# Molecular Engineering to Computer Science: The Role of Photonics in the Convergence of Communications and Computing

*This paper highlights some of the key semiconductor molecular engineering advances that contributed to advances in photonics and electronics to help establish and enhance today's information age.*

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**ABSTRACT** | Over the past 50 years advances in our ability to engineer materials on the molecular scale have fostered the development of many of today's information-age technologies. Among these is photonics; the branch of optical science relating to a broad range of applications of light including in information systems. Beginning in the 1970s, laser photonics emerged to spawn many important new applications, including enabling power-efficient, greatly expanded capacity and speed in transporting information. Over the ensuing decades, these applications have matured, fostering significant advances in information age technologies; not only for transporting information between people and systems, but also in routing and switching within computing and data storage systems. Today photonics research continues this trend, advancing the con-vergence of the two key 21st century information age technologies: communication and computing. This paper highlights some of the key semiconductor material science and molecular engineering advances that have contributed to these developments.

**KEYWORDS** | DARPA photonics programs; optical communication components; optical communication systems; photonic interconnects in digital systems; semiconductor lasers; semiconductor laser materials

## I. INTRODUCTION AND EARLY DEVELOPMENT

In the early 1900s, Albert Einstein set the stage for the development of lasers with his explanation of the photo-electric effect in terms of light quantization (photons) and subsequent introduction of stimulated recombination to balance the rate equations governing blackbody radiation. In 1958, drawing on Einstein's insights and decades of research on the quantum dynamics of radiative processes, Shawlow and Townes triggered the development of today's laser photonics by publishing the requirements for how simulated recombination could occur at optical frequencies to generate coherent optical signals through Light
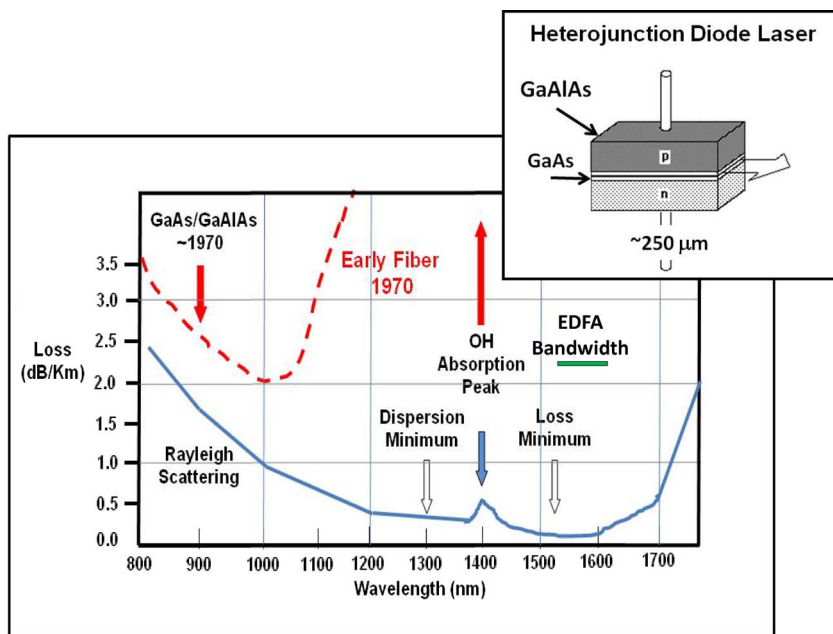
**Fig. 1.** *Spectral dependence of the loss coefficient for typical optical fibers circa 1970 and today. The background absorption reflects the $1/\lambda^4$ dependence of Rayleigh scattering losses, while absorption due to residual water (O–H) vibration absorption dominates the mid-IR range in early fibers. The rapid increase at longer wavelengths is due to phonon scattering in the constituent glass at these wavelengths [11]. Insert illustrates the layered structure of a AlGaAs:GaAs laser diode.*

Amplification by Stimulated Electron Recombination (LASER) [1].[1] Two years later their analysis was reduced to practice in two systems: an optically excited ruby crystal [2] and a helium neon gas discharge [3]. And, two years later lasing was also demonstrated in semiconductor diodes[2] [5]–[8].

Development of a laser communication system began almost immediately. By the end of the decade (1970) an experimental prototype was in place at AT&T's Bell Labs, with plans to begin installing optical links in long-haul networks by the end of the century. The initial Bell approach made use of a continuous wave (CW) gas laser that required external modulators. To overcome modulator bandwidth limitations, the plan was to use a number of lasers, operating at different wavelengths, all multiplexed onto a single beam and transmitted from source to receiver via a relatively cumbersome free-space optical waveguide [9].

Diode lasers, with doping profiles similar to fast switching tunnel diodes, were recognized as offering a compact alternative source that could be directly modulated at up to gigahertz rates. However, because carrier diffusion away from the diode junction resulted in room temperature threshold current density too high for CW

operation, these devices remained largely laboratory curiosities [9], [10].

## II. PHOTONIC COMMUNICATION TECHNOLOGY—THE EARLY YEARS

In 1970, two molecular engineering breakthroughs set the stage for today's systems. The first was the demonstration that glass fiber waveguides could be prepared with impurity induced optical losses low enough to be usable as an efficient transmission medium[3] [11]. The second was the demonstration that a unique semiconductor heterostructure design could reduce diode threshold current sufficiently to permit room-temperature operation [12]–[14]. This design consisted of layering materials having different bandgap energies (initially GaAs and AlGaAs) engineered to place the diode junction in the low bandgap material (GaAs) and positioned close enough to the wide-bandgap layer (AlGaAs) to block carrier diffusion; see insert of Fig. 1.

These breakthroughs were announced almost simultaneously; and remarkably, the emission wavelength of the laser ($\lambda \sim 900$ nm) very nearly matched the fiber loss minimum ($\lambda \sim 1000$ nm). While not exact, the match was close enough to shut off consideration of other approaches

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[1]In [1], the term MASER applies to the earlier microwave version of a laser and initially LASERS were referred to as optical MASERs.

[2]It is interesting to note that Jon Von Neumann, the mathematician and computer scientist, anticipated generation of stimulate emission in semiconductor p-n junctions in an unpublished 1953 letter to Edward Teller. This letter only became public much later [4].

[3]While not the subject of this paper, an account of the level of material engineering required to achieve the remarkable level of transparency realized in today's communication grade optical fiber is the subject of [11].
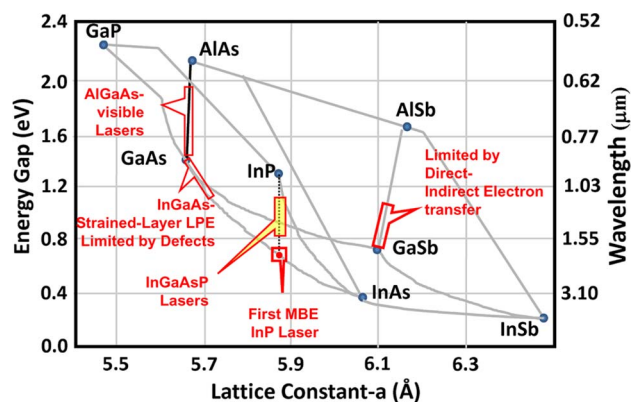
**Fig. 2.** *Bandgap energy (and wavelength) for some of the group III-V semiconductor materials considered for communications system applications plotted against lattice constant. Early attempts to prepare GaAs-based long wavelength devices using InGaAs suffered from excessive strain induced defects, while devices prepared by alloying Al with GaSb suffered from scattering of carriers into the conduction-band indirect valleys. Initial attempts to prepare phosphorous containing alloys by MBE were unsuccessful due to difficulty in controlling the phosphorous vapor pressure within the MBE chamber. This limitation was not a problem for depositing InGaAs, resulting in this alloy being the first MBE grown, InP-based, laser. Later advances in MBE techniques overcame the problems with phosphorous and allowed MBE growth of Q:InP laser material.*

to photonic networks, with plans to develop a diode-laser/optical-fiber transmission system using AlGaAs:GaAs lasers undertaken immediately. But as the quality of glass fiber improved, the loss minimum shifted to longer wavelengths, ultimately reaching ~1550 nm, as shown in Fig. 1. The significant advantages of operating close to the minimum in absorption motivated further research to find a material combination that could emit at these optimal longer wavelengths.

A number of possibilities, representing different lattice constants and energy gaps, were investigated as indicated in Fig. 2. The prevailing wisdom was that to minimize defect-induced nonradiative recombination the deposited films should be nearly lattice matched to the substrate. Ternary alloys (e.g., AlGaAs) were thought to be most easily prepared and were widely investigated; however, for a variety of reasons, these materials did not have acceptable performance. In 1977, the quaternary alloy InGaAsP, deposited on an InP substrate (Q:InP), was demonstrated to be capable of producing robust lasers emitting at the desired wavelengths [15]. Today quaternary materials are the primary choice for telecommunication lasers.

Early laser diodes were prepared using liquid phase epitaxy (LPE), a technique that is easily implemented, relatively low cost, and which provides the near-equilibrium thermodynamic conditions considered critical for achieving high-quality material [16]. But with LPE it was found difficult to produce optimal thin films, motivating consideration of alternative approaches. One alter-

native was molecular beam epitaxy (MBE), a technique with nearly atomic level control that can produce very uniform thin films. However, initial MBE results were disappointing; deposition was limited to GaAs alloys and the deposited films suffered from excessive nonradiative recombination. But, the advantages of MBE for thin film growth encouraged continued research and by the end of the decade MBE material suitable for both GaAs and InP lasers was being routinely produced [17].

Vapor phase epitaxy (VPE) was also investigated. VPE relies on decomposition of precursor gases containing the material to be deposited as the gas flows over, and chemically reacts with, the heated substrate. The first gases investigated required relatively high substrate temperatures making uniform, thin films difficult to achieve. The adoption of metal-organic compounds [metal-organic chemical vapor deposition (MOCVD)], which decompose at lower temperatures, enabled high-quality uniform thin films [18]. By the end of the decade (1980), all three techniques were in use to produce diode lasers. In the end, both MBE and MOCVD were scaled up to production levels and are widely in use today.

As these deposition methods were evolving, laser device researchers were engaged in developing material processing techniques to engineer complex laser designs. One example is the incorporation of etched gratings in the laser waveguide to provide wavelength-selective "distributed" feedback that stabilizes laser wavelength and reduces spectral linewidth [19]. The original motivation was to minimize pulse distortion in propagating through dispersive fiber, but stabilized lasers also found applications in coherent detection [20] and in increasing individual fiber capacity through wavelength division multiplexing (WDM) [21].

During this period, the expanding capabilities for preparing high-quality samples of GaAs and other group III-V semiconductors also sparked significant basic research interest in their intrinsic physical properties. Very thin films, uniform on an atomic scale, with abrupt interfaces and having tailored electrical and optical properties, were ideal for this research. These "engineered" material structures allowed investigation of some of the most fundamental properties of semiconductor materials. One significant example is engineered carrier confinement within "quantum wells" (QWs). QWs are similar to the carrier confinement structures used in diode lasers, but with the two wide-bandgap films physically separated on the scale of elementary optical excitations ($d \sim 8$ nm). Among other applications, these structures are ideal for the study of coherently bound electron-hole pairs (excitons) [22]. In addition, studies of transport in the 2-D electron gas that forms at abrupt, atomically smooth hetero-material interfaces, when electrons transfer from the doped wide-bandgap material into the adjacent undoped, low-bandgap layer, permitted detailed investigations of the unique properties of 2-D Fermi liquids [23].

Long before "nanoscience" was a recognized realm for scientific investigation, researchers applying the nanoscale material processing techniques developed for photonic applications were gaining significant insights into the fundamental optical and electronic properties of semiconductors materials. The significance of these results has been widely appreciated within the physics community, including the Nobel Prize committee.[4]

## III. THE DAWN OF OPTICAL FIBER COMMUNICATIONS

In 1980, after a decade of research and development, and more than 20 years earlier than had been originally anticipated, AT&T committed to the commercialization of photonics for telecommunications by initiating plans for the first trans-Atlantic fiber cable (TAT-8). GaAs devices had been used in earlier field trials, but the relatively less mature Q:InP devices were chosen for this application to take advantage of the lower long wavelength fiber loss. This decision settled a debate over what lasers to use in fiber systems and enshrined InP photonics for telecommunications applications. By the close of the decade the terrestrial long-haul network was also incorporating fiber technologies, and extension into shorter reach networks was well underway.

As fiber links proliferated, a number of significant molecular engineering developments emerged to enhance the capabilities of fiber systems.

First, the use of QW material for the laser gain medium was shown to lower threshold currents to levels compatible with complementary metal–oxide–semiconductor (CMOS) transmitter electronics, as shown in Fig. 3. With laser diodes and photodetectors capable of operating at gigabit rates, this result then tied advances in photonic transmitters to "Moore's law" advances in very large-scale integration (VLSI) microelectronics and allowed a quadrupling of transmitted bit rate with only a doubling of chip cost. In addition, because strain could be accommodated in these very thin QW active layers without introducing defects, strain was intentionally incorporated into devices to take advantage of its positive effects on material bandstructure, which led to further reduction in threshold current [24], [25]. And contrary to the lattice matching paradigm of the 1970s, strained QW lasers were found to be very reliable. Later advances in material engineering [short period QW superlattice and 3-D QW (Q-Dot)]



**Fig. 3.** *Milestones in semiconductor laser development illustrating the more than four orders of magnitude reduction in laser threshold current for standard lateral laser designs resulting from material engineering advances (after [10, Fig. 4]). Also shown are the dates of first demonstration of other innovative advances in laser structures.*

contributed to the more than four orders of magnitude reduction in laser threshold current density achieved for today's lasers, shown in Fig. 3 [10].

A second development took advantage of the optical properties of rare-earth-doped fibers, e.g., erbium. Erbium atoms when incorporated into fiber waveguides and optically pumped by a high-power GaAs laser copropagating with longer wavelength signal photons, create a medium in which stimulated recombination results in signal amplification [26], [27]. Erbium-doped fiber amplifiers (EDFAs) have a broad bandwidth ($\sim$80 nm, denoted as EDFA in Fig. 1) and allow link distances to be greatly extended before the need for electronic regeneration, greatly simplifying fiber network design.

A third development created an entirely new photonic capability: photonic integrated circuits (PICs). Taking advantage of low-cost-to-manufacture optical waveguides etched on large area silicon wafers, PICs initially provided a means to photonically interconnect devices and route signals, greatly expanding the options for designers by enabling innovative "silicon optical-bench" approaches to component assembly and packaging [28]. Of particular note is the arrayed waveguide grating (AWG), a PIC version of an optical spectrometer where interference at the common output of an array of different lengths of waveguides results in spatially separating signals according to their wavelength [29]. AWGs find widespread use in today's networks, allowing on-chip routing of signals from an input port to any of multiple output ports based entirely on wavelength.

Other molecular engineering advances achieved during this period, but which did not find immediate applications, include: strained Si:Ge films deposited on

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[4]In 1998, the Physic Nobel Prize was awarded jointly to Robert B. Laughlin, Horst L. Störmer, and Daniel C. Tsui "for their discovery of a new form of quantum fluid with fractionally charged excitations." Tsui and Störmer collaborated on transport measurements of an MBE-prepared GaAs/AlGaAs hetro-interface 2-D electron gas [23]. In 2000, the Prize was awarded "for basic work on information and communication technology" with one half jointly going to Zhores I. Alferov and Herbert Kroemer "for developing semiconductor heterostructures used in high-speed and optoelectronics." The other half was awarded to Jack S. Kilby "for his part in the invention of the integrated circuit."
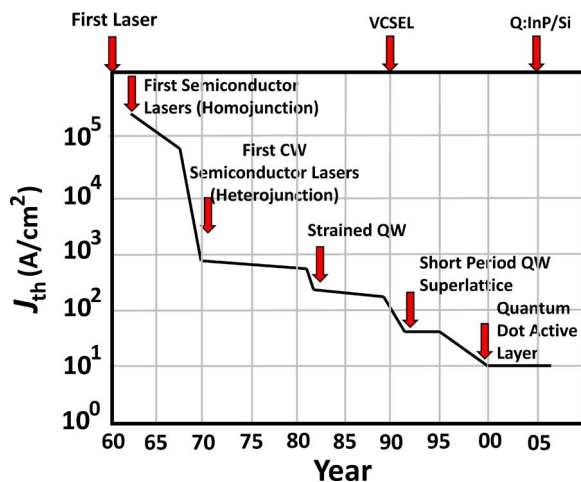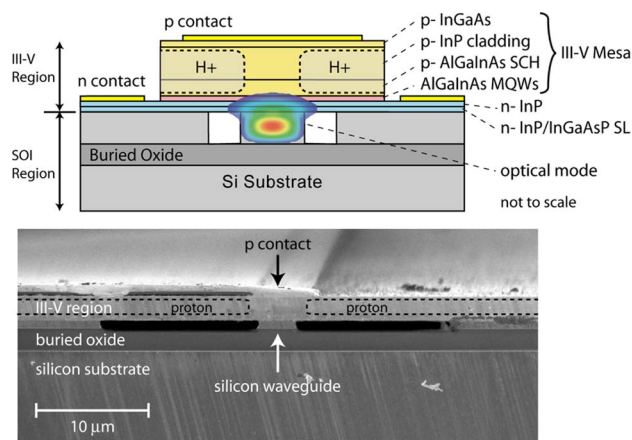
**Fig. 4.** *(a) Schematic of hybrid AlGaInAs:InP–Si laser layer structure with optical mode simulation results superimposed. (b) A scanning electron microscope cross-sectional image of a fabricated Q:InP–Si hybrid evanescent laser. (Courtesy of John Bower and Alex Fong [33].)*

silicon for use as long wavelength detectors compatible with integration with PIC waveguides [30] and techniques for transferring epitaxial films from their growth substrate to other, nominally incompatible substrates, e.g., Q:InP films transferred to silicon PICs to enable hybrid Q:InP–Si lasers (Fig. 4) [31].

Meanwhile, having been rejected for use as optical transmitters for long-haul telecommunication systems, GaAs photonic devices were finding multiple other applications, e.g., laser compact disk and bar-code readers, high-power devices for laser printing and EDFA pump sources, and light-emitting diodes (LED). Largely serving consumer markets, these applications motivated efforts to reduce manufacturing cost so that by the mid-1980s, AlGaAs lasers were available at a cost of under a dollar and visible LEDs at a fraction of this price. These developments demonstrated that the pricing of photonic components could benefit from the same "learning curve" experience associated with other large volume markets, e.g., silicon microelectronics. In contrast, wavelength-controlled devices used in telecommunications systems were more complex to manufacture and produced in much lower volumes at substantially greater cost (∼$1000).

## IV. THE CONVERGENCE OF PHOTONICS TECHNOLOGY FOR COMMUNICATIONS AND COMPUTING

Throughout the decade from 1985 to 1995, the demand for signal bandwidth was largely based on relatively modest voice and data traffic growth. However, the intrinsic high speed of diode lasers and the broadband capacity of optical fiber were widely appreciated for their ability to enable greatly expanded broadband services (video-on-demand, two-way video conferencing, etc.). And, while the details

of today's information age were still only on the dim horizon, the expectation was that future demand for broadband services would revolutionize telecommunications. Fiber was considered to have unlimited bandwidth, suggesting minimum cost to increase transmission capacity using embedded fiber, which led to the expectation that the economic driver for future network provisioning would shift from the cost of transmission plant, historically the major cost driver, to the cost of high-speed switching systems.

Anticipating this shift, photonics researchers began investigating the possibility of using photonics to reduce the cost and enhance the capability of switching systems [32]. The emergence of low-cost consumer photonic devices (liquid crystal displays, GaAs lasers and LEDs, CCD cameras, etc.) that might be reengineered for optical switching applications encouraged this agenda. In particular, a major factor was the expectation that the very fast (femtosecond) dynamics of nonlinear processes in photonic materials could provide the foundation for all optical, high-speed switches. This research agenda even extended to a serious attempt by Bell Labs researchers to develop an all-optical computer [33], [34]. In parallel with these developments, interest in enhancing high-performance computing capabilities through broadband communications emerged within the computer research community as part of the built up (within the United States) to the 1991 High Performance Computing and Communications (HPCC) Initiative.

It is within the context of applying photonics not only to the transport of information but also for short link routing and switching within subsystems that the convergence of the two 21st century information age technologies, communications and computing, was initiated.

## V. DARPA'S ROLE IN THE CONVERGENCE OF COMMUNICATIONS AND COMPUTING

In 1983, the U.S. Defense Department's Advanced Research Projects Agency (DARPA) produced an internal report laying out an ambitious plan to develop computer technologies for machine intelligence.[5] This plan envisioned a range of investments in technologies that included GaAs digital electronics for high-speed signal processing and GaAs-based monolithically integrated electronic and photonic devices to facilitate high-speed, fiber-optic interconnects. The marriage of these technologies was later termed optoelectronic integrated circuits (OEICs) which, unlike passive PICs, were primarily electronic chips with the addition of a few active optical components [37], [38]. Support for OEIC research

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[5]Although this DARPA report was not published, its contents were widely discussed among DARPA contractors and a discussion of its contents and the challenges it represented is contained in [35]. A critical analysis of how subsequent DARPA programs were managed to meet the specific goals outlined in this report is contained in [36].

extended beyond DARPA and included significant European and Japanese efforts [39], [40].

While some very remarkable results were achieved, challenging material requirements created difficulties for OEIC manufacture, which in turn, created a significant hurdle for introduction of photonic links based on this technology as a cost-effective replacement for copper interconnects [41], [42]. These limitations eventually led to failure of early OEIC components in the marketplace. For essentially the same reasons, almost as quickly as the idea for an all-optical computer had arisen, and even with the achievement of a working prototype [43], the difficulties in realizing a practical system led to the demise of interest in this application of photonics.

However, with the military's continuing requirements for high-speed signal processing, DARPA's interest in photonic enhancements in embedded computing systems remained high. The Agency's photonic device investments were largely redirected toward reengineering a key optical switch component employing the electro-optic properties of GaAs QWs that had been developed within the Bell Labs optical computing initiative [44]. The Bell researchers had achieved a high level of performance for these devices and had stimulated considerable interest among DARPA contractors, particularly university researchers. With the demise of all-optical switching as a goal, DARPA began funding research directed at converting this device structure into a low cost-to-manufacture laser that could satisfy a more modest, and hopefully lower cost, optical interconnect between electronic modules. Conversion of the switch into a laser essentially involved improving the switches optical and electrical properties by incorporating highly reflecting layers having low electrical resistance above and below the QW to create a compact laser cavity that could be electrically pumped. With considerable molecular engineering, researchers demonstrated that carriers injected into such a cavity could achieve sufficient optical gain for the switch to become a laser[6] [45], [46]. One unique feature of this laser is that its output beam is emitted orthogonal to the wafer surface, creating a vertical cavity surface-emitting laser (VCSEL).

Among the benefits of the VCSEL design is that once the precision material deposition is completed, the wafer can be processed, tested, and packaged at a cost comparable to LEDs, which by this time were being manufactured in considerable volume and selling for pennies a device. With significant DARPA support, and the benefits of manufacturing "learning curve" experience, VCSELs have become a key factor in photonics for high-performance computing systems. But, today one of their most widespread application is in the optical mouse, perhaps not a computer-to-computer interconnect but one of the most ubiquitous human–computer interface tools.

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[6]For a non-DARPA perspective on the research leading up to the development of GaAs VCSELs, see discussion in [47].

## VI. MATURING OF PHOTONIC TECHNOLOGY—FROM A DARPA PERSPECTIVE

Experience with communications during the First Gulf War (1990–1991) energized the U.S. Department of Defense's interest in emerging broadband capabilities. In response, DARPA expanded its portfolio beyond photonics for digital systems (computing) to include advancing optical network technology (communications). Before the commercial stimulus of World Wide Web (WWW), and at a time when commercial network providers were primarily concerned with the near-term challenges of point-to-point fiber links, the Agency undertook a series of projects having ambitious goals known as DARPA's Broadband Information Technology (BIT) Initiative. BIT's research goals included not only demonstrating transmission capacity far beyond what commercial providers were willing to support at that time, but to also identifying how wavelength-selective elements, e.g., AWG routers and wavelength tunable lasers, could deliver format and protocol transparent, extremely flexible, and rapidly reconfigurable networks. DARPA's BIT program engaged some of the most innovative industry researchers and seeded many of the advanced optical network concepts that are still being investigated today [48].

As the decade of the 1990s progressed, the rapid growth of Internet and web services produced an exponential increase in network bandwidth demand, which, as was envisioned in the original multiwavelength Bell Labs architecture [9], could be most readily met by relatively low-cost expansion of existing point-to-point links through adding wavelengths onto embedded fiber. As the decade came to an end, with link bandwidth enhancement via WDM being deployed in products, commercial interest in DARPA's BIT technologies began to grow [49]. By the end of the decade, venture capital investments in these technologies outstripped all others; and eventually, with investment far exceeding what demand was able to sustain, the market for advanced photonic networking technologies collapsed in the early 2000s [50].

Not being tied to market concerns, DARPA continued its investments in what had become two parallel Agency programs: one aimed at photonics for cost-effective interconnects within computing systems, and the other at demonstrating the benefits of rapid reconfiguration in long-haul networks. In the first case, an initial focus on interconnects between boards in computer backplanes was expanded to eventually address interconnects between chips on circuit boards and ultimately onto the IC chip as well. In 2002, anticipating the outcome of this research, the IEEE SPECTRUM magazine published a feature article titled "Linking with light" (Fig. 5) suggesting that, "having proven their worth in long-distance communications, photonic technologies would soon take on a similar role inside computers" [51]. However, this view was not completely accepted within the community developing computer

**Fig. 5.** *Schematic illustration of optical link evolution in future computer systems discussed in the 2002 IEEE Spectrum article "Linking with light" [51].*

systems; in the same year, the International Solid State Circuits Conference sponsored an Evening Panel Discussion devoted to the question "When will optical interconnects appear on high-performance microprocessors?" The panel unanimously concluded that photonics could not be effective for replacing electrical interconnects for spans below about 0.5 m.

Eight years later (2010), this conclusion has been proven wrong. As a result of increasing demand for high-performance, high-speed interconnections and improvements in photonic component designs, VCSEL optical links are widely in use in computing systems, and other research developments are having significant impact by demonstrating further photonic enhancements to digital system performance [52]. These include: prototypes of hybrid Q: InP-Si lasers and Si:Ge detectors for circuit-board (Fig. 6) and on-chip interconnects, as well as, complex PICs employing deep suboptical wavelength etching to engineer compact, low-loss, wavelength-selective ring-resonator routers for transport and processing of optical signals directly between and on IC chips [53]. These advances are confirming the predictions of the 2002 IEEE Spectrum article and have been widely publicized [54]–[56], including being highlighted in the Special Symposium on Photonics Applications in Supercomputers at the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (Los Angeles, CA, 2011).

## VII. THE FUTURE

Today the volume of customer-generated video network content is matching service provider's delivered content; and together these services continue to drive exponential increases in demand for network bandwidth. It is widely anticipated that demand for single-fiber transmission rates will exceed 10 Tb/s per fiber [57], more than five orders of magnitude greater than state of the art in the first fiber networks (OC-3 at ~155 Mb/s). With available optical
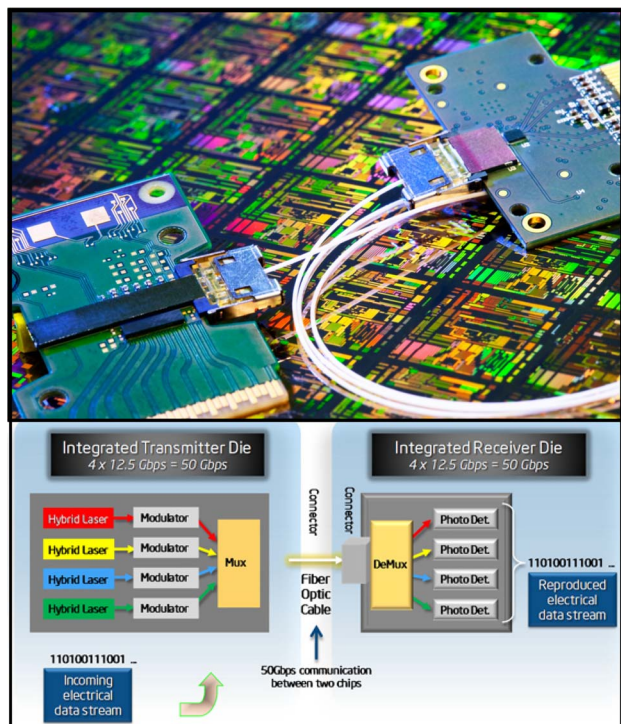
**Fig. 6.** *Intel Corporation's research packaged prototype, silicon-based, integrated Q:InP–Si laser and Strained Ge : SSi detector transmitter and receiver components. These photonic data interconnect OEIC components provide the capability to move data over long distances within computer systems at rates many times faster than today's copper technology; up to 50 Gb of data per second or the equivalent of an entire high-definition (HD) movie being transmitted each second; http://www.intel.com/pressroom/archive/releases/2010/20100727comp_sm.htm. (Courtesy of Mario Panicca [63].)*



**Fig. 7.** *(Top) Data corresponding to the historical evolution of record capacity and spectral efficiency (Bottom) as reflected in "hero experiments" for fiber-optic communication systems. Deployment in fielded systems usually follows a few years after the report of these "hero" results. (Courtesy of R. J. Essiambre [58].)*

amplifier bandwidth saturating, researchers are drawing inspiration from similarly spectrally constrained wireless systems, deploying more sophisticated signal processing schemes to increase fiber capacity (Fig. 7) [58]. Examples include high-speed, postdetection signal processing, forward error correction, and coherent detection to preserve both signal amplitude and phase to achieve multibit per bit capacity. And of course, these schemes benefit from on-chip integration of photonic and electronic components, contributing to the continuing upward slope of the data on system capacity shown in Fig. 8 [59], [60].

Further, the need to rapidly process requests within data centers is generating as much intradata-center, machine-to-machine communication as delivering the requested content to end users. One consequence is that today's data centers are facing a major electrical power challenge; in fact, it is estimated they account for 2%–3% of all the power consumed in the United States and increasing [61]. With the power dissipated transporting information within these systems far exceeding that required for processing, once the electrical-to-optical conversion is made, low-loss optical links and passive wavelength-selective routing
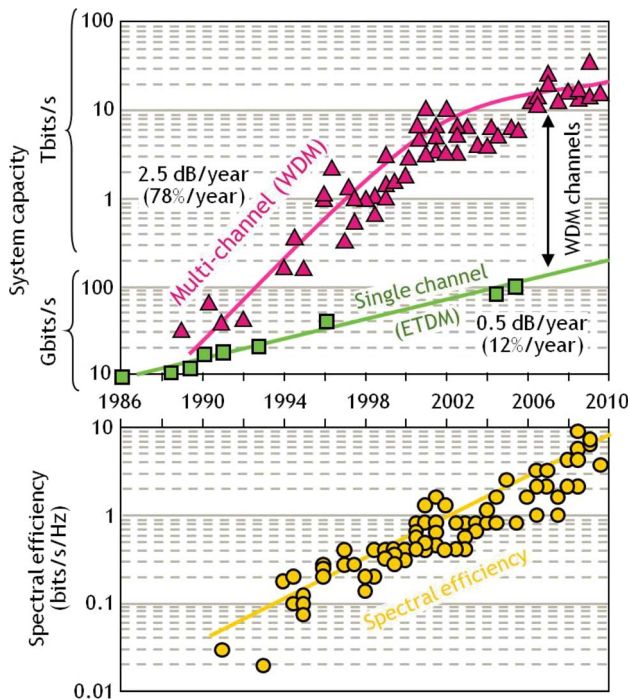
become very attractive low-power alternatives to electrical interconnects [62]. The high initial component cost which has impeded acceptance of photonics in the past may be more than offset by decreased lifetime operational costs.

So after decades of research leading to the demonstration of the performance advantages of photonics for high-speed transport of information, the tipping point for the continued penetration of photonics within high-performance computers and switching systems may be photonics ability to deliver this speed with significantly lower power dissipation. While the acceptance of photonics at the circuit-board and on-chip interconnect level is still an open question, and with many practical hurdles to overcome [63], as the energy requirements for moving information on chip begins to dominate over that required for computation, the same arguments for the energy saving benefits of photonics hold true.

And when deployed, systems that benefit from incorporating photonic technologies at the circuit-board/on-chip level will represent the complete convergence of "telco-like" communication and computing technologies.

## VIII. CONCLUSION

Over the last 50 years, advances in our ability to engineer the photonic and electronic properties of materials to
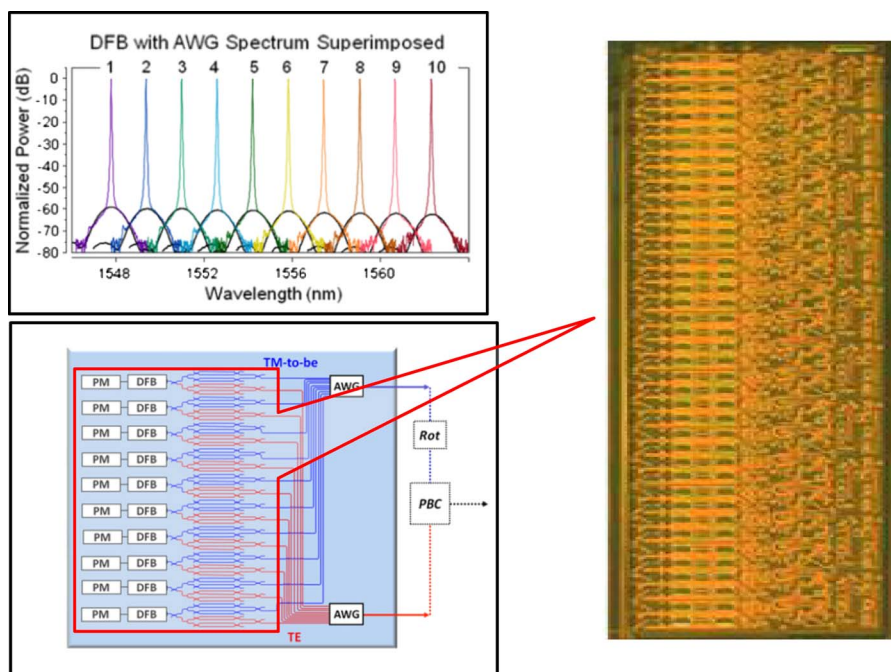
**Fig. 8.** *Infinera Corporation's large-scale InP PIC for high-speed optical transport incorporating ten tunable distributed feedback (DFB) lasers, 20 nested Mach–Zender (MZ) modulators comprising a total of 40 Mach–Zender modulators (MZMs), and the sense and control functions required for operation of the PIC. See also Infinera Corporation's white paper "Photonic integrated circuits; A technology and applications primer" available at http://www.infinera.com. (Courtesy of D. Welch [59], [60].)*

create today's nanoscale photonic device structures meeting exacting system requirements has played a critical role in establishing and enhancing today's information age capabilities. As technologists confront the end of Moore's law scaling, it is interesting to contemplate the ultimate role for photonics in the marriage of communication and computing.

One possibility being considered is to increase transistor density and reduce memory access time by stacking chips with through-wafer metal vias to provide interconnection between them [64]. In such an approach, advances in nanoscale photonic devices may further enhance performance through the incorporation of what might be the ultimate convergence of photonic and electronic technologies: interconnects based on signal propagation via relatively low loss, coupled-electron-photon excitations—*plasmonic interconnects* [65].

And further, with the development of very efficient, compact optical signal processing components, based on the nonlinear photonic switching properties of microresonators, current developments in optical chip and circuit-board signal routing may lead to a resurgence of interest in all-optical, or mostly optical, digital computing [66], [67]. ∎

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