# Are optical transistors the logical next step?

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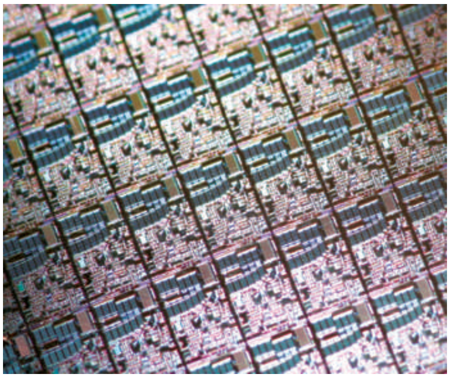
A transistor that operates with photons rather than electrons is often heralded as the next step in information processing, but optical technology must first prove itself to be a viable solution in many different respects.

The idea of an optical transistor — and the associated optical logic circuits that may follow — conjures images of light controlling light in some sparkling, transparent computer. This dream resurfaces on a regular basis as new optical and optoelectronic technologies become available[1,2]. We should, however, not be naive about what it takes to make an optical transistor useful. If we seriously want logic with light, then our devices must satisfy several qualitative criteria (Box 1)[3]. So far, nearly all proposals for optical logic fail on most of these criteria. Consequently, we should judge claims of 'optical transistors' quite critically. Only one device[4] has apparently ever satisfied these qualitative criteria well enough to allow large logic systems to be constructed[5].

Even if an optical transistor design meets these qualitative requirements, it would also need sufficient quantitative performance. The dominant physical quantity limiting information processing today is energy[6]: power dissipation limits the performance of silicon chips, battery life restricts mobile electronics, and power sourcing and heat sinking constrain large systems such as network switches or server farms. The overall energy consumption of information processing and communications is also becoming environmentally significant; the fraction of US electrical power consumed by data centres alone was estimated to be ~1.5% in 2006[7], which will rise by a factor of two by 2011 if historical trends continue. In another estimate[8], this industry was responsible for ~2% of global $CO_2$ emissions in 2007, a figure equivalent to that of aviation. We cannot therefore reasonably propose the use of optical logic for any mainstream application if it consumes more energy than silicon transistors. The total energy per logic




The electronic transistor has enabled the creation of integrated circuits with remarkable density and functionality. It is not yet clear whether optical technology will achieve the same success.

operation is at the femtojoule level, even for current silicon CMOS devices[9]. Future devices may require operational energies as small as tens of attojoules[9] — these are demanding targets for an optical device to reach, particularly because they represent the total energy for logic operation, not just the input signal energy.

Many different approaches to optical transistors have been proposed. Much early work was based on optical bistability[10] using nonlinear optical phenomena, mostly in resonators. Some methods use laser gain[11], and other recent work on the optically controlled switching of light exploits single molecules[2], quantum dots[12] or atomic systems[13]. Optoelectronic approaches integrating detectors and modulators allow sophisticated functionality[4].

Often, proposals for optical switching emphasize high speed as their main advantage, and they may indeed operate faster than silicon transistors[1,14]. Note, however, that current CMOS transistors have internal speeds in the picosecond range[9], with future projections in the range of 100 fs (ref. 9). In addition, it is the need to limit power dissipation that largely constrains clock rates in current electronic devices — lower operating voltages give slower speeds but correspondingly lower energies per operation.

It is sometimes argued that optical logic is a natural choice for schemes that process signals already in the form of light, such as telecommunications systems. In justifying higher optical logic energies, it is common to argue that the energy cost of converting data from the optical to electronic domain and back is inherently high[14]. Such conversion estimates, however, are often based on data from current commercial systems, instead of on the fundamental physics of such conversions or what could be achieved in a properly designed and intimately integrated approach. This telecommunications application is the subject of carefully argued and active debate in the field[14–16].

Given these many arguments against optically controlled optical switches, why would we even consider them? One reason is that light beams have already proved themselves to be better than wires for low-loss transmission at very high data rates. It is much easier for optical technology to compete with copper transmission lines rather than silicon devices[6,17]; indeed, this realization was a key outcome of earlier optical logic research[4,5].

As data rates continue to rise, optical communication is steadily progressing from long-distance telecommunications to ever shorter distance interconnects. The arguments for optical wiring are understood even down to chip-level[6], but chip-scale optical interconnect technology is still in its infancy.

The first major benefit of optical connections is the much higher densities of information possible in relatively long connections; this density improvement has already led to optical interconnects at the cabinet-to-cabinet level. A second benefit — not yet substantially exploited — is that optics could reduce the energy required for communication. In optical lines there is no need to charge the line to the signal voltage; essentially, we only need to transmit enough energy to charge the photodetector at the receiving end. This benefit, sometimes called quantum impedance conversion[17], follows from the photoelectric effect and can essentially remove the distance-dependence of interconnect energy. This possible reduction in energy could be very important; the energy spent on chip interconnects is now at least as large as that spent on logic and is expected to increase in future years[6].

One consideration about transistor logic not widely appreciated is that the interconnect energy problem persists down to the level of individual gates. The capacitance of an interconnect line whose length is the size of just one logic gate already exceeds the capacitance of the transistors in the gate[9], a fact that will probably remain true for future CMOS logic. All of these capacitances must swing by a logic-level voltage as the gate is operated. The energy dissipation in switching the gate itself is largely the energy to charge these capacitances. The interconnect energy therefore already dominates over the logic energy even for connections from gate to gate, let alone any longer connections. This energy problem creates a possible opening for an optical logic approach — particularly for gates connected over long distances — because the optics does not need to charge lines to the signal voltage. The possible advantages of the optical transistor are in its superior ability to connect and communicate information, not so much in the logic itself[18]. The possibilities of optical logic, however, represent significant challenges. Future transistors will have capacitances of tens of attofarads[9], and will therefore have energies of tens of attojoules for ~1V operation. Such energies correspond to only hundreds of photons, and hence we will have to make optical devices that are efficient at such levels. This may be possible using a nanoresonator device[13], or with a very small nanometallic antenna[18] or waveguide[19]. We could also use an active semiconductor element of ~100 nm or less, or even a single quantum dot[12]. The idea of the controlled fabrication and use of quantum dots for optical transistors is still speculative, but note that proposed future transistor gates are at the ~10 nm scale[9], so we may well be able to manufacture using such quantum structures.

One important point is that the hypothetical 'all-optical' device discussed above does not have to operate coherently with the light fields; indeed, such coherent interference is mostly a nuisance in

## Box 1 | Criteria for practical optical logic.

The electronic transistor and the logic gates based on it have qualitative features that are crucial for systems of any complexity, but very few optical transistors or logic devices possess them[3]. In addition to basic complete logic functionality such as NOR or NAND gates, the first four requirements below are essential for any logic device[20].

**Cascadability.** The output of one stage must be in the correct form to drive the input of the next stage. In optics, the output and input wavelengths, beam shapes and pulse shapes should be compatible.

**Fan-out.** The output of one stage must be sufficient to drive the inputs of at least two subsequent stages (fan-out or signal gain of at least two). Stimulated emission gain is not required, however — it is sufficient that small input power changes result in larger output power changes.

**Logic-level restoration.** The quality of the logic signal is restored so that degradations in signal quality do not propagate through the system; that is, the signal is 'cleaned up' at each stage (Fig. B1a). For optics, we must consider restoring beam quality and/or pulse quality as well as signal-level ranges.

**Input/output isolation.** We do not want signals reflected back into the output to behave as if they were input signals, as this makes system design very difficult. Transistors provide this isolation, but the microscopic physics of nonlinear optical processes and stimulated emission typically does not. Ideally, we want a device with separate input and output beams (Fig. B1b).

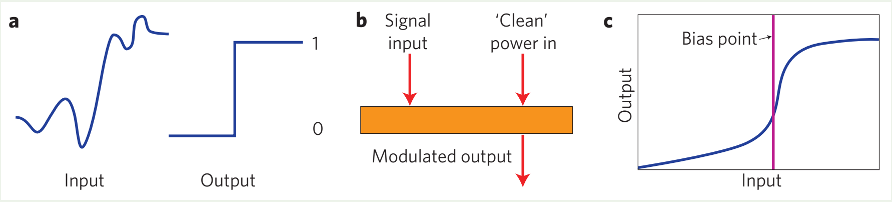



**Figure B1 |** Criteria for a practical optical transistor and optical logic. **a**, Logic-level restoration. The transistor must 'clean up' any degradations in signal quality. **b**, An optical transistor is required to have separate inputs and outputs. **c**, Critical biasing, showing signal gain around a bias point.

**Absence of critical biasing.** We do not want to have to set the operating point of each device to a high level of precision. A device with the input/output characteristic of Fig. B1c has signal gain around a bias point and also gives some logic-level restoration, but requires the bias point to be set very precisely. This device probably also lacks input/output isolation. Devices relying on coherent interference of light beams are also likely to require very precise setting of distances to hold relative phases.

**Logic level independent of loss.** The logic level represented in a signal should not depend on transmission loss, as this loss can vary for different paths in a system. For voltage logic levels in electrical lines, we may have to wait for the input capacitance of the receiving transistor to charge through the line resistance, but the logic voltage is essentially unaffected by resistive loss. In optics, however, beam power is obviously affected by loss. Hence, a simple power threshold cannot reliably distinguish between '0' and '1' unless we push the threshold close to zero, which requires a very large dynamic range in signal modulation and detection. Differential signalling (using the ratio or difference in two different powers to carry the logic signal) can solve this problem, but few optical processes or devices[4] can operate with such inputs.

logic systems. Furthermore, a device at the ~100-photon level could still operate in a quasi-classical fashion[13] where optical or quantum coherence is neither necessary nor even desirable. Hybrid devices such as photodetectors and modulators integrated very closely with transistors are also quite attractive as they may satisfy all the necessary criteria (Box 1).

Even more speculatively, we can imagine optical transistors that operate with single photons, and demonstrations of possible schemes of operation have already been made[12]. Such devices could allow truly quantum operations, including quantum logic and information processing. However, engineering a system that tackles the practical difficulties introduced by coherence and reversibility remains a major challenge. Nevertheless, optical approaches may well be essential for operation with single quanta.

Undoubtedly, realizing optical devices that meet the requirements outlined here is a significant challenge, and a clear concept that meets all the qualitative and quantitative demands discussed above is yet to be presented. However, emerging nanotechnologies such as nanoresonators, plasmonics and nanometallics, quantum dots and even single molecules open a truly exciting and still largely unexplored range of possibilities for research into optical transistors. Some of these approaches may also be compatible with silicon technology; such compatibility improves the possibility of mass-manufacture and promises the option of a hybrid optical/electronic technology to exploit the best of both worlds. We would be pessimists indeed not to believe these opportunities will somehow transform information processing, but we will need to be both realistic and creative to get there. ❐

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## References

1. Nazarathy, M. *et al. J. Opt. Soc. Am. A* **26**, A21–A39 (2009).
2. Hwang, J. *et al. Nature* **460,** 76–80 (2009).
3. Miller, D. A. B. in *SPIE Critical Reviews of Optical Science and Technology* Vol. CR35 (ed. Athale, R. A.) 68–76 (SPIE, 1990).
4. Lentine, A. L. *et al. IEEE J. Quant. Electron.* **25,** 1928–1936 (1989).
5. McCormick, F. B. *et al. Appl. Opt.* **32,** 5153–5171 (1993).
6. Miller, D. *Proc. IEEE* **97,** 1166–1185 (2009).
7. http://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Datacenter_Report_Congress_Final1.pdf
8. http://www.gartner.com/it/page.jsp?id=503867
9. http://www.itrs.net/Links/2008ITRS/Home2008.htm
10. Gibbs, H. M. *Controlling Light with Light* (Academic Press, 1985).
11. Oksanen, J. & Tulkki, J. *J. Lightwave Technol.* **24,** 4918–4924 (2006).
12. Fushman, I. *et al. Science* **320,** 769–772 (2008).
13. Mabuchi, H. *Phys. Rev. A* **80,** 045802 (2009).
14. Dorren, H. J., Calabretta, N. & Raz, O. *J. Opt. Netw.* **7,** 936–946 (2008).
15. Hinton, K., Raskutti, G., Farrell, P. M. & Tucker, R. S. *IEEE J. Sel. Top. Quant. Electron.* **14,** 938–945 (2008).
16. Tucker, R. S. *Opt. Switch. Netw.* **5,** 2–9 (2008).
17. Miller, D. A. B. *Int. J. Optoelectron.* **11,** 155–168 (1997).
18. Tang, L. *et al. Nature Photon.* **2,** 226–229 (2008).
19. Ly-Gagnon, D. S., Kocabas, S. E., Miller, D. *IEEE J. Sel. Top. Quant. Electron.* **14,** 1473–1478 (2008).
20. Keyes, R. W. *Science* **230,** 138–144 (1985).

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