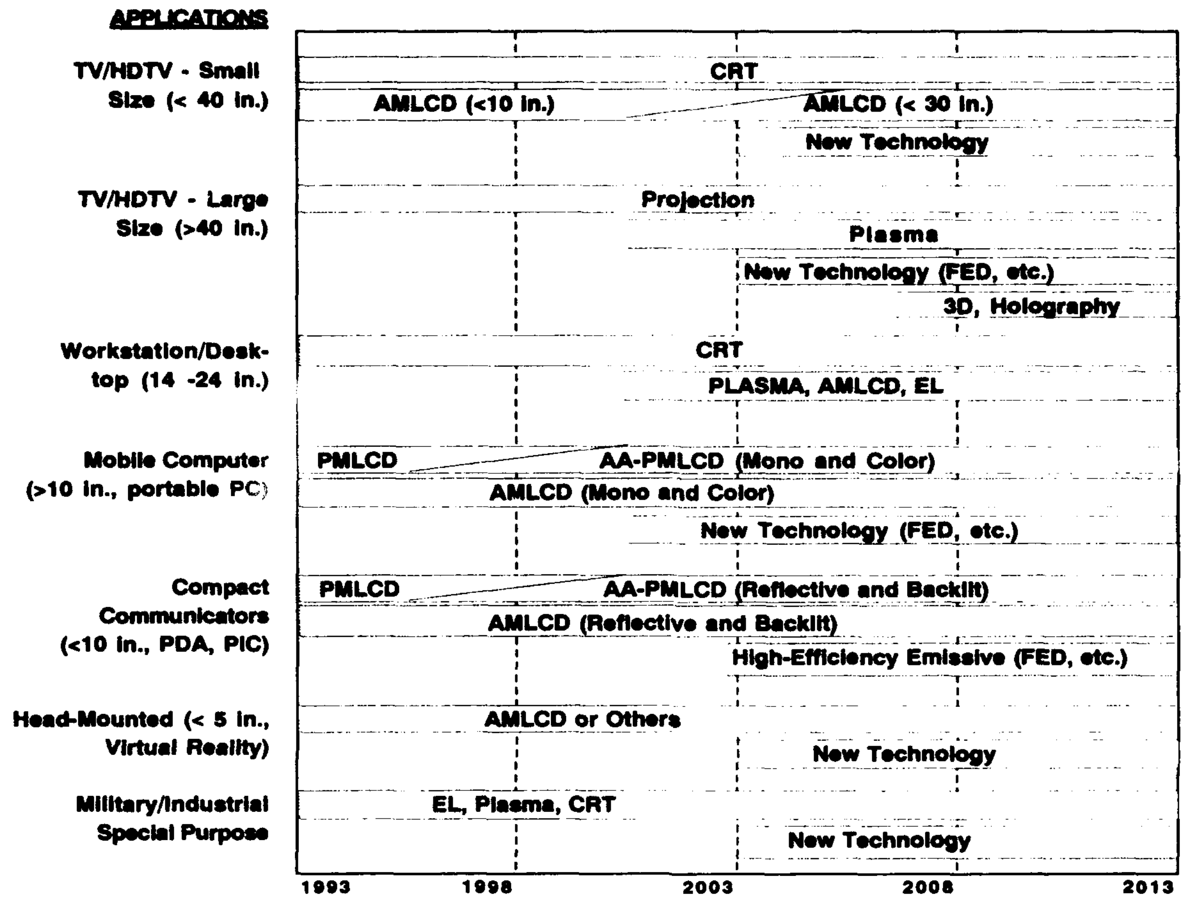
There are many types of displays that serve a wide variety of market applications. The major categories include five flat-panel display types and four other display types, as follows:

Flat Panel	Other
Passive matrix liquid crystal (PMLCD)	Cathode ray tube (CRT)
Active matrix liquid crystal (AMLCD)	Light-emitting diodes (LED)
Electroluminescent (EL)	Three-dimensional and holographic
Plasma panel (PDP)	Projection
Field emission (FED)	

Of these display types, CRTs and LEDs, and to a lesser degree PMLCDs, are mature technologies, although improvements continue to be made. Large North American companies are active in CRTs (Zenith) and LEDs (Hewlett-Packard), although most of their production is offshore. AMLCD, EL, and PDP are produced commercially, but in North America only by small companies in small quantities. FED is still in the developmental stage but has received increasing attention by several North American companies and government agencies. AMLCD has received several billion dollars in investment by major Japanese companies and is expected to dominate Japanese flat-panel activity throughout the rest of the decade. Currently, there is no large-scale flat-panel display manufacturing capacity in North America.

Figure 2.1 shows a product roadmap for display technology that indicates the various applications for display and the types of technologies that will be used in these applications over the next 20 years. CRT has been the workhorse for consumer television and desktop computer displays. This will continue for some time to come because of its attractive cost and performance attributes. In another decade, it is possible that some of the flat-panel technologies could begin to displace the CRT in these applications if their costs become low enough and the processes for producing large sizes are perfected. At very large screen sizes, projection displays are currently the technology of choice, although certain types of flat-panel technologies, such as plasma and FED, offer the potential for large screen sizes in the future.

FIGURE 2.1 DISPLAY PRODUCT ROADMAP



Portable applications, including laptop computers, use only flat-panel displays. Passive matrix LCDs have been the dominant technology in this application, but more recently, active matrix LCDs have made inroads into this application because of their better performance, especially in color displays. Their impact to date has been significant, even with their high prices; if prices fall as expected at a rapid rate, much further market penetration will result. In the near term, actively addressed passive matrix displays may provide performance approaching active matrix, but at lower cost. In the longer term, other technologies such as field emission may challenge LCD displays in the portable market.

Because of the lack of North American companies in major segments of the display business over the past decade, there is little infrastructure for large-volume display manufacturing in North America. Moreover, most of the companies involved in the business are too small to make the required investment for manufacturing scale-up. Although good technology exists in North America, there is no suitable mechanism at present to take this technology from the laboratory, or from small company development efforts, into large-volume manufacturing. The view of many in the display industry is that further government assistance is needed to overcome the barriers of financial and technology risk and to improve the competitive position of North American companies in this vital technology. However, it is clear that commitment from industry is also required, including suppliers, potential users, equipment manufacturers, and component producers (e.g., semiconductors).

Technical Priorities

Nine display technologies have been addressed, and roadmaps have been developed. The status of these technologies, as well as several key issues associated with their future development, are summarized briefly below.

Because nine separate display technologies have been addressed, there are a large number of possible R&D programs, that could serve legitimate needs to advance the various technologies. The roadmap process did not try to set priorities across the different display technologies, but did establish priorities for each technology.

There is much discussion about the best strategy to develop display technology, especially flat-panel technology, that should be developed in North America in light of the strong Japanese position in almost all display technologies. Some companies advocate focusing on technologies, such as field emission, that could potentially "leapfrog" the Japanese lead in active matrix LCD technology. Other companies advocate trying to catch up to the Japanese in active matrix LCD, or pursuing a slightly different course, such as actively addressed passive matrix LCDs. In fact, all of these approaches are being pursued in parallel by various companies, consortia, and government agencies. Thus, the technical priorities outlined below reflect the pursuit of several technology alternatives across a broad front. They focus on one or two critical technology areas for each type of display, although other supporting work will need to be carried out in parallel.

1. **Cathode Ray Tube (CRT):**
   This is a mature technology. It is the lowest cost display and has high resolution, complete color capability, full gray scale, and high contrast. Although this technology is dominated by the foreign competition, there will be a chance for North American companies to participate with the development of a new set of digital HDTV standards. These issues have more to do with electronics and software than the display itself, which is adequate for high-definition images. Future technology improvements will be incremental. Technology needs include: multibeam electron guns for higher resolution; alternative color selection technology; higher efficiency phosphors; and better deflection yokes, including new yoke materials and lightweight glass.

2. **Passive Matrix Liquid Crystal (PMLCD):**
   These have the highest production volume of flat-panel displays and are used widely in laptop computers, especially in monochrome displays. They are limited in terms of contrast, color saturation, response time, and resolution. Cost is still too high for many markets although they are less expensive than active matrix displays. Active addressing schemes will improve performance and this is the highest R&D priority for PMLCDs. Other technology needs include: lower viscosity liquid crystals; thinner cells; plastic substrates for lower cost and larger sizes; lower cost polarizers and color filters; and improved retardation films.

3. **Active Matrix Liquid Crystal (AMLCD):**
   AMLCDs have higher performance but are more expensive than PMLCDs. They currently have a small percentage of the laptop market but are the fastest growing flat panel display technology. They feature excellent color and video capability and provide high resolution but need

significant reductions in cost to continue their market growth. The technical advance with the greatest potential would be a low-temperature polysilicon process for thin-film transistors (TFTs); this would allow integration of the drivers as well as the transistors on the glass substrate and would result in higher resolution and lower cost. Other technical priorities are: a simplified amorphous silicon TFT process with fewer mask steps; and scale-up of the manufacturing process to larger substrate sizes.

4. **Electroluminescent (EL):**
EL displays are currently used mostly in industrial controls, test and measurement equipment, and medical instruments. Although previously limited to monochrome, with its recent move into color, EL technology has the potential to compete in many flat-panel applications. Although it remains too high in cost for most applications, gradual cost reductions are foreseen through the implementation of lower cost, more highly integrated drivers. Both lower costs and better gray scale are necessary to move into broader markets. Technology priorities include: development of a blue phosphor with high luminous efficiency that does not require high-temperature deposition and thus does not require expensive high-temperature substrates; reduced integrated circuit cost; and higher density interconnect technology.

5. **Plasma (PDP):**
These are currently used in military applications, as well as some commercial and a few laptop computer applications. As with EL displays, the market for plasma displays has been limited by high cost and limited color capability. Although color capability was recently introduced, the cost is still high. As with other niche display technologies, the high cost is primarily a function of the low production volumes and should come down as volumes increase. PDP displays need lower cost and improved color and gray scale capability for broader applications. Technology needs include: new materials for barriers and phosphors that would provide an increase in the luminous efficiency by a factor of 10 and would have longer lives; this would increase brightness and/or reduce power requirements for portable applications. Other needs are low-cost integrated circuit drivers; and longer-lived secondary electron emitters.

6. **Field Emission (FED):**
Field emission is a new technology — a flat panel version of the CRT — that has the potential of offering the performance of a CRT in a flat-panel configuration at a low cost. At this point, there are many technical obstacles to be overcome before commercial products can be produced. However, the three most critical areas that programs should be focused on include development of: cathode plates, either microtip or structureless thin film (e.g., thin-film diamond); efficient low-voltage phosphors; and spacers. In addition, vacuum assembly techniques need to be developed for the manufacturing of these devices.

7. **Light-Emitting Diodes (LEDs):**
This is a mature technology that primarily is used in instruments, moving message panels, and outdoor signs. Significantly larger markets for LEDs will open up with the availability of full

color, which requires a low-cost bright blue LED. Significant progress has been made in the SiC material system, which is the basis for the only commercial blue LEDs today (which also happen to be from a North American source). Technology needs include: higher-efficiency blue and green emitters; and the development of alternatives to SiC blue, such as ZnSe and GaN. In late 1993 (since the roadmap workshop), Nichia Chemical Company in Japan announced a high efficiency blue LED made from epitaxial GaN on sapphire. The LED has good performance and lifetime, although at high cost. This development has spurred worldwide interest and could open up larger markets.

8. **Three-Dimensional and Holographic:**
Three-dimensional displays are still in their infancy, and their development to commercial products depends on the merging of many elements from many different technologies — 3-D displays are systems derived from or supported by the other display technologies rather than fundamental technologies. They are currently oriented toward applications in CAD, medical imaging, avionics, remote operation, and ultimately entertainment. Technology needs include: high-resolution, high-speed liquid crystal light valves; high-brightness electroluminescent arrays; precision electronically steerable light sources, spatial light modulators based on LCDs; and solid-state red, green, and blue lasers.

9. **Projection:**
The current applications are mainly in entertainment (large-screen TV) using CRT projection; future applications include desktop professional use and HDTV for the home. The successful development of projection displays depends on the convergence of many technology elements. Commercial (non-CRT) projection displays are available today, but their cost is high, and their energy conversion efficiency is low. Future technology will be based on projection of high-brightness light source(s) through a light valve. To open up broader markets, more efficient liquid crystal light valves need to be developed, as do efficient solid-state red, green, and blue lasers, and high-density, low-cost integrated drivers. These requirements overlap, or are supported by, developments in other technology areas.

Cross Cutting Technical Priorities

In addition to the specific technology efforts discussed above, there are a number of technology developments, especially in the manufacturing area, that support many display types. Work is needed in the following areas:

- Large-area photolithography
- High-resolution printing techniques
- Packaging/integration of displays and drive electronics
- Low-cost drive electronics
- Inspection and repair techniques
- In-process measurement techniques

3. Optical Communications

Background

The applications of optical fiber communications have been steadily expanding. Optical communications technology found its first principal application in long-haul terrestrial telecommunications. Then, as reliability was proven, its use was adopted for undersea applications. As costs have dropped and transmission requirements have increased, its use has spread to shorter distance applications.

Optical communications is now widely employed by telephone companies for local interoffice (between central switching office) applications. Use in the subscriber loop (that is, between the central office and the home or business) is now growing rapidly. Initial loop application has been for the portion originating at the central office, which is known as the feeder. Currently, the use of fiber optics in the loop close to the subscriber, known as the distribution portion or fiber to the "X" (where "X" can be curb, home, etc.), has started to grow rapidly.

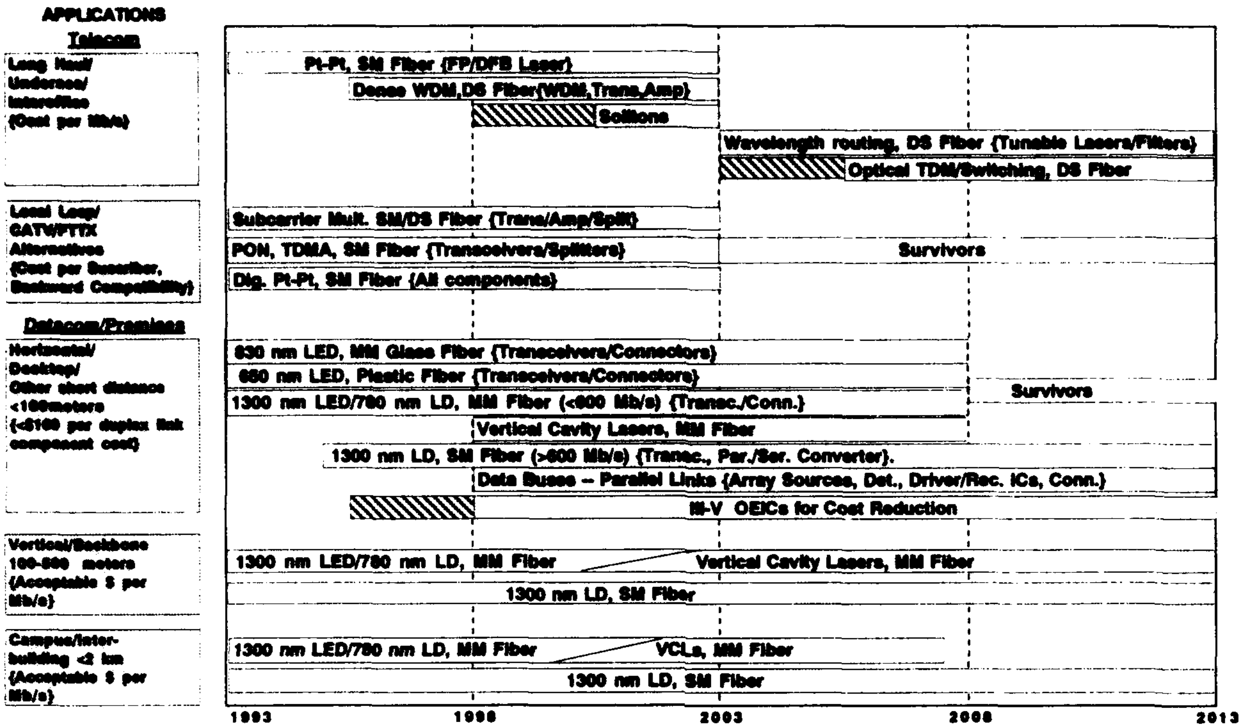
Cable television (CATV) companies have also been using fiber extensively. They use it to carry signals over long distances and to bypass coaxial cable runs which previously would have employed large numbers of repeaters. Final distribution uses coaxial cable. This approach increases service choices and signal quality while minimizing plant costs and ensuring compatibility with existing user apparatus. The hybrid fiber/coax approach has also recently begun to be adopted as a transition to all fiber networks by telephone companies for subscriber loop applications.

To date the penetration of optical communications into the premises data communications environment has been modest. Over the next two decades, it is anticipated that a large market will develop to satisfy the growing demand for high-speed data equipment interconnection and to satisfy the need for improved access to information for applications such as multimedia.

The OIDA report Market Opportunities in Optoelectronics estimates that the 1993 market for fiber optic equipment in the local loop was $2.3 billion. It is forecast to grow to $8.2 billion in 1998 and to $23 billion in 2003. In a similar fashion, the data communications market for fiber optic equipment, which was just $0.8 billion in 1993, is forecast to grow to $2.6 billion in 1998 and to $6.3 billion in 2003.

Figure 3.1 shows a product roadmap for optical communications that indicates the variety of components that will be required over the next 20 years in both telecommunications and data communications applications. Long-haul telecommunications will evolve from single wavelength point-to-point links using regenerative electronic repeaters to high data rate, very long repeaterless spans with wavelength division multiplexing and optical amplifiers. Ultimately, wavelength routing and all optical switching may be implemented. In the local loop, the architecture is not yet fully determined. Approaches involving passive optical networks (PONs) are being explored, along with more conventional point-to-point approaches. Subcarrier multiplexing, which has been successfully used in CATV networks, is being explored for the delivery of video to the home. It is expected that a single

FIGURE 3.1
OPTICAL COMMUNICATIONS PRODUCT ROADMAP



{Critical components/parameters}, MM = multimode glass fiber,
SM = 1300 nm dispersion minimum, single mode glass fiber,
DS = dispersion-shifted, single mode glass fiber.

standard approach will take some time to emerge and that different areas of the world could favor different approaches for the foreseeable future.

Data communications applications, especially the horizontal/desktop area, are also moving through a period of uncertainty. Several technical approaches are competing, and this clouds the near-term outlook. The critical issue is reducing costs in shorter distance (less than 1 km) data networks to compete with copper-based solutions. In the longer term, there will likely be a reduction in the number of approaches to this problem, which will allow economies of scale to be achieved.

North America is the world's largest market for both fiber optic data communications and telecommunications equipment. With regard to manufacturing, North America currently enjoys a competitive position in optical communications. North American companies are strong competitors at all levels of the business, from optical fiber and active and passive components, to communications equipment and subsystems.

The optical communications business will experience tremendous growth over the next decade as fiber is extended from the central office further toward business and residential customers, and as the use of higher-capacity local area networks increases. The business will shift from the current low-unit-volume environment to a high-unit-volume environment in the late 1990s.

The main challenge for North America is to develop cost effective technologies across the spectrum of performance. This should be attacked in two ways:

(1) Focus development on inherently low cost technology by:

•Adapting optoelectronics and optics from the consumer and industrial sectors and using existing low-cost IC packaging techniques.

•Selecting manufacturable components and modify them for adequate performance for the volume applications.

•Employing optics with loose packaging tolerances.

•Developing automated simulation and testing tools to lower the design and test phase of manufacturing. This is cost-driven techhnology development.

(2) Implement a paradigm shift in the manufacture of high performance optoelectronic modules and cables that will allow a scale up of component production from the modest volumes required today to the millions of units per year required within ten years. Fiber optic components today are asembled virtually by hand, at high cost, low throughput, and with consequent high costs for test and inspection. To meet the requirements of the future, these components will have to be assembled, packaged, aligned, and tested in a highly automated environment, at costs an order of magnitude lower than today's costs.

Optics in switching and computing is certainly the most speculative of the areas in this phase of the technology roadmap process. At this time, there is little current commercial use of optics in switching and computing. Many of the systems concepts, the technologies, and the devices are still in the basic research phase. There is, however, a strong possibility that these may generate a new paradigm in optoelectronic systems, using large amounts of optoelectronics and electronics together to make information processing systems of significantly improved capabilities. There is now a good opportunity to establish a lead in the necessary technologies and the skill base for this potential paradigm shift.

TECHNICAL PRIORITIES

Evolving technology requirements have been considered for the following types of systems:

- Telecommunications
  - -Long haul/interoffice
  - -Fiber in the loop
- Data Communications
  - -Horizontal/Vertical
  - -Vertical Backbone
  - -Campus/Inter-building

These requirements have been translated to the components level and are reflected in technology issues regarding:

- Package design and manufacturing
- Semiconductor devices
- Passive components
- Active fiber components and fiber

Even though packaging was considered as a separate issue, it is clear that it plays a key role in all of the other areas addressed, especially in regard to cost.

In high performance data communications the main issue is cost. The achievable performance of components for low bit rates is more than adequate for the foreseeable future. However, the cost of transmitters and receivers, as well as the associated cost of connectors and fiber installation, is inhibiting the growth of the market. Therefore, the main thrust of efforts in technology must be toward cost reduction. For low-to-moderate data rates, a new paradigm is needed in which the approach to device design and packaging is cost-driven, with performance just adequate to meet the needs of the application. Table 3.1 summarizes the issues/barriers that will lead to low cost.

Table 3.1

Issues/Barriers

- Proliferation of Standards
- Overconstrained requirements
  - Reliability
  - Performance Attributes
- Designing out thermoelectric cooler
- Modeling/simulation tools for robust packages, especially at high frequency
- Cost of custom ICs versus ability to use ICs to simplify package design
- New test methodologies for cost reduction, early failure identification, functionality
- Need to better couple device design to package design to allow trade-offs for tolerances, coupling, cost reduction, etc.
- Precision assembly and alignment approaches; precision piece parts
- compatibility of tests for discrete components versus new subassemblies
- Improvement in device uniformity by establishing robust device fabrication processes, especially since high volumes are not present to drive learning curve improvments
- Molding/plastic packaging
- Hermeticity, welding
- Thermal managment
- Simpler Packages
- Concurrent engineering.

ICs: Integrated Circuits

Although there are several categories of technical priorities for optical communications. they all have the goal of reducing component costs in order to accelerate the deployment of fiber optics in the local loop and in local area networks for data communications. The focus needs to be primarily on low cost telecommunications and high performance data communications applications. The priorities for each category are discussed below.

1. Transmitters and Receivers

The high cost of fiber optic transmitters and receivers is a major impediment to market growth. In order to reduce costs significantly, several steps must be taken.

First, packaging and optical alignment in transmitters and receivers represent major cost barriers. More effort is needed to develop new packaging approaches that use lower cost materials (such as plastic), that reduce the number of piece parts, and that lend themselves to volume manufacturing. Of particular importance is the development of automated approaches for passive fiber alignment. A set of optoelectronic packaging platforms that would accommodate both optical and high speed electronics requirements will promote desired standards. For low- to medium-speed data communications components, a new approach must be developed, perhaps based on high-volume consumer electronics and packaging technology, that emphasizes low-cost volume production first and performance second.

Furthermore, because of the proliferation of approaches to both fiber in the local loop and high speed data communications, an industry consensus regarding the approaches to these applications and the resulting specifications for transmitters and receivers would be highly desirable. Development of common chip sets for specific applications approach will allow higher volume production of these components and thus lower production cost.

Finally, for semiconductor lasers, LEDs and detectors, there needs to be an emphasis on the development of high-yield processes, including wafer-scale manufacturing, the development of device structures compatible to wafer-scale probing, the incorporation of in-situ measurement and process control to epitaxial growth and wafer processing equipment, and the development of on-wafer testing methods.

Receiver chips with integrated photodiodes are just beginning to emerge from development and demonstrate yield and low cost potential (through simplified testing and part count reduction). The enhanced and automated design and testing infrastructure for these OEICs needs concurrent development with the chips.

An attractive alternative for data processing interconnects is a parallel fiber link first in microcomputer clusters and later within large computer and switching equipment frames. Industry consortia are developing this technology today through the ARPA-sponsored Optoelectronic Technology Consortium (OETC) project (a 32 channel bus for up to 100 meters and a cost target of $100 per line) and the NIST sponsored JITNEY project (a 24 channel bus for up to 30 meters and a cost target of $10 per linc).

In telecommunications, cost is also an important issue, especially in fiber in the loop applications. Although there are a number of major fiber in the loop projects underway around the world, and others have been announced, the cost of components is still considered to be a major problem, especially as fiber moves closer to the customer premises. In the long haul/interoffice network, cost is much less an issue, but performance issues are much more important. For the next generation of long haul systems, technologies such as wavelength division multiplexing and fiber amplifiers will be required to eliminate repeaters and increase capacity, with the cost of components a secondary consideration. Table 3.2 highlights major impediments to the progress of the deployment of fiber in the loop.

Table 3.2
Critical Barriers for Telecommunications

1. Standardization
2. Low-Cost, high-precision component assembly and design
3. Fiber termination/managment/installation
4. Reliability- lasers, EDFAs
5. Tunable filters
6. Gain Equalization
7. High return loss terminations
8. Frequency standards for WDM

EDFM:Erdium Doped Fiber Amplifiers WDM:Wavelength Division Multiplexing

2. Connectors

Both the initial cost of connectors and the labor required to install them are major concerns, especially in local area networks. Lower cost connector approaches, including polymer and polymer-ceramic composites, need to be developed, with a goal of $4 installed cost per mated connector pair for single mode and $3 for multimode fiber. Lowering the installed cost also requires the development of low-cost field termination techniques or a combination of factory termination and simplified field assembly techniques. Low cost (< $1 per line) ribbon fiber connectors are also necessary for parallel data links.

3. Fiber/Cable Management

Applications such as fiber in the loop and local area data networks require the handling and termination of large numbers of individual fibers. This results in high labor-related installation costs. There is a need for improvement in the design of fiber cable, in fiber and cable management apparatus, and in the materials and special tools used in fiber handling and termination that will result in significantly lower installation costs.

Table 3.3

Higher Capacity Links (>100 Mb/s-km)

	Time Frame
<u>Targeted Applications</u>	
FITL	1993
WAN	1993
Optical routing	2003
High-speed optical routing	2013
<u>Key Technical Attributes/Specifications</u>	
High-speed TDM	1993-2003
High-speed SCM	1998-2003
High-speed WDM	2003
<u>Cost Targets</u>	
$100 per link (FITL)	1993
$10 per link (FITL)	2003
$1,000 per link (WAN)	1993
$100 per link (WAN)	2003
<u>Enabling Technology/Technical Obstacles</u>	
Device design	1993
WDM - wavelength select/route	1998
WDM - wavelength tune/translate	1998
TDM - high-speed lasers, mode lock	1998
SCM - linear lasers and high dynamic range detectors	1998
PIC, arrays	2003
Photoic switching	2013
<u>Manufacturing Issues</u>	
III-V OE materials/processing control	All
In-situ materials monitoring	1993
on-wafer testing	1998
Low-cost wavelength standard/control	2003
<u>Applicable Standards</u>	
ATM;SONET - OC 192	1998
WDM standards	1998
Operation at 40 Gb/s	2003

FITL: Fiber in the loop
WAN: Wide area network
TOM: Time division multiplexing
SCM: Subcarrier multiplexing
WDM: Wavelength division multiplexing
PIC: Photonic integrated circuit
ATM: Asynchronous transfer mode
SONET: Synchronous Optical Network
OE: Optoelectronics

4. Couplers, Splitters and Wavelength Division Multiplexers (WDMs)

Splitters and couplers will be key components in fiber in the loop applications, particularly in passive optical networks (PONs). As in the case of transmitters and receivers, packaging and alignment are major cost elements that need to be reduced. In the case of planar couplers and splitters, fiber pigtailing is commonly done and adds significantly to the cost. An automated passive alignment approach needs to be developed in the near term, and in the longer term pigtailing should be eliminated altogether. Similar considerations apply to WDMs.

5. Other Components

In addition to these major near-to-medium term priorities, work needs to be carried out to develop a broad range of components for future system architectures with reasonable cost and the required performance attributes. These components include:

- Array transmitters and receivers of prescribed wavelengths
- Ribbon fiber connectors
- Dense WDMs requiring tunable lasers and filters
- Integrable modulators
- Higher performance laser diodes for both digital and analog modulations
- Wavelength agile components for translation and add/drop
- Integrable isolators and polarizers

Although these components are mainly performance driven, lowering the costs is necessary to open up new markets.

6. Optics in Switching and Computing

Given the fact that there is little current use of optics in switching and computing, it is important to understand why it should be considered important and worth devoting resources to. There is considerable understanding now of some basic reasons why optics should be helpful in switching and computing. Many of these are related to the interconnection of information within the processor. For example, optics has little or no problem with frequency-dependent loss or cross-talk in signal lines. Optical connection automatically solves problems of electrical isolation and has high immunity to electromagnetic interference. Optical media are intrinsically very high bandwidth and are also transparent to very high bandwidths when switching them with some classes of switches. Optics can communicate over substantial distances without loss or degradation of the signal, especially when using optical fibers.

There are also more radical possibilities with optics if free-space connections are used. Such connections can be made with relatively simple lenses and could use thousands of light beams in two-dimensional arrays. There would be several advantages to such systems if they could be implemented, including the ability to eliminate signal skew and clock skew with large numbers of connections, and also the possibility of global interconnect topologies where all of the connection lines cross one another. It is also worth noting that, given a good enough integration technology, optics can communicate with fundamentally lower energy than electrical connections. This is because optics counts photons rather than measures voltage.

In principle, therefore, optics can address most of the physical problems with electrical interconnections, and such problems are a significant limitation on electrical machines today. This is especially true for machines with many high-speed interconnections, such as on backplanes or in switching computers or image processing machines.

Optics has additional possibilities through some of its intrinsic analog functions such as Fourier transforms with lenses. There are also other possibilities, such as photorefractive nonlinear processors, optical volume storage of information, and ultimately ultrafast logic gates. In general, optics has strengths in those areas where silicon used on its own has weaknesses in addressing difficult systems problems. Hence, there are strong reasons to consider the future use of optics. A goal of this roadmap activity is to help to identify some of the roadblocks that currently prevent optics from being used to make more cost-effective and higher-performance information processing and switching machines.

It is very important that there is systems and applications research rather than merely research on devices themselves. Without the systems and applications research, there will not be the best utilization of the device research because the device research will not be best focused. Secondly, systems and applications research will help to identify the potential future areas of commercial application of these technologies that will, in turn, help to provide the investment for the technologies. Systems and applications research at the present time is probably more important to stimulate than the device technologies themselves.

The second main need is to identify and implement mechanisms that make it easier for systems and applications researchers to have available to them the advanced optoelectronic technologies. Such a mechanism would help to break the "chicken and egg" problem of systems and technologies. Some experimental cooperative activities are being explored now, such as the ARPA CO-OP, that attempt to make experimental technologies available through foundry arrangements to systems researchers. This and other schemes should be explored further. Success with such schemes could greatly increase the efficiency of systems and applications research.

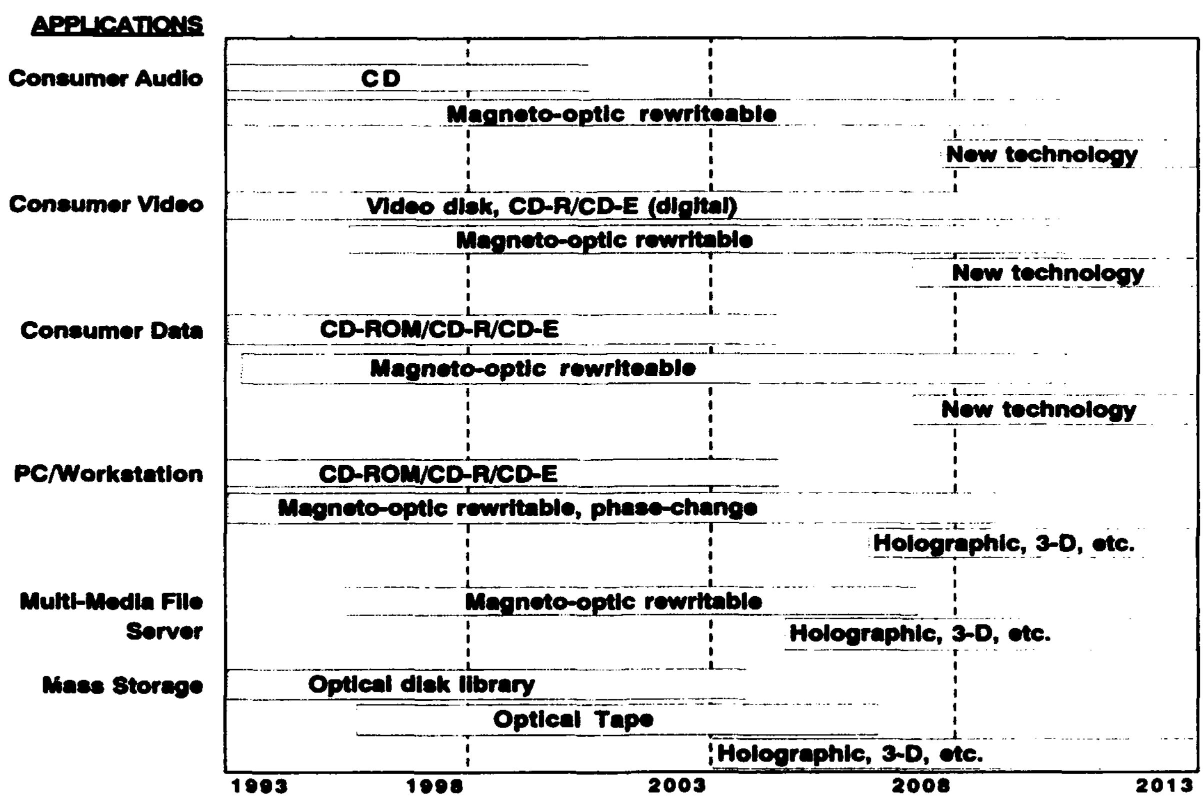
4. Optical Storage

Background

Optical data storage encompasses a wide range of products and applications, ranging from the familiar consumer CD and video disk players, to rewritable magneto-optic drives used in workstations, to optical disk libraries that store terabytes of data. According to the previous OIDA report, Market Opportunities in Optoelectronics, the worldwide market for all optical data storage devices was $8.6 billion in 1993. It is projected to grow to $18 billion in 1998, and to $31 billion in 2003. Thus, optical data storage is a significant business, with the potential to grow to reach magnitudes comparable to today's magnetic storage business in around ten years.

Figure 4.1 shows a product roadmap for optical storage that indicates the likely evolution of technology to meet the future requirements of various applications. In consumer applications, audio compact disk (CD), CD-ROM, and video disk have been the mainstream optical storage technologies for the past decade. In the consumer audio market, Sony has introduced the MiniDisc, a small format rewritable magneto-optic technology. While it has been initially slow to catch on, partly because of its high price, it is expected to eventually replace the CD as the principal method of delivering consumer audio entertainment. Similarly, the video disk will be superseded by magneto-optic recording technology that will provide the data density necessary to record digital HDTV signals, as well as additional attributes such as random access.

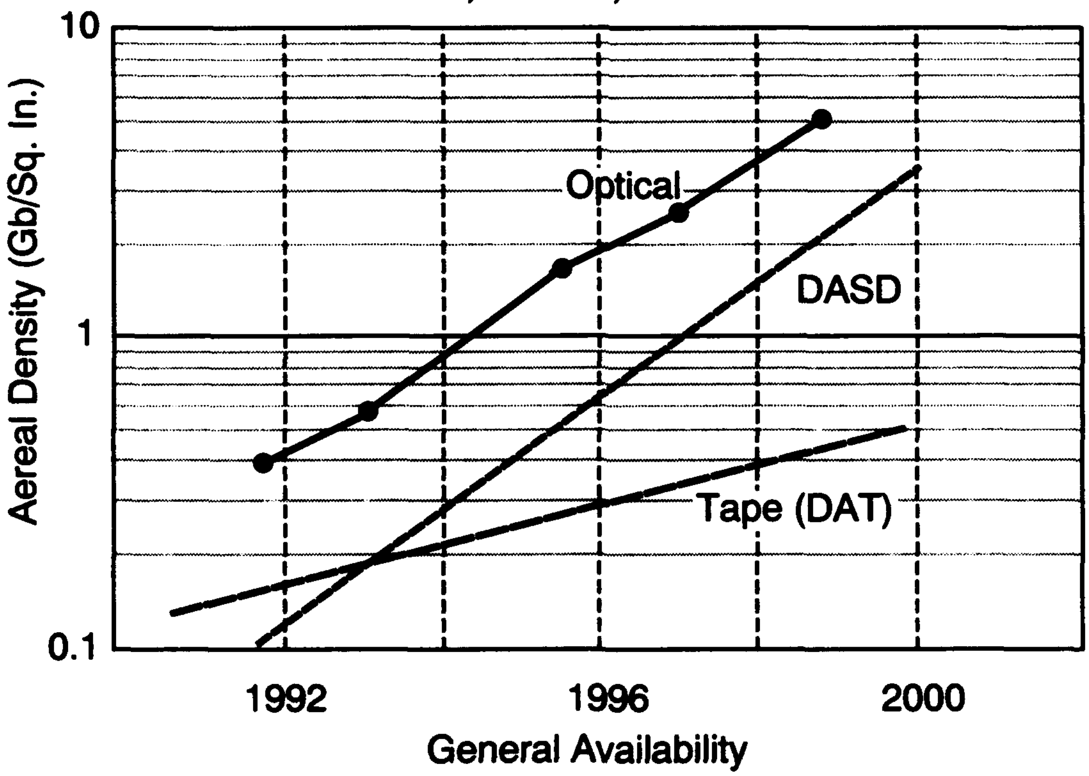
FIGURE 4.1 OPTICAL STORAGE PRODUCT ROADMAP



There has recently been an explosion of activity in consumer CD-ROM because of the burgeoning interest in multimedia, as well as the introduction of new formats such as CD-I, Photo-CD, and CD-ROM-based video games. Early in 1994, Sony introduced the Data Discman, a data storage version of its MiniDisc audio product. This is the likely beginning of a gradual shift to magneto-optic technology for consumer applications, as drive costs come down and consumer data storage needs continue to expand. However, CD-ROM products, including recordable versions based on phase-change technology, are expected to coexist in the market for many years to come.

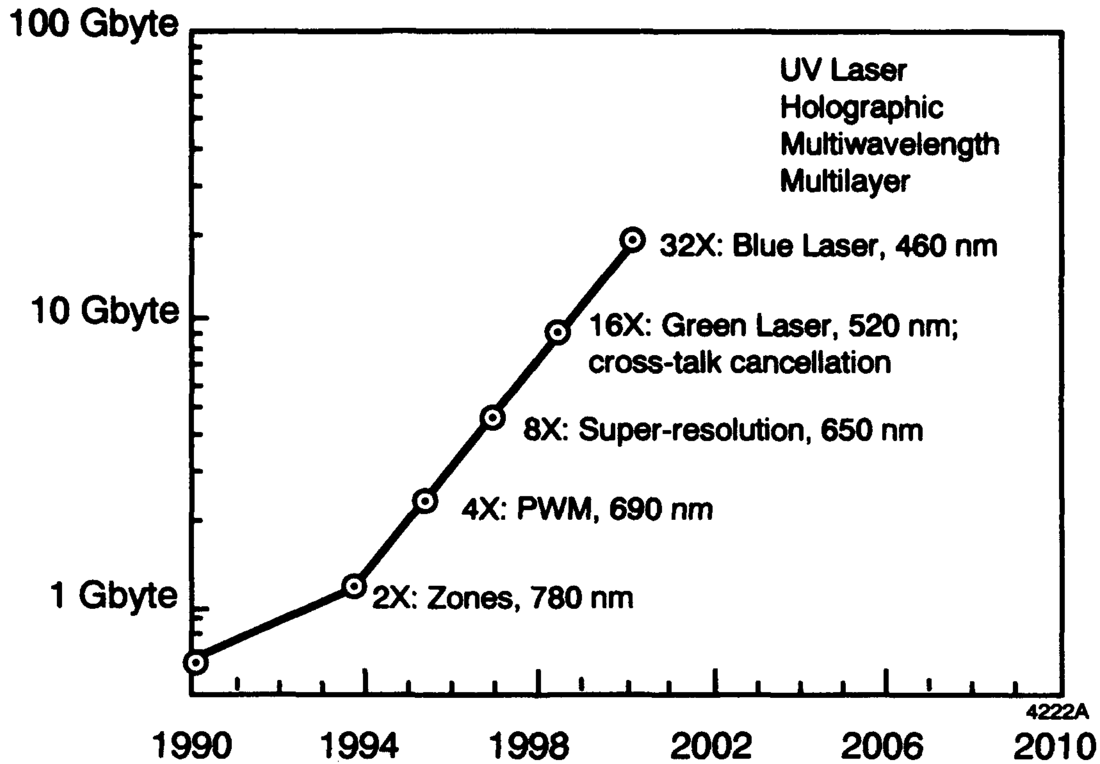
In the workplace, CD-ROM has had significant penetration as a data/application distribution medium, but the mainstream business application of optical technology has been magneto-optic. It is expected to grow in importance as drive costs come down and areal data densities increase. Figures 4.2 and 4.3 show projections of areal density improvements over time for optical, magnetic hard disk (DASD), and tape technologies. Over the past several decades, magnetic hard disks have shown a steady 35-40 annual growth rate. In the past few years, however, progress has accelerated to a 60-65 ercent growth rate. The message is clear: optical technology needs to accelerate its progress if it is) maintain its historic areal density advantage. This, however, is also a technological opportunity for North American companies to regain competitiveness.

FIGURE 4.2
COMPARISON OF RECORDING TECHNOLOGIES
DASD, OPTICAL, AND TAPE



DAT: Digital Audio Tape DASD: Direct Access Storage Device

FIGURE 4.3
OPTICAL RECORDING CAPACITY PROJECTION FOR 5 $^1/_4$-INCH MEDIA



PWM: Pulse Width Modulation

The use of magneto-optic storage will be driven especially by applications such as multimedia file servers which will require very large data storage capacities (terabytes) as well as random access and high data transfer rates. Optical disk libraries are currently being used in mass storage applications such as insurance records and government archives, where they are cost-effective and which require only moderate access times (seconds). Optical tape libraries are a possible future option.

After the turn of the century, it is expected that advanced optical technologies, such as holographic or three-dimensional storage, will supersede the technologies discussed above. They will provide not only higher storage densities and lower costs than this decade's technologies, but advanced features such as parallel input and output. Development of these technologies will be driven initially by mass storage and other computer- and network-related storage requirements, but eventually they are expected to evolve into the consumer sector as well.

To date, the Japanese have dominated the optical storage industry, in both consumer and computer-related applications, with the Europeans (mainly Phillips) in second place. There is some commercial magneto-optic activity in North America, but it is struggling in the face of strong Japanese competition. In the consumer area, Kodak has introduced an innovative new product, the Photo CD, but its success in the marketplace has yet to be determined.

The challenge for the North American optoelectronics industry is to create a technological edge that will allow the development of superior optical storage devices, and then to translate that technological leadership into products that can be produced in large volumes at competitive cost. In this effort, the challenge comes not only from foreign competitors in optical storage, but also from magnetic storage technology, which dominates the data storage market, and which continues to increase performance and reduce costs at a rapid rate.

Several aspects of optical storage technology have been addressed, including:

- Media
- Lasers and optical heads
- Nonconventional optical storage

The focus of the discussions on media and on lasers and optical heads was on conventional magneto-optic storage, which is the principal rewritable optical storage technology now and for the near-to-medium term future. Nonconventional optical storage refers to advanced concepts such as 3–D storage, which may become prevalent after the year 2000.

Technical Priorities

The priorities for optical storage technology are grouped into four categories that have as an underlying theme the need for industry and academia to work more closely in accelerating the pace at which new optical technology is brought to the marketplace. No single industrial participant has the ability, by itself, to bring all of the components needed for advanced optical storage systems to commercialization. Moreover, many technological breakthroughs take place at companies or universities which may not have optical storage as a main focus of their activities. Therefore, there is a clear need for centralized, dedicated facilities that provide a place to develop breakthroughs, with the infrastructure needed to provide pre-production engineering samples and advanced measurement and testing capabilities.

1. Short Wavelength Sources

A top priority is to establish a centralized facility for the fabrication and evaluation of short wavelength laser devices. Today, infrared and red injection laser diodes are dominated by overseas manufacturers. The next major advance in laser technology will be the development of practical green and blue devices with wavelengths in the 400-520 nm range. Upconversion devices based on frequency doubling approaches are likely to be the first shorter wavelength recording sources to be commercialized. The ATP-funded program on Short Wavelength Advanced Technology (SWAT) is a key step in the right direction to provide leadership for North American industry. This consortium of industrial and academic participants is addressing the basic technical issues for fabricating an integrated multibeam blue light source.

It is essential that a program be put in place that capitalizes on the output from SWAT and other related programs. A central facility, perhaps at a national laboratory, could examine the issues in making advanced engineering samples. Such early devices are essential to begin the design of recording systems and to provide information on the manufacturability and reliability of these new lasers so that commercialization decisions can be made by industry.

Semiconductor lasers based on new material systems (e.g. CdZnSe on GaAs, SiC on SiC, GaN on sapphire) that emit directly in the blue and green should also be addressed. These potential short wavelength laser sources offer a practical path to a generic low cost device for both consumer and commercial optical storage applications. Recent technological advances in the U.S. are encouraging, and an enhanced program of industrial and academic participants built around a centralized laser facility could greatly accelerate the commercialization of this core technology for North American industry.

2. Optical Disk Media

In a similar manner to that for lasers, optical disk media needs an infrastructure for facilitating the development and evaluation of advanced engineering samples. For optical media, the recommendation is to establish a test center where high capacity media can be tested, evaluated and measured under realistic conditions. A newly funded ARPA program, operated through the National Storage Industry Consortium (NSIC), has this concept at the heart of its blue media research effort. This program needs to be broadened and enhanced to encompass other methods of achieving higher capacity (e.g. super-resolution, multilayers), and to seek major advances in substrate technology. It is essential that the optical media center be established where continuity of dedicated personnel and resources can be insured if such an activity is to have real impact.

3. Applications

The value of optical storage in the marketplace is intimately tied to the applications that it serves. Optical storage must exploit its unique attributes to provide a lower cost and more efficient solution to people's storage needs. To this end, interdisciplinary programs are recommended that couple hardware and software technology with the major emerging applications. Areas such as multimedia, with its prominent use of video, are placing major demands on the storage delivery systems. Bringing in the application considerations early will help drive the right choice of technology for development.

4. 3-D Optical Memories

The last focus area concerns the exploitation of 3-D optical memories. The technology roadmap in Table 4.2 indicated a major paradigm shift sometime in the next decade from two-dimensional storage to techniques that more fully exploit the ability of light to add an additional dimensional component. These 3-D optical storage approaches offer not only dramatic new improvements in capacity and performance, but also, as in the case of holographic techniques, highly parallel input/output and unique associated retrieval properties. Today there are a multitude of approaches with the common challenge of developing recording materials with all the necessary properties to build a practical storage device. Continued industry/university programs in this area are needed, coupled with more prototype recording system evaluation. The recent ARPA program on holographic storage is a major step in improving North American competitiveness in this future optical storage technology. In addition, optoelectronics programs in general need to encourage synergy between areas such as storage, display and communications, where common components or techniques can accelerate commercialization.

5. HARDCOPY

BACKGROUND

The use of electronic printers in the office, the home, and in commercial applications is a substantial business opportunity (estimated at $10 billion in North America alone in 1993) that will continue to grow in spite of the continuing evolution of "information age" technologies that appear to be displacing the need for information in hardcopy form. In fact, the use of paper for printed materials will continue to grow, at least through the end of the decade, although at a somewhat reduced rate from the preceding 20 years. Even though more and more information will be generated and stored in electronic form, there will still be a need to produce hardcopy and thus a need for the printers that generate text or images from digital data.

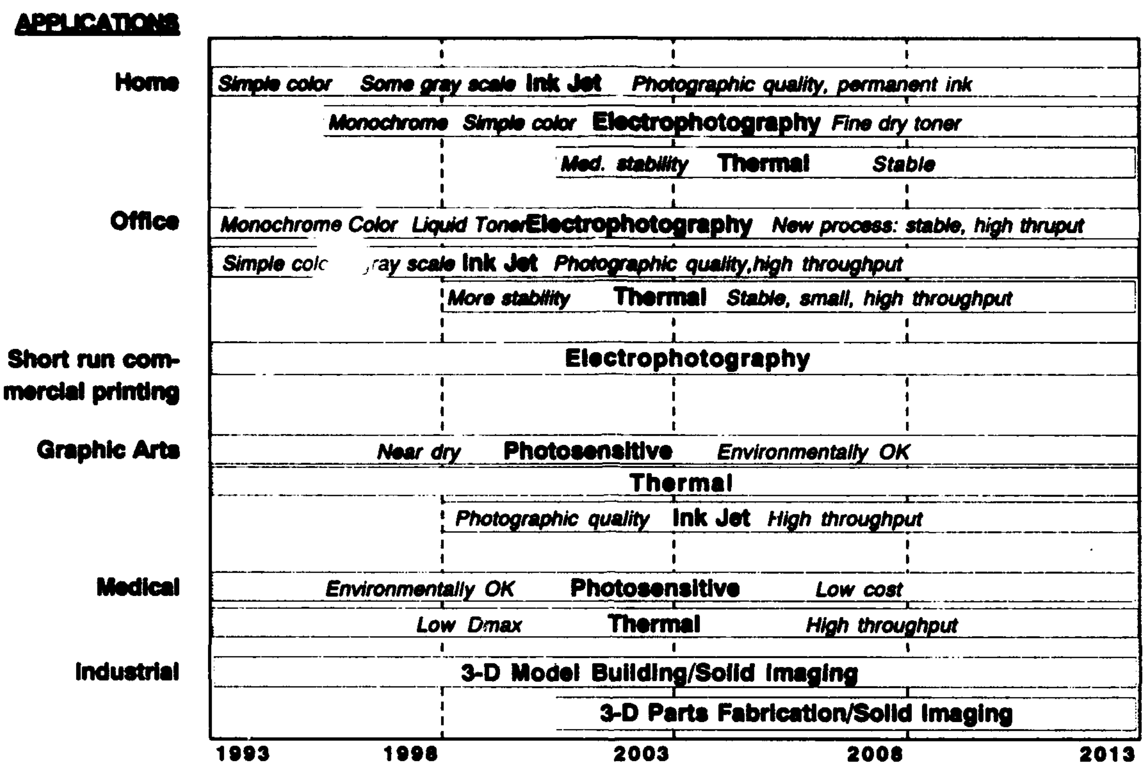
Optoelectronics is an enabling technology for much of the electronic printing business. The primary example is the laser printer, which is one application of electrophotography. Laser printers constitute the vast majority of nonimpact printers shipped worldwide. The use of laser printing is also growing rapidly in plain-paper fax machines and is a key element in digital copiers.

Other printing technologies, such as thermal and photosensitive printing, have not previously used optoelectronic approaches, but new applications are driving them in that direction. For example, new medical imaging systems utilize laser diodes to write directly onto thermal media or photosensitive film to produce high-resolution, continuous-tone images from digital data generated from CAT or MRI scans. As the costs of the lasers and other components come down, such printers may find their way into commercial graphic arts or even office applications.

One technology considered in this chapter is not optoelectronic in nature- the ink jet printer. It has been included because it is the most rapidly growing electronic printing technology, because it has a strong North American manufacturing presence, and because it will provide strong competition for laser printers as the print quality and print speed improve. Currently, ink jet printers are primarily displacing dot-matrix printers, which are in decline after peaking in sales in 1992.

Figure 5.1 is a product roadmap for hardcopy technology showing the evolution of various printing technologies and their applications over the next 20 years. Home applications (printing images from video tapes, photo-CDs, etc.) are the most cost-sensitive and are thus most likely to be penetrated first by ink jet printers, which are the lowest cost of the printer types considered. In later years, as the costs come down, thermal printers and laser printers will find their way into the home as well.

FIGURE 6.1 HARDCOPY PRODUCT ROADMAP



Office printing applications are currently dominated by electrophotographic printers because of their high speeds, multiple font capability, high print quality, and moderate costs. They certainly will remain in the office for many years to come. However, ink jets are beginning to make inroads, especially for applications in which color is required. Color laser printers remain prohibitively expensive, while color ink jets are available in the $500-$1,000 range. In the longer term, ink jet printers will increase their penetration in the office and may become the technology of choice for personal desktop printers.

In the commercial printing area, electronic printers are not fast enough to handle most commercial printing jobs. However, new applications, especially in short-run printing, are providing opportunities for laser printers, and these are likely to grow in importance in the future. In the graphic arts area, only thermal and photosensitive printers have the image quality necessary for the demanding requirements of this application. Color ink jet printers will be used for proofing only. The use of thermal and photosensitive printers in medical imaging applications was discussed above. This application is just beginning but should become a major part of the medical imaging business over the next five to ten years.

An emerging application in the industrial sector is printing in three dimensions, also known as 3-D model building or solid imaging. This is a method for generating three-dimensional objects directly from computer designs. The most common technique uses an ultraviolet laser to expose layers of photopolymer to build up the model one layer at a time. Although this method is used primarily for creating models and prototypes at present, eventually it will be extended to the production of actual parts using engineering plastics or even metals.

A final aspect of hardcopy is the scanning of printed text or images to convert them to digital data. A scanner is basically an optoelectronic device that uses a light source and photodetectors to generate electronic signals from the reflected image on the page. Scanners are expected to continue to improve their capabilities in terms of resolution and speed, but major improvements are still required in the reproducibility of color.

The overall position of North American industry in the hardcopy business is mixed. In laser printers, there is a very large industry presence by North American companies, but Japanese companies control the basic technology and supply of the print engines to most of them. To recapture a technology position in this industry may require a completely new paradigm in electrophotography, such as the development of a simple one-step color process.

In ink jet printers, North American companies have a very strong position, as they do in thermal and photosensitive printers, although conventional thermal head technology is controlled by the Japanese. In scanners, much of the technology, especially sensor arrays, is also Japanese, but North America has a strong capability in the software aspects of this field. Solid imaging has made a strong beginning in North America, but the challenge is to ensure that the technology remains North American-based and that the supply of critical components such as lasers does not become dependent on offshore suppliers.

Technical Priorities

In the future, hardcopy systems will of necessity be digital, dry, and environmentally benign, with color capability becoming standard. At present it is impossible to say with any certainty which technology will enjoy a leading position for which applications, although it is safe to say that if present trends continue, ink jet, electrophotography, and various embodiments of thermal transfer will play a dominant role in the future. The trends are clearly toward more portability, faster throughput, color capability, lower power requirement, and zero adverse environmental impact.

The priorities here are not restricted to optoelectronics, even though this is OIDA's primary area of interest, because the areas covered by the workshop were much broader. These priorities focus only on strategically important areas where there is still an opportunity to significantly impact the technology.

Solid imaging is the most important technology based on its potential to make a significant impact (it is coincidental that it happens to be optoelectronics related). The need for high-power, low-cost UV lasers and special materials for solid imaging are the top two priorities on its list of needs. Still in its infancy, this technology area offers opportunities to North American companies that bridge industries. It is as applicable to auto production as it is to computers or consumer electronics. The ability to do rapid prototyping can make any North American industry more competitive. The longer-term vision would be to use the same techniques to do pilot production and possibly even high-volume manufacturing.

1. Solid Imaging

In support of solid imaging, an R&D project is needed to produce low-cost ultraviolet imaging systems (particularly high-power UV lasers and precision x-y scanning systems). In addition, basic materials work in support of this technology should include research on photopolymers, powder technology to produce full-density plastic parts, and inert high-temperature materials to be used in systems which directly deposit molten metals to form metal objects. Such work could be appropriately be performed: (1) at a National Laboratory; (2) via sponsored research at universities; or (3) under sponsorship of a consortium composed of university, National Labs, and industry representatives.

2. Ink Jet

Ink jet printing is next-highest priority for R&D investment involving industry, government, and academia. Two priority areas are: (1) materials and process technology for piezo and bubble-driven large ink jet arrays; and (2) new ink jet colorants for liquid and hot-melt systems.

North American manufacturers currently have a large share of the multibillion-dollar ink jet market, but the competition from Japan is intense. In order to continue ink jet's rapid growth, some fundamental problems in the processing of large array printheads must be solved, and new colorants for inks must be developed. Lightfast colorants are particularly critical given the increasing use of color images, where it is necessary to maintain the quality of a print once color matching or enhancement has been done. Other important parameters that could be improved through R&D investments in ink chemistry are water fastness and color gamut. Large investments in pigment as well as dye technology development and manufacturing will be required to remain competitive with Japanese manufacturers.

3. Generic Technologies

Listed below are a number of generic hardcopy needs that impact the ability of North American manufacturers to compete in the global market. These areas could also benefit from funded research at universities or National Laboratories. They are:

- Research to determine a single, optimal color standard for all printer markets
- Software to enhance ease of use of color; i.e., automatic color rendering
- Low-cost, high-capacity storage needed to handle large image files
- Materials and fabrication processes for each of the technologies compatible with the environment
- Development of a paper which provides outstanding print quality for all printing technologies

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David Robinson	Jerrold
Paul Holmes	Motorola
Ron Nelson	Motorola
Dennis Bone	New Jersey Bell
Gordon Day	NIST
Lynn Hutcheson	Raynet
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited

Industrial Market
Working Group, San Jose, CA
March 23, 1992

Ed Harder	3M
Donald Lake	EG&G Reticon
Jan Stein	EPRI
Mark Chandler	Hewlett-Packard
Hal Edmondson	Hewlett-Packard
Roland Haitz	Hewlett-Packard
Robert Bogart	Laserscope
Tim Gray	Lightwave Electronics
Gordon Day	NIST
Richard Elkus	Prometrix
Richard Craig	SDL
David Mentley	Stanford Resources
Robert Burmeister	Stanford University
James Harris	Stanford University
Lenny Lipton	StereoGraphics
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Joe Morrissy	Three-Five Systems
Tom Brandt	U.S.C.
Steven Den Baars	U.S.C.

Military and Civil Aerospace
Market Working Group, Los Angeles, CA
April 14-15, 1992

Andy Yang	ARPA
Steve Emo	Allied-Bendix
Russ Maddingly	AMP
Anis Husain	ARPA
Marc Beacken	AT&T
John Seals	AT&T
William Womack	AT&T
Dwight Duston	BMDO
Luis Figueroa	Boeing
Susan Miller	Eldec
Jack Freeman	Fibercomm
Robert Buckley	Hughes
Irwin Newberg	Hughes
Huan-Wun Yen	Hughes
Richard Lind	Hughes/GM
Adrian Popa	Hughes/GM
Joseph Williams	IBM
Chin Chang	Litton
Ka-Kha Wong	Litton
John Todd	McDonnell-Douglas
Gordon Day	NIST
Richard Craig	SDL
Robert Burmeister	Stanford University
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Deepak Varshneya	Teledyne Ryan Electronics
Louis Coryell	U.S. Army
Fred Leonberger	United Technologies
Kevin Malloy	University of New Mexico

Computer Market
Working Group, Newark, NJ
April 23-24, 1992

Andy Yang	ARPA
John Knudson	3M
Arnold Funkenbusch	3M
Robert Southard	AMP
Terry Anderson	Ancor
Ron Brown	Applied Magnetics
Robert Leheny	Bellcore
Jay Zeman	AT&T
Arpad Bergh	Bellcore
Matt Goodman	Bellcore
Richard Binder	CNRI
Roy Love	Corning
Donald Keck	Corning
David Davies	DEC
Chris Baldwin	DEC
Del Hanson	Hewlett-Packard
Terry Loseke	Hewlett-Packard
John Crow	IBM
Ken Jackson	IBM
Edward Engler	IBM
Frank Shott	IBM
Mon-Song Chen	IBM
John Susko	IBM
Paul Ruppert	Lawrence Livermore Labs
Jess Diaz	Motorola
Michael Lebby	Motorola
Donald Johnson	NCR
Peter Pleshko	IBM
Robert Steele	Strategies Unlimited
John Day	Strategies Unlimited
Tom Brandt	U.S.C.

Automobile Market
Working Group, Detroit, MI
May 21, 1992

Roger Brekken	3M
Diane Verploegh	3M
Edward Schmitt	AT&T
Ralph Machesky	Chrysler
Dale Maschino	Delco Electronics
J. Marie Stumpf-Carome	Edjewise
Edward Sickafus	Ford
Marek Wlodarczyk	FST
Tim Fohl	GTE
Tim Bour	Hewlett-Packard
Kevin Brown	Hewlett-Packard
Michael Dunn	Hewlett-Packard
Mark Hodapp	Hewlett-Packard
Eirc Kifer	Hewlett-Packard
James Leoffler	Hewlett-Packard
Mary Hibbs-Brenner	Honeywell
Huan-Wun Yen	Hughes
Linos Jacovides	Hughes/GM
Michel Sultan	Hughes/GM
Robert E. Steele	Hughes/GM/Packard
Michael McKale	Inland Fisher Guide
Edward Carome	John Carroll University
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Tom Brandt	U.S.C.
David Cole	University of Michigan

Consumer Market
Working Group, Bethesda, MD
August 19, 1992

Andy Yang	ARPA
Robert DeMaster	3M
Jack Warren	3M
Sven Roosild	ARPA
Vaneeta Kuzma	AT&T
Arpad Bergh	Bellcore
Robert Fredericks	Bellcore
Heidi Hoffman	Dept. of Commerce
Kai Toh	IBM
Joseph Carpenter, Jr.	NIST
Christina Gabriel	NSF
Aland Chin	Polaroid
John Day	Strategies Unlimited
Bruce Lupin	TV Answer
William Rowe	Zenith

OIDA Forum on Market Opportunities
Washington, D.C.
September 15-17, 1992

Andy Yang	ARPA
Rafael Valiente	3M
Paul Pankow	3M
James Havener	3M
Tom Walker	3M
Dale Murray	AMP
Terry Bowen	AMP
Narinder Kapany	AMP/Kaptron
James Goell	AMP/Lytel
Barbara Yoon	ARPA
Robert Leheny	Bellcore
Mark Hartney	ARPA
Anis Husain	Honeywell
Jim McNeely	AstroPower
Sandra Collins	AstroPower
Edward Schmitt	AT&T

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OIDA Forum on Market Opportunities
Washington, D.C.
September 15-17, 1992

Jay Zeman	AT&T
Kenneth Pooie	AT&T
Richard Smith	AT&T
Charles Snider	Bandgap Technology
Henry Cialone	Battelle-Columbus
Arpad Bergh	Bellcore
Matt Goodman	Bellcore
Lou Lome	BMDO
Erich Bloch	Cncl. on Competitiveness
Joe Ballantyne	Cornell University
Roy Love	Corning
Ajit Thakur	Corning
Donald Keck	Corning
Donald Carlin	David Sarnoff Res. Ctr.
Heidi Hoffman	Dept. of Commerce
Gray Hall	Dept. of Energy
Edmund Smith	DuPont
Arthur Strube	DuPont/BT&D
Robert Brown	Eldec
Katherine Vejtasa	EPRI
Mark Chandler	Hewlett-Packard
Ron Moon	Hewlett-Packard
Wayne Snyder	Hewlett-Packard
Bill Sullivan	Hewlett-Packard
Roland Haitz	Hewlett-Packard
Del Hanson	Hewlett-Packard
Peter McIntyre	Hewlett-Packard
Robert Procsal	Honeywell
Iwan Roberts	Hughes
Huan-Wun Yen	Hughes
Richard Lind	Hughes/GM
Adrian Popa	Hughes/GM
Robert E. Steele	Hughes/GM/Packard
John Crow	IBM
Mark Brodsky	IBM
Janet MacKay	IBM
John Susko	IBM
Frank Shott	IBM
Richard Lear	Lawrence Livermore Labs
Harry Lockwood	Lockwood Group
David Lewis	Martin-Marietta
Ron Nelson	Motorola
Judson French	NIST
Aaron Sanders	NIST
Thomas Russell	NIST
Joseph Carpenter, Jr.	NIST
Christina Gabriel	NSF
Eugene Wong	OSTP
Peter Pleshko	PEMM Services
Bill Hamilton	Raytheon
David Myers	Sandia National Labs
Robert Lang	SDL
James Freedman	SRC
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
James Bowser	Three-Five Systems
John Brock	TRW
Larry Coldren	U.C.S.B.
Dan Dapkus	U.S.C.
Tom Brandt	U.S.C.
Leon Newman	United Technologies
Steven Bishop	University of Illinois
Steve Brueck	University of New Mexico

Display Workshop
Newark, NJ
March 2, 1993

David Cross	3M
Neil Bergstrom	Apple Computer
Thomas Credelle	Apple Computer
John Zavada	ARO
Allan Kmetz	AT&T
Salvatore Lalama	AT&T
Tom O'Neill	Bandgap Technology
Terry Nelson	Bellcore
Robert Tolliver	Clinton Electronics
Peter Bocko	Corning
Philip Heyman	David Sarnoff Res. Ctr.
John Bartoszek	DEC
Ron Pacheco	DEC
Wayne Hofer	Dept. of Energy
Jesse Eichenlaub	Dimension Technologies
Todd Touris	Dimension Technologies
Terry Stuart	Displaytech, Inc.
Elliot Schlam	Elliott Schlam Associates
Gary Jones	FED Corp.
Bill Glenn	Florida Atlantic Univ.
George Craford	Hewlett-Packard
Roland Haitz	Hewlett-Packard
Larry Hubby	Hewlett-Packard
William Bleha	Hughes
John Batey	IBM
Fred Kahn	Kahn International
William Doane	Kent State University
John West	Kent State University
Jeffrey Jacobsen	Kopin
Norman Bardsley	Lawrence Livermore Labs
Tony Bernhardt	Lawrence Livermore Labs
Steve Benton	MIT Media Lab
Paul Gulick	Motif
Karen Jachimowicz	Motorola
Ron Nelson	Motorola
Herb Bennett	NIST
Peter Pleshko	PEMM Services
Tim Flegal	Planar Systems
Chris King	Planar Systems
Ross Pollack	Plasmaco
Larry Weber	Plasmaco
Bill Hamilton	Raytheon
Thomas Holzel	Raytheon
Roger Johnson	SAI Technology
James Jorgensen	Sandia National Labs
Walter Worobey	Sandia National Labs
Bob Duboc	Silicon Video
Joseph Castellano	Stanford Resources
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Phil Bos	Tektronix
Tom Buzak	Tektronix
Douglas Ketchum	Thomas Electronics
Joe Morrissy	Three-Five Systems
Jan Talbot	U.C.S.D.
Robert Miller	U.S. Army
Dominick Monarchie	United Technologies
William Rowe	Zenith

Optical Communications Workshop
Rosemont, IL
April 22, 1993

Gary Boyd	3M
Terry Smith	3M
Tad Szostak	3M
Ram Rao	Ameritech
Pedram Leilabady	Amoco
Bruce Vojak	Amoco
Terry Bowen	AMP
Tim Bock	AMP/Lytel
James Goell	AMP/Lytel
Randy Wilson	AMP/Lytel
Robert Leheny	ARPA
Phil Anthony	AT&T
Mel Dixon	AT&T
Randy Giles	AT&T
David Harrison	AT&T
Art Judy	AT&T
Jan Lipson	AT&T
Suzanne Nagel	AT&T
Manuel Santana	AT&T
Ken Walker	AT&T
Laury Watkins	AT&T
Tom O'Neill	Bandgap Technology
Arpad Bergh	Bellcore
Matt Goodman	Bellcore
Peter Kaiser	Bellcore
Dilpreet Jammu	BNR
Paul Jay	BNR
Peter Murphy	BNR
Gen Ribakovs	BNR
Joe Iamartino	Computer Craft
Dave Charlton	Corning
Michael Dobbins	Corning
Thomas Holmes	Corning
Roy Love	Corning
Mark Newhouse	Corning
Don Channin	David Sarnoff Res. Ctr.
Steve Storozum	Fibermux
Joanne LaCourse	GTE
Bill Miniscalco	GTE
Ron Moon	Hewlett-Packard
Paul O'Donnell	Hewlett-Packard
Harry Wang	Hughes
Robert E. Steele	Hughes/GM/Packard
John Crow	IBM
Paul Green	IBM
Jon Herlocker	IBM
Kenneth Jackson	IBM
Mark Lowry	Lawrence Livermore Labs
Cal Miller	Micron Optics
Davis Hartman	Motorola

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Optical Communications Workshop
Rosemont, IL
April 22, 1993

Douglas Franzen	NIST
Robert Phelan, Jr.	NIST
Bill Babcock	Portasystems
Dave Horsma	Raychem
Elias Snitzer	Rutgers University
Steve Eglash	SDL
Norm Meres	Siecor
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Larry Coldren	U.C.S.B.
Dan Dapkus	U.S.C.
Robert Hobbs	United Technologies
Steve Kang	University of Illinois
Ira Jacobs	Virginia Polytechnic

Optical Storage Workshop
Tuczon, AZ
April 27, 1993

Michael Haase	3M
Bill Mitchell	3M
Demetri Psaltis	Cal Tech
Mark Kryder	Carnegie Mellon Univ.
Mark Roelofs	DuPont
Brian Bartholomeusz	Eastman Kodak
Joseph Miceli	Eastman Kodak
C.C. Yang	Hewlett-Packard
Marvin Klein	Hughes
Edward Engler	IBM
Blair Finkelstein	IBM
Terry McDaniel	IBM
Glenn Sincerbox	IBM
Herb Bennett	NIST
Tom Leedy	NIST
Kent Rochford	NIST
Susan Peterson	NSIC
Tony Clifford	Optex
George Storti	Optex
Milford Kime	Polaroid
Bert Hesselink	Stanford University
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Jim Merz	U.C.S.B.
Shaya Fainman	U.C.S.D.
Tom Brandt	U.S.C.
James Burke	University of Arizona
Fred Froehlick	University of Arizona
Dennis Howe	University of Arizona
Masud Mansuripur	University of Arizona
Tom Milster	University of Arizona

Optics in Switching/Computing Workshop,
Baltimore, MD
May 7, 1993

Alan Craig	Air Force OSR/NE
Robert Leheny	Bellcore
Rod Alferness	AT&T
Alan Huang	AT&T
David Miller	AT&T
Michael Haney	BDM Federal
Ernst Munter	BNR
Demetri Psaltis	Cal Tech
Nabeel Riza	General Electric
Ravi Athale	George Mason University
Bill Rhodes	Georgia Tech
Gilmore Dunning	Hughes
John Crow	IBM
Scott Hinton	McGill University
Richard Williamson	MIT Lincoln Labs
Davis Hartman	Motorola
Mira Djelic	MRI
John Walkup	NASA Ames Research Ctr.
David Christensen	NIST
Robert Phelan, Jr.	NIST
Thomas Russell	NIST
Peter Guilfoyle	Opticomp
Al Gerrish	Optivision
Paul Prucnal	Princeton University
Xiang Yang	Quantex
Albert Jambordino	Rome Labs
Robert Kaminski	Rome Labs
Jeffrey Meyer	Sandia National Labs
David Myers	Sandia National Labs
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Bruce Berra	Syracuse University
Jonathan Heritage	U.C.D.
Larry Coldren	U.C.S.B.
Sadik Esener	U.C.S.D.
Sing Lee	U.C.S.D.
Sandy Sawchuk	U.S.C.
Mark Neifeld	University of Arizona
Bahram Javidi	University of Connecticut
George Papen	University of Illinois
Mohammed Islam	University of Michigan
Stu Tewksberry	University of W. Virginia
Akis Goutzoulis	Westinghouse

Hardcopy Workshop
Rosemont, IL
June 3, 1993

Charles Hull	3D Systems
Steve Birkeland	3M
Ed Harder	3M
Steve Barasch	Apple Computer
Annette Jaffe	Apple Computer
Tom Ashley	B.I.S.
Sara Church	Bureau of Engraving
Robert Peiffer	DuPont
Elizabeth Patton	Eastman Kodak
Michael Piatt	Eastman Kodak
William Ray	Electrographics
Howard Taub	Hewlett-Packard
Arthur Diaz	IBM
George Imperial	International Paper
Foster Fargo	Iris Graphics
Mark Timpe	Knight-Ridder
Cardinal Warde	MIT
Thyagaraj Sarada	Pitney Bowes
John McCann	Polaroid
Wolfgang Stutius	Polaroid
James Mason	R.R. Donnelley
John Endriz	SDL
Linda Creagu-Dexter	Spectra
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Ron Adams	Tektronix
Hue Le	Tektronix
Richard Chartoff	University of Dayton
Allan Lightman	University of Dayton
Ivan Rezanka	Xerox

Forum on Technology Roadmaps
Alexandria, VA
October 20, 1993

Andy Yang	ARPA
Steve Birkeland	3M
Ray Bodnar	3M
James Bylander	3M
Paul Leeke	3M
Bill Mitchell	3M
Paul Pankow	3M
Connie Giuliano	A.P.T.
Narinder Kapany	AMP/Kaptron
James Goell	AMP/Lytel
Randall Wilson	AMP/Lytel
Brian Hendrickson	ARPA
Anis Husain	ARPA
Robert Leheny	ARPA
Sven Roosild	ARPA
David Slobodin	ARPA
Louis DiNetta	AstroPower
Jim McNeely	AstroPower
Allan Kmetz	AT&T
Jan Lipson	AT&T
David Miller	AT&T
Suzanne Nagel	AT&T
Peter Runge	AT&T
Tom Stakelon	AT&T
Harry Sugar	AT&T
John Tartaglia	Bandgap Technology
Arpad Bergh	Bellcore
Dwight Duston	BMDO
Lou Lome	BMDO
Gen Ribakovs	BNR
Herman Willemsen	BNR
David Cheney	Cncl. on Competitiveness
Amy Petri	Cncl. on Competitiveness
Deborah Wince-Smith	Cncl. on Competitiveness
Thomas Holmes	Corning
Donald Keck	Corning
Roy Love	Corning
Mark Taylor	Corning
Calvin Carter	CREE Research
John Connolly	David Sarnoff Res. Ctr.
Ron Pacheco	DEC
Richard VanAtta	Dept. of Defense
Wayne Hofer	Dept. of Energy
Joseph Slawek	EG&G Judson
Elliot Schlam	Elliott Schlam Associates
Ravi Athale	George Mason University
Roland Haitz	Hewlett-Packard
Rick Kniss	Hewlett-Packard
Peter McIntyre	Hewlett-Packard
Ron Moon	Hewlett-Packard
Howard Taub	Hewlett-Packard
Adrian Popa	Hughes/GM
Robert E. Steele	Hughes/GM/Packard
Maurizio Arienzo	IBM
John Crow	IBM
Edward Engler	IBM
William Kulpa	IBM
Tony Bernhardt	Lawrence Livermore Labs
Mark Lowry	Lawrence Livermore Labs
David Watkins	Los Alamos National Lab
Walter Butler	Martin-Marietta
William Key	Martin-Marietta
Aram Mooradian	Micracor
Joel Frendt	Micron Display Technology
Richard Williamson	MIT Lincoln Labs
Davis Hartman	Motorola
Ron Nelson	Motorola
Peter Dawson	Nat'l Research Council

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Forum on Technology Roadmaps
Alexandria, VA
October 20, 1993

Herb Bennett	NIST
Joseph Carpenter, Jr.	NIST
Gordon Day	NIST
Douglas Franzen	NIST
Judson French	NIST
Tom Leedy	NIST
Robert Phelan, Jr.	NIST
Thomas Russell	NIST
George Uriano	NIST
Christina Gabriel	NSF
Tom Tucker	NTTC
Don Carlin	Optex
Tony Clifford	Optex
Lionel Johns	OSTP
Peter Pleshko	PEMM Services
John McCann	Polaroid
Wolfgang Stutius	Polaroid
James Jorgensen	Sandia National Labs
David Myers	Sandia National Labs
Richard Craig	SDL
James Freedman	SRC
Robert Burmeister	Stanford University
Eric Bergles	Strategies Unlimited
John Day	Strategies Unlimited
Robert Steele	Strategies Unlimited
Pat Green	Tektronix
James Bowser	Three-Five Systems
Joe Morrissy	Three-Five Systems
Dan Dapkus	U.S.C.
Nick Colanari	UNIAX
Dominick Monarchie	United Technologies
James Burke	University of Arizona
Dennis Howe	University of Arizona
Steven Bishop	University of Illinois
Mario Dagenais	University of Maryland
Steve Brueck	University of New Mexico
Russell Dupuis	University of Texas
Ken Mitchel	Waterloo Scientific
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