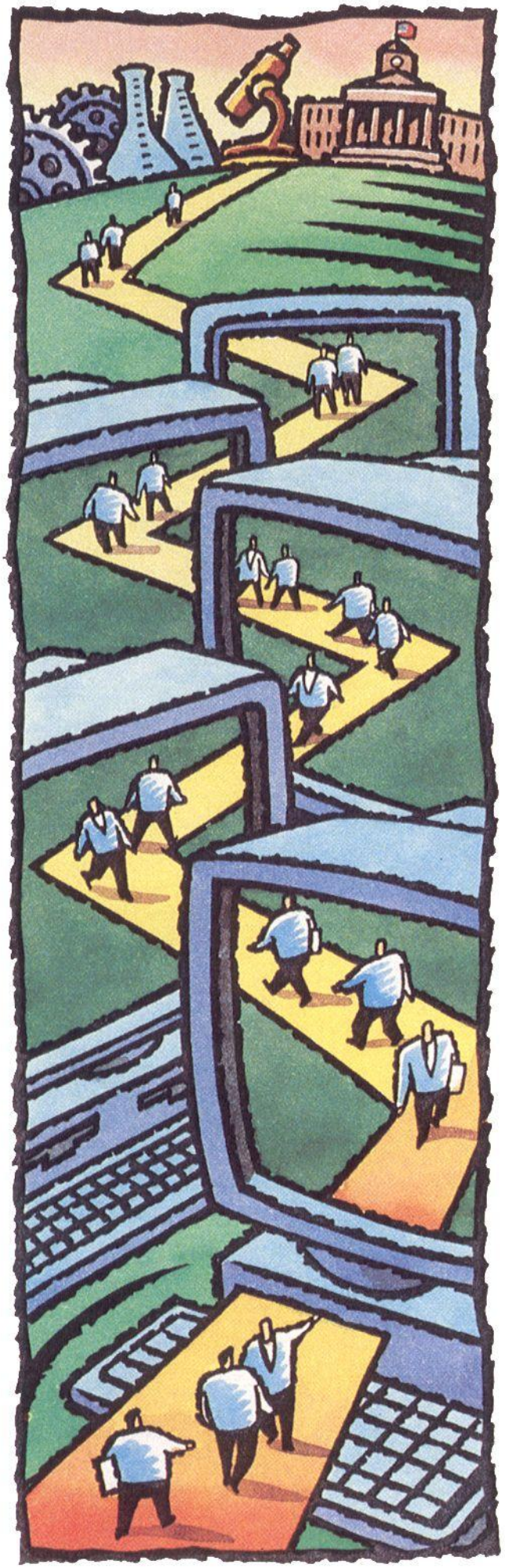

THE ECONOMICS OF SCIENCE: FROM PHOTONS TO PRODUCTS

By Lionel C. Kimerling

The paradigm of the large industrial laboratory is fading. This article looks at the optoelectronics industry and suggests that new technologies with economic impact will be created from effective networks of large and small enterprises coupled with university centers of innovation.

Imagine that you are Samuel B. Morse in the early 1800s. You are captivated by basic research into the nature of electricity reported by Franklin, Volta, Galvani, Oersted, Ampere, and Faraday. This royalty free knowledge base of electromagnetism prompts an idea that copper wires could be used to transmit an electronic version of the smoke signal over long distances. The obvious ad-

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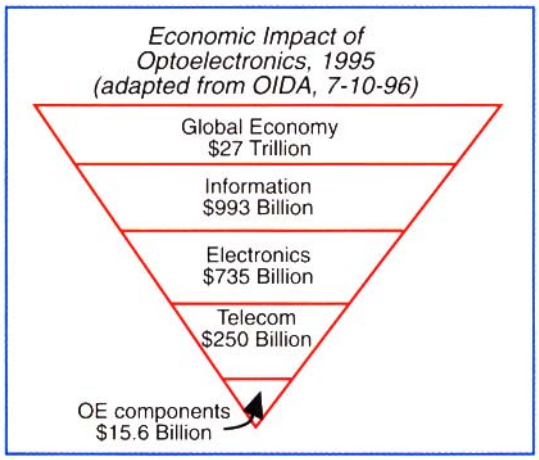

Figure 1. Optoelectronics provides the foundation for an enormous amount of economic activity.

vantages are a no line of sight requirement, convenience, and higher information content.

Long distance communications began as a digital technology with smoke signals. The information travelled at the physical limit, the speed of light, but the content was small due to the low modulation rate of the transmitter. As Morse, you experiment using personal funds until they are exhausted. You apply to the U.S. Department of Commerce for a grant to complete a prototype. Congress, however, is not interested in your proposal, and you wait for 12 years to get a small appropriation. In 1844 you demonstrate Baltimore to Washington communications by telegraph.

Now consider the prospects of the fruits of your research having as great an impact on society. The path from science to product—concept, market, and commercialization—has not evolved greatly in these times of rapid change. Each step builds on prior generations of knowledge and needs. Bell used electricity in his telephone 23 years after Morse's transmission, and the transmission standard moved from digital to analog voice. Some 50 years later Marconi demonstrated wireless telegraph transmission. Basic science in the first half of the 1800s provided the foundation for an unimagined $250 billion telecommunications industry and a global $1 trillion information industry.

Today's capital markets ask the following questions: Is there a compelling relationship between fundamental science and economic gain? Can a society, a company, or an individual argue that unfettered exploration of the unknown will yield a return to the investor? The answer to the first question is an unqualified "yes." Science has most definitely enhanced material welfare and created prosperity. The second question has a positive answer as well, when viewed within the proper time frame. The course of concept to product sales is normally a 10–20 year path of building business, market, and manufacturing infrastructures. These infrastructures support the flow of knowledge into products. Small enterprises can emerge and flourish in niche markets, but industries are built on infrastructure. To an enterprise, this infrastructure is known as the technology supply chain.

Technology supply chains in optoelectronics

Today, telecommunications rests firmly on an optoelectronics foundation. As shown in Figure 1, optoelectronic components: lasers, fibers, detectors, and displays, represent a very small ($15 billion), but enabling, part of the industry. The semiconductor laser was discovered following fundamental explorations into the nature of energy transfer in gas molecules, the quantum nature of light, and semiconducting compounds. The impact of the laser on the connectivity of our society will echo forever.

Similarly, the transistor, discovered at Bell Laboratories in 1948, has returned dividends to AT&T far beyond the initial vision. The transistor is an example of focused, basic research that successfully provided an alternative to the vacuum tubes whose heat generation threatened central office "melt-down" in an expanding telephone industry. The research began with surface science and continued to semiconducting materials and methods for their ultrapurification. Today, silicon transistors drive gigahertz modulation rates that represent "impossible" data rates by smoke signal standards. These transistors, together with compound semiconductor lasers and detectors, and optical fibers composed of glass (SiO_2), have increased system information carrying capacity (see Fig. 2) to the extent that voice and image transmission now enable the explosive growth of the Internet. This rate of growth in system performance, more than 100 times per decade, defines the path of a "killer technology" that is destined to pervade all aspects of society.

Let us consider the economics of science as it functions today through the lens of case studies in the optoelectronics industry (Fine and Kimerling, "Biography of a Killer Technology," OIDA Future Vision Program, 1997). The industry is essential to high-speed data networking and telecommunications: two of the fastest growing, global economic sectors. What is the nature of the "technology supply chain" of the industry?

Bell constructed a very effective vertically integrated chain that connected basic research to end user at AT&T. Research created technology options that were developed into products and deployed to provide service to the user. This model worked well in the absence of market feedback. It was a science-driven structure that dictated

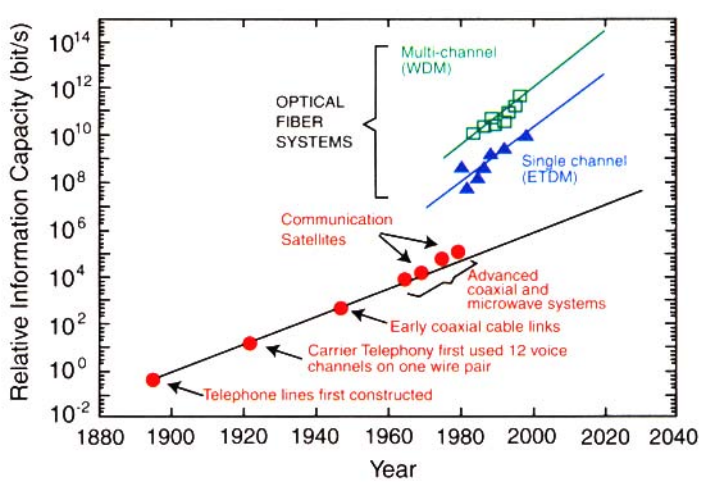

Figure 2. Communications capacity is growing at a "killer technology" pace.

solutions to the market. Today, market pull has invaded the communications industry. The vertical disintegration of Lucent Technologies from AT&T has yielded a market responsiveness that was not previously possible. The lesson of AT&T is that technology supply chains are temporary constructs that must change with time to couple science to products with optimal economy.

Rule of 10

Lucent Technologies/Bell Laboratories, as Intel, is a company that has perfected the high performance end of its business. In addition, Lucent (and Corning) with fiber and Intel with microprocessors have had the enviable position of offering high volume, high margin products. Both companies are systems driven by end users in research and product design. Both companies employ an approximate "Rule of 10" in research expenditures: one part to research to develop next generation options; 10 parts to development to select options and design products and manufacturing processes; and 100 parts to manufacturing to execute stable fabrication and distribution to customers. This heirarchy is typical of large industrial enterprises today that apportion R&D at a level of about 8–10% of sales. Both companies will face a technology supply chain challenge when margins contract in a future market of readily available commodity products. Today, the value point in each of their chains is high performance, and their chains are not optimized for commodity economics.

Hewlett Packard

Hewlett Packard (HP) is a world leader in visible light emitting diodes (LEDs) for displays. They were motivated to find a better performing alternative to "nixie tubes" for their instrument displays. In 1968 HP developed the GaAs dot matrix display chip. The hand-held calculator and wrist watch markets temporarily led to high volume production and sales. When these markets transitioned to liquid crystal displays (LCDs), HP was left with nearly 20 years of corporate commitment to R&D on LEDs with little market expansion. During the period of the 1970–1990s, the product portfolio expanded from indicator lamps to alphanumeric displays to bar code readers to communications products. HP built their business on a materials platform that readily translates into high volume, commodity manufacturing. Today, HP is a world leader in visible LEDs and well positioned to compete in the high volume (infrared) datacom and consumer electronics markets.

Corning

Corning is a materials company that revolutionized the telecommunications industry with a chemical vapor deposition (CVD) process for producing high purity SiO_2 (silica) glass fibers. Corning's research was the "technological parent" of optical fiber. The research breakthrough occurred in 1970, but the commercial breakthrough did not occur until 1982 when MCI

placed the first major fiber order with Corning. The Corning commitment to a corporate vision for fiber during the 1970s constituted the "commercial parent" role of the corporation. During that time Corning developed a strong patent portfolio, seeded the market with connector and splicing technologies, and was active in setting standards for telecommunications. Today, Corning has shed its traditional line of culinary products to become a photonics-centered company.

SDL

SDL is a small photonics company for which the dual parentage roles were critical. Organized by employees of Xerox and Spectra-Physics to commercialize the Xerox high-power laser technology in 1983, its products were limited to small research, military, and space applications until 1992. During these formative years the company continued to develop new concepts through research, and new applications for high-power lasers. Today commercial products, led by pump lasers for fiber optical amplifiers, are the main revenue source, and their telecommunications business has grown 240% during the past five years. The role of "commercial parent" was effectively played by government during the incubation period. As competition grows, SDL sees their success depending on developing high volume markets and a low cost manufacturing capability. Here again a materials processing core competence is considered essential.

In a very real sense, scientific inquiry has defined the consciousness of civilization.

It is clear that technology supply chains in the rapidly expanding telecommunications component industry are strongly grounded with internal research. This structure arises to a large extent from the fragmented nature of the industry. Small niche products play an important role; there is no standard architectural building block, and the size of the industry sectors, such as optoelectronics at $15 billion in annual revenues, is too small to attract a united infrastructure. The silicon integrated industry offers a counter example.

The highly integrated, integrated circuit industry

The Semiconductor Industry Association (SIA), Sematech, SEMI/Sematech, and Semiconductor Research Corp. are examples of a current success in the transformation of research to revenues. These organizations oversee the Technology Roadmap, manufacturing, supplier base, and university relations for the industry. Three criteria aid the success: a revenue base of critical size ($150 billion per year), a high growth rate (15–20% per year), and a standard component building block, namely complimentary metal oxide semiconductor integrated circuits (CMOS ICs). The SIA Technology Roadmap presents a 15-year consensus technology forecast (updated every five years) by industry and academia that enables the joint exploration and development of new concepts. Sematech is a consortium of integrated circuit (IC) manufacturers that evaluates manufacturing tools and processes. SEMI/Sematech is a consortium of equipment and materials suppliers that coordinates the development of advanced manufacturing capabilities. And, the Semiconductor Research Corp. (SRC) is a consortium of IC and supplier companies that stimulates university research in support of the Technology Roadmap and the development of a qualified employee base from the students.

The Roadmap is effective because the circuit architecture fundamentals are basically constant and only new materials and process advances have been required to maintain a pace of 100-fold per decade increase in performance with no increase in cost. As this "killer technology" pace becomes threatened, new directions are stimulated. Two current programs are exemplary of the role of this infrastructure in providing for the industry future. The SIA has concluded that certain technologies will encounter physical limits, and that radical paradigm changes will be required within the 15-year Roadmap time frame. A pool of funds has been set aside to sponsor multiuniversity Focused Research Centers (FRCs). These FRCs have the express charge of off-the-roadmap basic research to lay the foundation for change. Two centers in design and interconnection have been commissioned. A 10-year time frame has been set to establish breakthrough competencies in the chosen areas.

The second example is more grounded in engineering. As the semiconductor industry grows, it becomes a significant user of energy, water, and chemicals in its local communities. Engineers who can incorporate environmental, safety, and health (ESH) concepts into processes and materials that meet the performance goals of the Roadmap are considered essential to the long term health of the industry. A multi-university Center for Environmentally Benign Semiconductor Manufacturing, jointly supported by the SRC and the National Science Foundation (NSF), is charged with discovering new technologies and design templates that take ESH from a staff oversight role to a core, well-integrated engineering role. The SRC involvement particularly promotes the entry of these uniquely educated students into the industry.

Science and society

In a very real sense, scientific inquiry has defined the consciousness of civilization. The industrial revolution was built on the transformation of the mechanical advantage of engines to an economic advantage that increased productivity by amplifying human labor. However, more important than the industrial revolution and the political change of the 18th and 19th centuries, was the freedom of the scientist to explore and discover the fundamental laws of nature. Science was the standard upon which the freedom of the individual emerged, and it has been the lever of an enormous economic advantage upon which rests our current prosperity. Today, the value of science *Continued on page 52*

tro-optics, or remote sensing. Twelve plus years industry experience in development of prototype laser systems, fiber optic sensors, and other electro-optic devices. Proven ability in writing winning proposals for novel ideas. Experience in FORTRAN, BASIC, C, Labview. Nine publications and three patents. Interested in relocating to Germany.

8-C—M.S. in Physics, with a strong background in optics. Seeks position as an optical engineer, scientist, or group leader. Experience with optical design, interferometry, spectroscopy, ophthalmic optics, IR, UV, optical testing, metrology, semiconductor technology, electronics, radiometry and photometry, analytical chemistry, detectors, lasers, gas discharge and incandescent lamps, LEDs, simulation, and software development. Knowledgable in the optical properties of polymers, crystals, semiconductors, and glasses. Have led optics-related projects. Publications; two patents; located in Central Tex.; willing to relocate.

7-A—Ph.D. (1993). Optical scientist with extensive in-depth optical modeling experience. Seeking an industrial R&D or engineering position in the photonics industry. Instruments designed for the telecommunication and biomedical applications have annually produced multi-million dollar business. Excellent writing and communication skills. Mastered optical design software such as CODE V and OSLO. Twelve publications; hold patents.

7-B—Ph.D. (1997) in Optical Engineering. Seeking a postdoctoral or R&D position. Ten years experience in PIV, optoelectronics, instrument developing, image processing, and micro-controller (software and hardware) designing. Broad background in analog, digital electronics, and mechanics. Excellent computer programming skills include VC++, FORTRAN, FoxPro, and various assemble languages (8080, 8051, 8098, Z80, etc.).

Design vs. utility patents

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the housing design. A point to remember about this scenario is that if a third party wished to make and sell the identical kaleidoscope without infringing the inventor's intellectual property rights, a license for each form of intellectual property would need to be obtained.

The designs around us

Should you have the good fortune to be reading this column at the OSA Annual Meeting in Baltimore, take note of all the different designs of the products on display in the Exhibit Hall. Many of the designs are ornamental and are appropriate subject matter for a design patent. Given the straightforward form of a design patent application and the relatively reasonable filing fee ($330 for large entities, $165 for small), it is worth keeping in mind that patent protection is available for the appearance of a product, as well as for its structure and function.

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Economics of science

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is accepted in an economic sense as the transportation, electronics (including telecommunications), and pharmaceutical industries lead in investment, and as society looks for cures to problems from energy sources to health.

The optoelectronics industry is a model case study for the economics of science. Basic research into the nature of electromagnetism provided the foundation with no concept of application. Today, a blend of basic research for niche products and focused research for performance improvement supports a rapidly growing information industry. As business plans are clarified, research at large enterprises has become more aligned with product strategy, and fundamental exploration flourishes at small companies and universities. Government support for R&D has been critical during technology incubation periods. As industries mature, economics drives consolidation, but research drives growth by creating new options.

Research promises large economic benefits to the optoelectronics industry. New photonic switching phenomena; monolithic, highly integrated microphotonic circuits; and a high yield, high volume compound semiconductor process technology are parts of the vision that will create the future of the information industry. New technologies can be gated, however, by any link in the technology supply chain—from raw material supply to manufacturing to consumption. The temporal confluence of need and solution depends, for instance, on the intellectual interaction of technical and non-technical minds to create markets for new technologies. The future seems to rest today, not on leadership by a great industrial lab, but on the effective networking of large and small enterprises with university centers of innovation. This new technology supply chain structure will define the landscape for science in the next several decades.

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