

Photonics to save energy and increase density in information processing

David A. B. Miller

*Ginzton Laboratory, Spilker Building, 348 Via Pueblo Mall, Stanford CA 94305
dabm@stanford.edu*

Abstract: We argue we can substantially reduce energy dissipation and increase interconnect bandwidth density using parallel synchronous free-space optical channels inside and between racks, exploiting integrated waveguide photonics, and avoiding power-hungry time-multiplexing. © 2020 D. A. B. Miller

Energy dissipation in information processing and communications consumes ~10% of all electricity [1]. Unless we reduce the energy per bit, continued exponential scaling of our use of information cannot continue. Much or even most of this energy is for interconnects inside machines. At the same time, we have difficulty communicating large enough amounts of information inside systems. A key goal is to reduce from the many pJ/bit energies of current optical approaches to ~ 10 fJ/bit or lower total system energy for interconnects; such a reduction could transform information processing and switching systems. Optics can be the solution to both these energy and density problems, but to achieve both at once will require that we change our approach [1].

Though not currently implemented in silicon photonics, optoelectronic output devices are possible with <10 fJ/bit operating energies and without the need for resonators; Ge quantum well modulators grown on silicon (see discussion in [1]) could provide such performance, for example. At the receiving end, low-capacitance photodetectors integrated within a few microns of electronic input circuits could eliminate most receiver energies by avoiding the need for low-noise voltage amplification. Approaches such as these could eliminate much of the energy in the physical process of sending and receiving information, consistent with a ~ 10fJ/bit total energy goal.

Current approaches inside large systems already use optics, in fibers. But the need to put more information on each fiber leads to high power dissipation because of the energy cost of time-multiplexing. Achieving communications energy below ~ 1 pJ per bit becomes very hard in conventional time-multiplexed communications because of the energies in high-speed receivers and transmitters, time-multiplexing circuits, and clock and data recovery circuits, each of which can consume pJ's per bit.

Most of the interconnect energy in systems is likely at short distances, from the edge of the chip outwards, and is likely "inside the box". Fortunately, there is a system approach that could retain high density of communication while eliminating the pJ/bit circuit energies of current approaches. The key is to eliminate time-multiplexing for such interconnections. Wavelength multiplexing would be one approach, but very large numbers of different wavelengths (e.g., > 100) could be difficult to exploit controllably. The other degree of freedom available in optics is space. In free space, we can routinely exploit thousands to even millions of channels in imaging optics. If we were to image such large numbers of optical connections in two-dimensional arrays on and off chips, and even between boards and racks, then we could achieve the necessary densities of connections while completely eliminating the need for time-multiplexing and its associated energies [1].

Hence, with some technology development to implement known approaches such as Ge quantum well modulators and low-capacitance integrated photodetectors, together with some free-space optical systems, then we could approach the 10fJ/bit number. Such free-space optics does not have to challenge the basic laws of physics to achieve sufficient numbers of connections, and the basics of the necessary optical technology itself have been available for some decades. We also now have a deep understanding of the numbers of available channels in optical systems and how we might approach exploiting them [2][3].

Fig. 1 sketches a "straw-man" scheme for such optical systems [1]. A key step is the creation of a hybridized "photonics" layer on top of silicon chips. Such a layer could incorporate the necessary modulators, waveguides and couplers for such free-space systems, together with more conventional connections also to fibers, and detectors could be on the "transistor" layer as shown, or in hybridized photonics layer.

Further details will be presented in the talk.

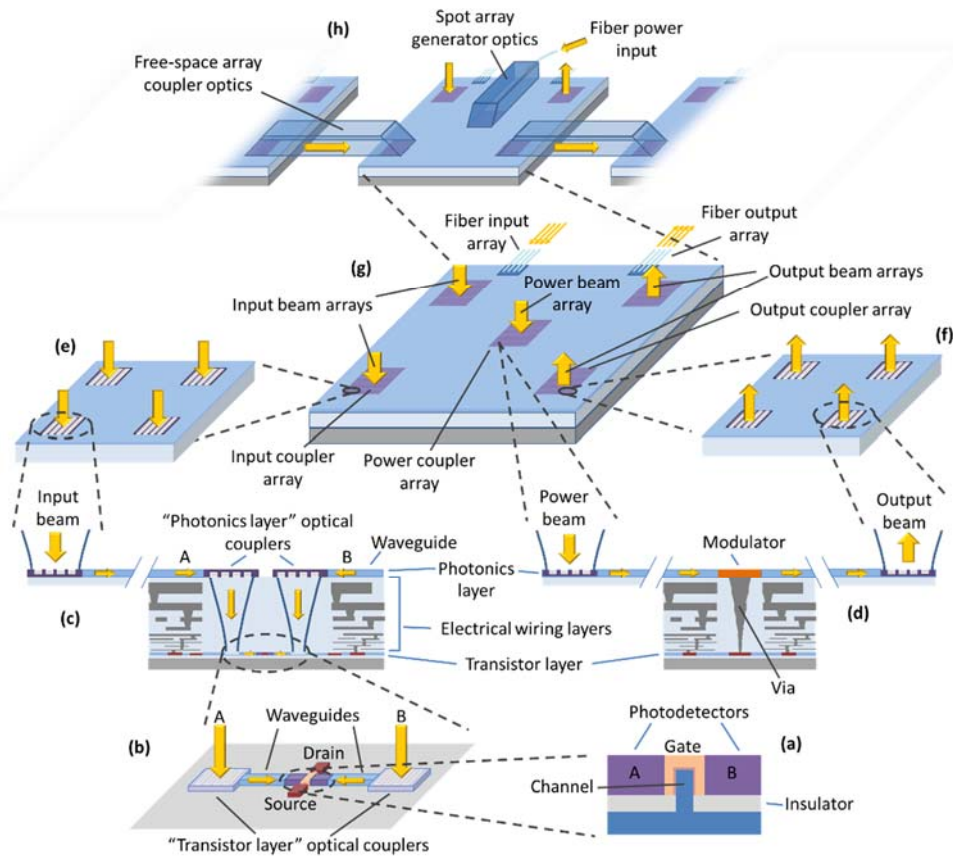


Fig. 1. Sketch of an optical platform for dense, low-energy interconnects, shown at multiple different length scales, from the transistors up to free-space arrays off a larger chip [1] (copyright IEEE, used with permission). (a) A pair of photodetectors is integrated beside the gate of the corresponding transistor input (here shown in the form of a FinFET structure). (b) Optical beams *A* and *B* are connected through “transistor-layer” couplers and short (e.g., $\sim 1\mu\text{m}$) waveguides to the photodetectors. (c) A photonics layer (e.g., as in silicon photonics) on top of the electrical wiring layers of the chip, with couplers between free space and waveguides in the photonics layer, and also from the photonics layer to detectors below. (d) Electrical “via” connections through the electrical wiring layer connect from output transistors to modulators in waveguides in the photonics layer. (e) and (f) show portions of input and output couplers and beam arrays. (g) shows a larger picture of the photonics layer on top of the entire chip, with various 2D coupler arrays: input and array coupler and beam arrays; a power array coupler and beam array; and linear arrays of fiber inputs and outputs. (h) shows spot array generator optics fed by input power from some central optical power source through a fiber, and how multiple chips might be connected laterally and vertically using free-space connections.

[1] D. A. B. Miller, “Attojoule Optoelectronics for Low-Energy Information Processing and Communications: A Tutorial Review,” *IEEE/OSA J. Lightwave Technology* **35** (3), 343-393 (2017) doi: 10.1109/JLT.2017.2647779

[2] D. A. B. Miller, “Waves, modes, communications, and optics: a tutorial,” *Adv. Opt. Photon.* **11**, 679-825 (2019) doi: 10.1364/AOP.11.000679

[3] J. M. Kahn and D. A. B. Miller, “Communications expands its space,” *Nature Photonics* **11**, 5 – 8 (2017) doi:10.1038/nphoton.2016.256