A roadmap for nanophotonics

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Nanophotonics has emerged as an exciting new arena concerned with the interaction of light with nanostructured materials. But if nanophotonics is to maximize its impact on the market and the next generation of technology, those within the field will need to form a cohesive plan.

More than 30 years ago molecular beam epitaxial deposition enabled scientists to produce nanometre-thick layers of semiconductor materials. This advance opened a whole new field of materials and device research based on the idea that one-dimensional superlattices of semiconductor layers would offer useful electronic properties that were not accessible with bulk materials.

Although the promised rewards in electronics have yet to materialize, a marvellous array of quantum optical properties have been discovered and applied in commercial products, such as quantum-well lasers and vertical-cavity surface-emitting lasers (VCSELs). Since then, researchers have produced zero-dimensional quantum dots with even more impressive optical properties in terms of radiative oscillator strength and reliability. The exploitation of optical phenomena on the nanoscale — nanophotonics — is opening up a diverse field of study that promises to deliver novel technological solutions.

Quantum confinement is essentially an electronic effect because it is derived from the squeezing of electronic wavefunctions to dimensions smaller than those dictated by the dielectric medium of the host. By optical analogy, plasmonics uses nano-sized conducting media to confine light in extremely small volumes, at the expense of the accompanying high dissipative loss. This trade off between size and loss favours devices in which the propagation distance is also of nanoscale dimensions.

On the other hand, exploiting a large contrast in refractive index between two materials has enabled the implementation of optical waveguides or 'light pipes' with dimensions given by λ/n_r, where λ is the wavelength of the light and n_r is the refractive index of the material. Photonic crystals make use of nanometre-sized periodic arrays of high- and low-index materials to create an energy-band structure that controls the flow of photons. Devices based on this concept can guide, couple and slow the propagation of light.

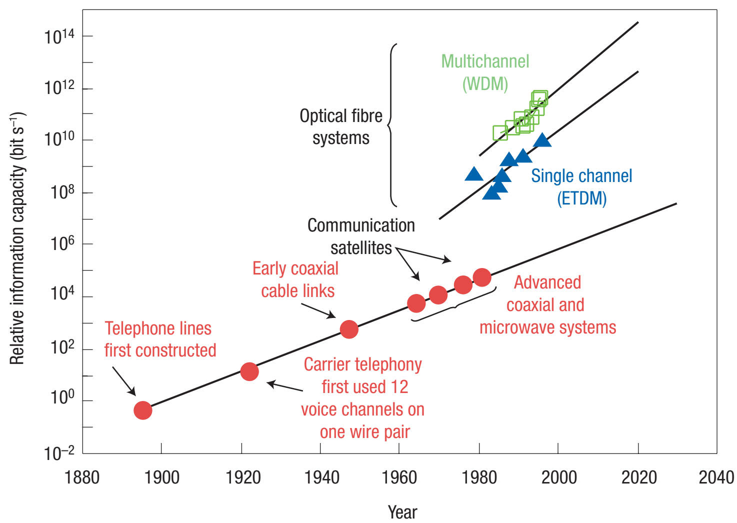

Figure 1 Trend in the information-carrying capacity of a single line (wire or optical fibre) with time and technology. (WDM: wavelength-division multiplexing; ETDM: electronic time-division multiplexing). Reproduced with permission from Kimerling, L. C. *Opt. Photon. News* **9,** 19 (1998). Copyright (1998) OSA.

A NEW PLATFORM FOR THE INFORMATION AGE

The commercial excitement for nanophotonics is based on the perceived advantages of large-scale, monolithic integration of photonic circuits with electronic circuits. The threshold for the commercial displacement of electronic interconnects by optical ones is given by a value for the figure of merit (FOM, given by the product of the distance, x, and the bandwidth) of about 10 Mbit s^{-1} km (Fig. 1.) This value of the FOM heralded the emergence of the fibre-optic platform for telecommunications. But at the level of the integrated electronic chip, the equivalent FOM is on the scale of Tbit s^{-1} cm. Today's signal-processing chips, such as microprocessors, are calling for a Tbit s^{-1} transmission capacity on-chip, and photonic interconnection is being seriously explored as a way to meet this demand. Another advantage of light-based circuits is that they are capable of signal processing by encoding a radiofrequency signal onto a light wave and using dispersive devices to provide time-domain analysis, such as a fast Fourier transform.

Electronic–photonic integration at the chip level will mark the establishment of a second platform for the information age: first, the fibre platform and second, the planar waveguide (called by electronics specialists the 'photonic wire') platform. This new platform will need to be capable of integrating more than a million optical devices per square centimetre into circuits with support electronics, and must offer high-volume manufacturing (>10^7 components or chips per year) at low cost. However, the timetable for the emergence of this optical platform is dictated by the creation of the necessary infrastructure in circuit design, adaptation of CMOS processes to optical devices and the development of new materials. Without doubt, the intellectual and material resources for achieving this will require coordination along the entire technology supply chain. Whereas in most industries coordination occurs through market mechanisms, the microelectronics industry provides a prime example of how coordination can be improved intentionally through an industry technology roadmap.

THE NEED FOR A TECHNOLOGY ROADMAP

It is now half a century since the invention of the transistor and the advent of solid-state electronics. The rate at which integrated circuits (ICs) have both improved in performance and declined in cost has been unparalleled, bringing revolutions not only in computing and telecommunications, but actually catalysing societal change. Nevertheless, micro- or nanophotonics has failed to achieve the ubiquity of its electronic analogue. Why?

What has been crucial to the growth of the electronic microchip (and the accompanying technological and economic changes) has been the existence of an active, comprehensive and influential roadmapping effort involving the electronic IC supply chain. Industrial roadmaps have several benefits, but the one most relevant to IC progress has been the level of coordination between different stakeholders within the supply chain. This has driven efficient allocation of capital and other technological development resources. In the case of ICs, this was achieved through the standardization of materials and manufacturing platforms.

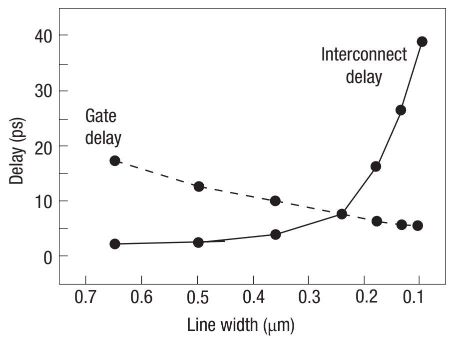

Figure 2 Trends in transistor gate delay (switching time) and interconnect delay (propagation time for an aluminium/silicon dioxide system) with IC fabrication technology. The crossover point represents the start of the 'interconnect bottleneck', where optical technology could have come to the rescue. With copper wires and advanced dielectric materials, the crossover happened at a linewidth of 0.18 μm. Reproduced with permission from Kimerling, L. C. *Opt. Photon. News* **9,** 19 (1998). Copyright (1998) OSA.

Ultimately, this standardization and the attendant supply-chain coordination in electronics have brought two things: first, previously unimagined levels of computational performance and, second, a cost entry point that is low enough to enable the integration of electronics into almost every product market segment imaginable. The latter outcome — market adoption — is clearly an attractive goal for those involved in any technology supply chain, and producers of microphotonic and nanophotonic devices are no exception. However, being able to deliver in terms of performance and cost is not enough to ensure the expansion of the nanophotonics industry and broad uptake of the technology; there must be a market interested in those attributes as well.

ELECTRONIC–PHOTONIC CONVERGENCE

Many within the nanophotonics industry feel that just such a market opportunity has emerged. This is the interconnect bottleneck that has arisen as a natural consequence of device miniaturization. As transistor gate dimensions shrink, designs push the limits of the metal interconnection lines that provide the communication paths between devices, and interconnect performance has become the dominant limit to IC performance. Evidence for this constraint is reflected in the increasing gap between the gate delay (switching speed) of a transistor and the propagation delay between transistors of an integrated circuit (Fig. 2).

Photonics provides an obvious potential solution to this problem. The answer is not to push for the wholesale replacement of electronics by photonics, but rather for the segmentation of tasks to those domains that are most appropriate — a convergence of electronics and photonics. Given the obvious technical challenges to making use of photonics at the micro- or nanoscale (for example, material incompatibilities, lack of design knowledge and the lack of a manufacturing infrastructure), chipmakers have continued to push the incumbent metal-based, electronic technologies. Optical manufacturers would be wise to note that in the era of the dirt-cheap transistor, their technology will only be adopted when it can become as cost effective or can provide benefits other than bandwidth (such as energy savings, reduced electromagnetic interference or a smaller volume footprint). The same rate of change that makes the IC market an attractive one also means that technologies that aim to tap into that market (that is, optical ones) must keep pace or risk being pre-empted.

SETTING STANDARDS

The nanophotonics industry should take a lesson from the very market it wishes to penetrate: coordination across the supply chain, including forms of component and manufacturing standardization, to facilitate high-paced growth. Roadmaps provide a vehicle for such coordination, and various efforts to establish one have begun around the globe. On 25 January of this year, representatives of several major photonics roadmapping projects met at Photonics West in San Jose, California, to identify emerging common themes and goals for nanophotonics. The group included representatives from Japan's Optoelectronic Industry and Technology Development Association (OITDA), Taiwan's National Nano Device Laboratory, Korea's Institute of Science and Technology, the European Photonics Industry Consortium and the MIT Communications Technology Roadmapping Project (of which the authors are co-directors).

On synthesizing the input of these groups, it became clear that a nanophotonics roadmap must address several key issues. First, the technological needs of emerging nanophotonics markets have to be mapped out in detail. Second, a viable, high-volume, low-cost manufacturing platform must be defined. Third, it is crucial to develop a low-cost electronic–photonic integrated packaging solution (that is, the physical manner by which modular electronic and photonic devices communicate to the off-chip world). Finally, the infrastructure needed to design, manufacture and integrate electronic–photonic technology must be developed.

Beyond these high-level goals, several specific technology strategies are also becoming clear. A great deal of time has been spent discussing the candidacy of fibre-to-the-home (FTTH) as the launching point for electronic–photonic convergence. Although FTTH will be an important market for optical devices, the characteristics of that market — most notably, long product life cycles — make it insufficient to support the needed infrastructure for electronic–photonic integration.

Alternative entry points for this electronic–photonic convergence could come from the areas of box-to-box interconnects for server clusters, data-storage area networks and consumer video applications. All of these are sustainable, high-volume markets that sell more than 10 million units per year. At present, the bandwidth-cost target is \$1 per Gbit s^{-1} for approximately 10-metre distances. But as electronic–photonic integration is considered for broader applications, this cost target could drop to \$0.50 per Gbit s^{-1} or less. However, there is no assurance that the technology will be ready for entry into the projected market window beginning in 2012 (as predicted by industry insiders as the window of opportunity for optical interconnect server needs). Only coordinated, large-scale efforts will ensure that this opportunity for microphotonics to make its mark is not lost.

Completely novel opportunities for photonics are also emerging at much shorter distances (approximately one metre). In particular, photonics offers a potentially attractive solution to mobile phones and other portable devices that are incorporating larger, higher-resolution displays and require higher-bandwidth connections to drive those displays. Nevertheless, bandwidth alone is insufficient to explain the appeal of photonics in these markets. Instead, the appeal derives from other characteristics, such as resistance to electromagnetic interference or energy consumption per volume of required space. Delivering on this may create the largest market yet for photonics, but will require a fresh approach to design and production.

Microprocessors will require very large bandwidth communications on-chip as multicore designs reach beyond 16 cores per chip. The associated bus congestion leaves chip designers with few options for optimizing electronic interconnects. Effective optical integration on-chip will have to rely on wavelength-division multiplexing to deliver information capacities per footprint that significantly exceed those of electrical wires, with no power-dissipation penalty. Looking into the future, this sort of architecture would be realized with an off-chip, multiwavelength optical power supply that provides photons in the same way that an electrical power supply delivers electrical current.

Irrespective of market, packaging remains a critical obstacle in the path to widespread adoption of microphotonic- or nanophotonic-based devices. With packages representing more than 80% of the delivered cost of a device, it is not possible for photonic solutions to compete broadly. Ultimately, a board-mountable chip package and system with electrical and optical input/output without fibre attach is essential.

Furthermore, the infrastructure needed to deliver nanophotonics technology to market is lacking. Optical-circuit design must evolve to a higher level of abstraction so that designs can move beyond discrete, serial links. Unified electronic–photonic circuit design simulators are required. On the manufacturing front, issues of process integration and materials standardization will have to be solved simultaneously, through pioneering facilities that confront both the fabrication and the operational challenges facing electronic–photonic convergence.

NEXT STEPS

Photonic technologies have already revolutionized communications and have the potential to do the same for the fields of imaging, sensing and computing applications. Realizing this potential requires a healthy nanophotonics components industry. However, the market and technology barriers to this health are, at this time, significant. Achieving sustainable product standards, reducing cost through integration, converging electronic and photonic technologies and adopting a common industry infrastructure for technology research, development and production represent a set of tasks too great for any one firm. In the end, events like those held at Photonics West this year hold great promise. Through cooperation that crosses institutional as well as national boundaries, we can create both revolutionary nanophotonics products and a sustainable industry.