Optics for low-energy communication inside digital processors: quantum detectors, sources, and modulators as efficient impedance converters

D. A. B. Miller

AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

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I argue that optics can reduce the energy for irreversible communication of logic-level signals inside digital switching and processing machines. This is because quantum detectors, quantum sources, and modulators can perform an effective impedance transformation that matches the high impedances of small devices to the low impedances encountered in electromagnetic propagation. Current physics and device concepts are sufficient to realize this advantage over electrical communications given appropriate integration technology. This energy argument suggests that all except the shortest intrachip communications should be optical.

There is considerable debate as to the potential of optical or optoelectronic devices compared with electronic devices for use in computing and information-processing machines. Here I point out one feature of optics not yet stressed: that optical detectors, sources, and modulators can operate as efficient impedance transformers, which allows lower energy for communication of information than is commonly obtained using transmission lines within electronic digital systems. For detectors and sources, this impedance transformation results directly from the quantum nature of the physical processes, and it is this quantum nature (rather than the nature of beam propagation) that distinguishes this as a feature of optics. With recent developments in efficient optical devices, this theoretical advantage may be realizable in practice.

Fundamental energy limits for optical and electronic digital logic devices have been computed.[1-3] Although optical-device energies continue to improve (e.g., self-electro-optic-effect devices[4]), optics cannot readily be justified on logic-device switching energies alone. However, much of the energy and area in electronic chips is for communication *between* logic devices.[2,5] Optics is known to be an interesting engineering solution to some such communications problems.[6,7] In this Letter I compare the energies required to communicate information electronically and optically from a relatively fundamental viewpoint. The advantages that emerge are in addition to other potential advantages of optics, such as high bandwidth, two-dimensional parallelism,[8] and ground-loop isolation.

I consider the irreversible communication of a logic-level voltage from one (electronic) device to another. All energy involved in irreversible communication is deliberately dissipated to avoid backcoupling through the system (as, e.g., in the proper termination of transmission lines to prevent reflections); this is the usual case in current logic systems (although in theory no such dissipation is required in hypothetical reversible systems[9]). For reasons of thermal fluctuations (especially at room temperature) and switching threshold uniformity, the logic-level voltage is $V_0 \sim 1$ V in most semiconductor devices.[2]

There are two extreme types of electrical transmission line: resistive and lossless. In the resistive line (as in most connections within integrated circuits), the line capacitance, C, is charged through the line resistance, and the total energy required is at least

$$E_R = CV_0^2, \tag{1}$$

corresponding to $(1/2)CV_0^2$ for the energy stored in the charged capacitor and the same for the dissipation in the resistor during charging. In the lossless case, which is the goal for most longer-distance communications, the propagation is electromagnetic and essentially at the velocity of light (e.g., as in a coaxial line). For a voltage pulse of duration τ in a transverse-electromagnetic mode (TEM) in a properly terminated line of characteristic impedance $Z = Z_0/\eta$ (where $Z_0 = 377\ \Omega$ is the free-space impedance), the energy required is

$$E_{LL} = \eta V_0^2 \tau / Z_0. \tag{2}$$

It is easily shown that $E_{LL} = CV_0^2$ also, where C is the capacitance of the length l of the line charged at any one time by the pulse, corresponding now to $(1/2)CV_0^2$ for each of the stored electric and magnetic energies (since those are equal for TEM propagation). [Such pulse propagation is optimistic since synchronous digital machines often charge the entire line length to avoid timing problems associated with different line lengths (clock skew).]

These energies are, however, often very much larger (e.g., 20 pJ for a 1-V, 1-nsec pulse in a 50-Ω line or 1 V in a fully charged 300-mm line) than the switching energy of a small logic device (e.g., ≪1 pJ). Unfortunately, we cannot practically make either high-impedance lines or lines with low capacitance per unit length to lower these energies; to do so would require extreme geometries. For example, a coaxial line with inner conductor radius r_1 and outer conductor radius r_2 has

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impedance $Z = (Z_0/2\pi\sqrt{\epsilon_r})\ln(r_2/r_1)$ and has capacitance per unit length of $(2\pi\epsilon_r\epsilon_0)/\ln(r_2/r_1)$, where ϵ_r is the relative dielectric constant. This logarithmic scaling is typical for conductors separated by more than the size of one conductor. Free-space propagation of beams with appropriate focusing optics does not solve the problem either, since we still have $E_{LL} \sim V_0^2\tau/Z_0$, where V_0 is the classical (root-mean-square) voltage between one side of the (linearly polarized) beam and the other side, independent of beam size.

We can restate this as an impedance-matching or voltage-transforming problem: small devices carry small currents and are therefore essentially high-impedance (and low-capacitance) devices, both for outputs and inputs, but electrical transmission is unavoidably low impedance (or high capacitance per unit length). Unfortunately, there does not seem to be a currently practical way of making classical inductive transformers sufficiently small and efficient to match the propagation to individual small electronic devices, nor am I aware of any such demonstration even in the laboratory. Note that all the energy transiently stored in electric and magnetic fields in the transformer is dissipated in our irreversible communications.

A solution is to use optical modulators or quantum sources, and quantum detectors, as impedance transformers. One such transformation mechanism is easily understood by example with a photovoltaic semiconductor photodiode. We know that, for a good photodiode operating into, say, a 1-MΩ load, we can generate an output voltage $V \sim 1$ V even at low light powers (e.g., 2 μW). But Eq. (2) tells us that to generate a (root-mean-square) voltage V_0 of 1 V from one side of the beam to the other side requires a power $P = E_{LL}/\tau = \eta V_0^2/Z_0 \sim 2.7$ mW for $\eta \sim 1$. However, although the voltage between one side of the beam and the other side is ~27 mV for our 2-μW beam, we can generate ~1 V with a current of ~1 μA for a typical photodetector, corresponding to a reasonable energy efficiency. This transformation results because the photodiode is a quantum detector for which the classical field or voltage is irrelevant and indeed need not even be well defined (as, e.g., in squeezed states[10]). The relation is now between electrical charge and number of photons, i.e., between current and power; once we choose the load resistor, the effective impedance transformation is defined.

The minimum incident optical energy E_L required to generate a voltage change V_0 on a photodetector of quantum efficiency β and capacitance C_D by discharging C_D with the photogenerated charge is

$$E_L = \frac{\hbar\omega V_0 C_D}{\beta e}, \quad (3)$$

where e is the electronic charge and $\hbar\omega$ is the photon energy. (This is a static result, but the dynamic result, where the diode is loaded with resistance R and is driven by a light pulse of length τ, is similar as long as $RC_D \gtrsim \tau$. We might wish to use a somewhat larger energy in this case to allow settling of the system for several time constants, as in typical electronic systems.) $\beta \sim 1$ is feasible, especially for reverse-biased diodes. Photodiode capacitance comparable with the logic-device input capacitance is also feasible at least for micrometer-sized and larger devices, provided that the photodiode is integrated close to the logic device using the same fabrication technology.

Such a quantum impedance transformation can also operate in an optical emitter; an ideal simple quantum emitter will emit one photon per excited electron, with a drive voltage of $\sim\hbar\omega/e$. Note that (1) for optics compatible with arrays of devices, the light must be nearly diffraction limited to allow efficient coupling into a small detectors and (2) the emitter must operate efficiently at low energy. The practical solution for diffraction-limited performance is to use a laser. Unfortunately, it is difficult to make a laser efficient at low energy. A good laser diode running at 2 V and 10 mA may be reasonably efficient, generating many milliwatts of light, but it will consume 20 pJ in 1 nsec, which is identical to the dissipation for a 1-V, 1-nsec pulse in a 50-Ω line. These basic energy arguments are well known[11] and explain why laser diodes have not been attractive logic devices in large or complex systems. Low-threshold laser diodes are now feasible,[12] and there is no fundamental problem in reducing thresholds further given smaller gain volumes and higher reflectivity cavities, although practical problems remain for integration with electronics.

An approach that avoids low-energy emitters is to use modulators. We may use one external, efficient, powerful laser and optically split the beam to give many low-power diffraction-limited beams for our modulators. Historically, optics has not had a sufficiently low-energy modulator, although practical technologies do exist, such as lithium niobate or semiconductor electro-optic waveguides, for modulators that are competitive with direct modulation of laser diodes.[13] As with laser diodes, such modulators could be designed in principle for low-energy operation, and they also can transform impedance because (electrical) voltage controls the (optical) power.

Quantum-confined Stark effect[14] (QCSE) electroabsorption modulators, which contain quantum wells in a diode structure, are another option and can be used as an existence proof that modulators are possible with similar energy–size scaling to that of photodiodes. At certain wavelengths, the optical transmission can be changed significantly (e.g., by a factor of 2) by reverse biasing with moderate voltages (e.g., 5 V for a 1-μm-thick quantum-well region). For every photon absorbed, typically one electron of current must flow, because this device is also a photodiode, giving an effective impedance transformation similar to that of photodiode detectors. This device is therefore efficient even at low powers, just like the photodiode detector.

For QCSE modulators, there are two energies involved: the energy required to charge the capacitance of the device, CV^2 (~3 fJ/μm^2, scaling with area, for a device running at 5 V with 1-μm thickness of quantum wells), and the energy dissipation associated with the photocurrent (~5/1.5 times the optical energy to be absorbed for a 5-V device at 1.5-eV photon energy). Lower-voltage (e.g., 1-V) designs are possible (e.g., using waveguides). Importantly, QCSE modulators can be integrated with electronic components and op-

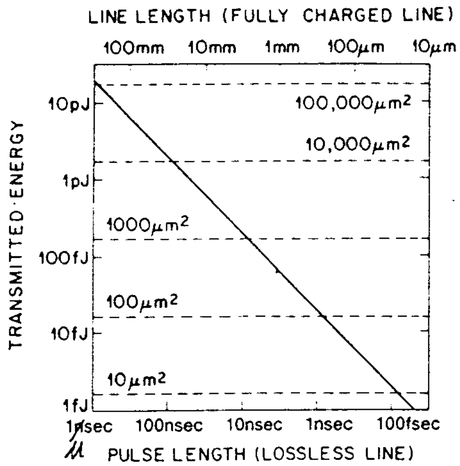

Fig. 1. Comparison of optical and electrical communication energies. Solid line, electrical energies; dashed lines, optical energies. In both cases, 1 V is assumed to be generated in the receiving device. The energy calculated is the minimum energy that must be launched into the transmission medium to achieve the desired voltage at the receiver. For the optical case, I assume unit quantum efficiency (one photoelectron per incident photon) with a photon energy of 1.5 eV (corresponding to a wavelength of ~830 nm) and a depletion layer thickness of 1 μm, with a dielectric constant of 13. The top scale is the length of line (either lossless or resistive) that can be fully charged with the energy given (assuming capacitance per unit length of 67 pF/m, the same as that of a 50-Ω lossless air-spaced coaxial line). The bottom scale is the maximum duration allowed in a lossless line for a square 1-V pulse with the energy given.

tical detectors with standard fabrication techniques. In fact, the combination of optical detectors and quantum-well modulators is the principle of the self-electro-optic-effect device; integrated devices have already been demonstrated.[15]

Figure 1 compares the energy that must be transmitted for the optical and electrical cases. Here I have used Eq. (1) to calculate the energy for the resistive line, Eq. (2) for the lossless line, and Eq. (3) for the optical case. In Fig. 1 some arbitrary assumptions have been made. Lines could be made with impedance somewhat larger than 50 Ω. On the other hand, 67-pF/m line capacitance is probably optimistically low for practical resistive lines. Electrical energies do become relatively more favorable for lower-voltage operation because they vary with the square of the voltage. On the other hand, the areas for optical detectors chosen for Fig. 1 range from those of relatively large discrete detectors down to an area representative of a small integrated detector and do not approach the limiting detector sizes optically possible (e.g., of the order of one square wavelength). If we chose to use nonwaveguide QCSE modulators so that we could communicate arrays of light beams perpendicular to the chip surface, the actual drive energy for the optical case with modulator size equal to detector size, using current 5-V QCSE modulators, would be about one order of magnitude larger than the optical energies shown in Fig. 1 because of the high drive voltage.

We could argue for changes in the precise numbers in Fig. 1. However, Fig. 1 is presented on logarithmic scales, and details related to factors of the order of unity do not alter the basic conclusions: (1) small optical devices offer lower communication energies than fully charged lines for all except short distances, such as those between nearby devices on a chip, and (2) pulses propagating on ideal lossless lines offer energies comparable with those of small optical devices only for short pulses. Interestingly, conclusion (1) is identical to that of Ref. 7, which was made based on a more specific engineering analysis. Note that these conclusions are not changed even for perfectly lossless (e.g., superconducting) electrical lines.

In conclusion, optical detectors, sources, and modulators can be efficient effective impedance transformers that allow irreversible communication of logic levels directly out of and into small logic devices. Optics may thus enable us to reduce the total operating energy of a digital system and reduce the physical size of chips by removing large driver devices. These energy arguments suggest that, to minimize energy, all except the shortest-distance communications within chips should be done optically. This therefore gives a strong physical argument for optics for communications-intensive digital processing.

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