Optical interconnects to chips – why and how

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Density problem in electrical interconnects

This gives a universal form of scaling for simple digital connections (i.e., no repeaters, no multilevel modem techniques)

\[
\text{bit rate } B \propto \frac{A}{\ell^2}
\]

Once the wiring fills all space, the capacity cannot be increased either by making the system smaller or by making it larger.

Optics completely avoids this scaling limitation because it has no resistive loss and because of its small wavelength.

J. Parallel and Dist. Comp. 41, 4252 (1997)
Introduction

The “scarce resource” inside large machines is becoming energy which may mostly be used in sending information for the very large number of short distance communications inside racks and boards and even chips.
Introduction

But we are getting stuck at picojoules per bit or more for all communication off chips and for longer distances.

Why is this?

After all, we now have many demonstrations of optoelectronics operating at ~ 1 – 10 fJ/bit energies.
Introduction

Is there any path to 10fJ/bit (total system energy) for off-chip interconnect while still retaining and expanding the very large required bandwidth densities?
Major references

On energy, systems, and device physics


On waves and channels for optical communication


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Why picojoules/bit off-chip energies?

In electrical systems because charging centimeter wires takes picojoules.
Why picojoules/bit off-chip energies?

In optical systems, three reasons

1 - because we have not yet integrated optoelectronics and electronics closely enough and with low enough capacitance especially photodetectors
Why picojoules/bit off-chip energies?

2 - because we have not yet invested enough in the technology for the right low-energy optoelectronics
e.g., Ge quantum well modulators in silicon photonics
for specific optics
e.g., very low loss couplers, array optics
Why picojoules/bit off-chip energies?

3 - because we waste picojoules per bit in circuits to drive and receive the signals
### Energies for communications and computations

<table>
<thead>
<tr>
<th>Operation</th>
<th>Energy per bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless data</td>
<td>10 – 30μJ</td>
</tr>
<tr>
<td>Internet: access</td>
<td>40 – 80nJ</td>
</tr>
<tr>
<td>Internet: routing</td>
<td>20nJ</td>
</tr>
<tr>
<td>Internet: optical WDM links</td>
<td>3nJ</td>
</tr>
<tr>
<td>Reading DRAM</td>
<td>5pJ</td>
</tr>
<tr>
<td>Communicating off chip</td>
<td>1 – 20 pJ</td>
</tr>
<tr>
<td>Data link multiplexing and timing circuits</td>
<td>~ 2 pJ</td>
</tr>
<tr>
<td>Communicating across chip</td>
<td>600 fJ</td>
</tr>
<tr>
<td>Floating point operation</td>
<td>100fJ</td>
</tr>
<tr>
<td>Energy in DRAM cell</td>
<td>10fJ</td>
</tr>
<tr>
<td>Switching CMOS gate</td>
<td>~50aJ – 3fJ</td>
</tr>
<tr>
<td>1 electron at 1V, or 1 photon @1eV</td>
<td>0.16aJ (160zJ)</td>
</tr>
</tbody>
</table>

Most energy is used for communications, not logic.
Energy and information

Though it does take more energy to send a bit over longer distances, there is massively more information sent at shorter distances so much so that most energy dissipation is in shorter links and interconnects inside machines.
Logic and wiring capacitance

To run a gate we have to charge the transistors and the wires that communicate in and out of the gate.

But the wiring capacitance even to neighboring gates is of the same size as or larger than the transistor capacitance.
Logic and wiring capacitance

So most energy in information processing is in communications, not in logic itself, even at the gate level. And communication costs more energy for all longer distances.

Logic and wiring capacitance

Hence most energy dissipation in information processing is in charging and discharging wire capacitance which is $\sim 2 \text{ pF/cm}$ (or $200 \text{ aF/micron}$).

Just “touching” a bit typically costs many fJ in CMOS.
Power dissipation in electrical wires

Simple logic-level signaling results in large dissipation

For a wire capacitance $C$

we dissipate at least $\frac{1}{4}CV^2$ per bit in on-off signaling

E.g., at 2pF/cm and a 2 cm chip, at 1 V on-off signaling

the energy per bit communicated is at least $\sim 1\text{pJ}$
Energy and information

The dominant energy dissipation at short distances inside machines is charging and discharging wire capacitance.
Physically saving energy with optics

To save energy in the physical process of communications, we should stop wasting energy in charging and discharging electrical lines. This is a fundamental quantum-mechanical advantage of optics: “quantum impedance conversion” — charge the photodetector, not the wire.
Quantum impedance conversion

The photoelectric effect means we can generate a “large” voltage in a detector
e.g., a fraction of a volt
with very little signal power or energy
and very little classical voltage in the light beam (< 1mV for 1nW)
“quantum impedance conversion”

1 nW with 1 eV photons
1 GΩ
~ 1 nA
~ 1 V

Quantum impedance conversion

Optics only has to charge
the photodetector and the transistor
to the logic voltage
not the interconnect line

1 nW with
1 eV photons

1 GΩ

~ 1 nA

~ 1 V

Exploiting quantum impedance conversion

To exploit this advantage, first we should reduce energy in optoelectronic devices so the energy to send information optically becomes less than that of wires even for short distances, e.g., centimeters or even shorter.

Reducing optoelectronic device energies

Integrate sub-fF photodetectors right beside transistors to reduce “front end” capacitance $C_{FE}$

Note that system energies tend to go down in proportion to $C_{FE}$

Reducing $C_{FE}$ is as important as increasing laser efficiency and there is more headroom here

We can’t have a 1000% efficient laser but we can reduce $C_{FE}$ by X10–X100

Reducing optoelectronic device energies

Push operating energies into the sub 10fJ range for output devices

Low-energy modulators, lasers, LEDs
- nanophotonic structures
- use of the strongest mechanisms
e.g., quantum-confined Stark effect in Ge quantum wells
  stronger than other mechanisms, including current 2D materials
So that capacitive charging energies do not dominate, we need
- small devices for low device capacitance
- very close integration to limit wiring capacitance

<table>
<thead>
<tr>
<th>Structure</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>100×100µm square conventional photodetector</td>
<td>~1pF</td>
</tr>
<tr>
<td>5×5µm CMOS photodetector</td>
<td>4fF</td>
</tr>
<tr>
<td>Wire capacitance, per µm</td>
<td>~200aF</td>
</tr>
<tr>
<td>FinFET input capacitance</td>
<td>~ 20 – 200 aF</td>
</tr>
<tr>
<td>1 micron cube of semiconductor</td>
<td>~100aF</td>
</tr>
<tr>
<td>100 nm cube of semiconductor</td>
<td>~10aF</td>
</tr>
<tr>
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</table>

A Ge quantum well waveguide-integrated modulator measures 10 microns long, 0.8 microns wide, and 500 nm thick in the intrinsic region. It operates on silicon and is designed without a resonator.

Selective area growth of quantum wells in SOI waveguides results in a capacitance of approximately 3 fF. With a 4 V bias and a 1 V swing, it achieves 3 dB modulation at 1460 nm. The dynamic energy per bit is estimated to be 0.75 fJ.

Recent progress in foundry fabrication is reported by S. A. Srinivasan et al. in IEEE JQE 56, 5200207 (2020).

S. Ren et al., IEEE PTL 24, 461 – 463 (2012)
D. A. B. Miller, Optics Express 20, A293-A308 (2012)
Using optics to eliminate circuit energies

If the dissipation in the associated circuits is large

low-energy optoelectronic devices cannot be exploited effectively

So

stop wasting energy in the electrical circuits used to run interconnects
Using optics to eliminate circuit energies

Eliminate receiver circuit dissipation typically 100’s fJ/bit to pJ’s/bit

How? - Integrating low capacitance photodetectors beside transistors

This may eliminate need for voltage amplification altogether

receiverless operation

or limit it to ~ one simple low-energy gain stage

“near-receiverless” operation

Using optics to eliminate circuit energies

Energies for receiverless operation

E.g., 1 fJ received optical energy generates ~ 1 fC of charge, so
- in 1 pF (conventional detector) generates ~1 mV signal
- in 30 fF (solder-bumped detector) generates ~33 mV signal
- in 1 fF (integrated detector) generates ~1 V signal
Eliminating receiver energy

Integrate optoelectronics beside transistors
e.g., within a few microns at most
This allows excess capacitance in
the scale of only 100’s of aF
And total input capacitance of
~1fF or lower
Time-multiplexing energies

Time-multiplexing takes energy e.g., pJ’s per bit in SERDES (serializer/deserializer circuits)
Time-multiplexing energies

Why does time-multiplexing take energy?

1 - Because we touch a bit many times to time-multiplex or demultiplex it
e.g., moving it in registers and buffers
e.g., if we estimate 1 – 100 fJ/bit for every time we touch it
we quickly get to pJ/bit energies
Time-multiplexing energies

2 - Because we run some of the circuits at very high speeds which takes even more energy per bit operation

3 - Because we also have to perform clock and data recovery (CDR) for synchronization which similarly takes $\sim \text{pJ's per bit}$ in CDR circuits
Other circuit energies in links

Any use of advanced multilevel signaling only requires more circuitry and energy.

Any use of error correction only requires more circuitry and energy.

-Time-multiplexing and advanced signaling to get more information per channel only make the energy per bit problem worse.
Why do we use such circuits?

Because we think we are limited by the number of available channels for interconnection

e.g., the number of fibers
forcing maximum wavelength multiplexing
and time-multiplexing as well

Because we think we cannot run large systems synchronously

*But neither of these beliefs are actually correct*
Large synchronous systems?

Time delays are not predictable in electronics because of

- pulse dispersion
- the temperature coefficient of the resistance of copper

Time delays are predictable in optics

- E.g., < 10 ps variation with temperature in 10 m fiber
- Free-space optics has equal paths even for large numbers of beams
Large synchronous systems?

For precision $\ll$ one clock cycle in optics, we only need path lengths controlled to $\sim$ cm e.g., cutting fiber to lengths, or free-space imaging

We could run $\sim$ 10 m scale systems with all delays being an integer number of clock cycles without any clock phase recovery
Array optics?

Move to free-space optical systems with 1000’s to 10,000’s of connections

avoiding time-multiplexing (and all SERDES/CDR energies)

so we can run at low, energy-efficient clock rates

e.g., a few GHz to ~ 10 GHz

directly compatible with efficient silicon digital chips
Number of possible free-space channels

The number of possible optical channels (per polarization) between two surfaces of areas $A_T$ and $A_R$ separated by a distance $L$ at a wavelength $\lambda$ as limited by diffraction, is

$$N_c = \frac{\Omega_T A_R}{\lambda^2} = \frac{A_T A_R}{L^2 \lambda^2}$$

E.g., at 1 $\mu$m wavelength

for 10 cm x 10 cm surfaces separated by 10 m

$$N_c \approx 10^6$$

for 2mm x 2mm surfaces separated by 2 cm

$$N_c \approx 4 \times 10^4$$

Orbital angular momentum beams

These conclusions are not changed if we “add” orbital angular momentum beams or modes.

Orbital angular momentum is not an additional degree of freedom in optics beyond the existing spatial degrees of freedom.
Orbital angular momentum beams

For usual optical systems we can get just as many orthogonal channels using beams with no angular momentum at all.

Proof

Free-space arrays of beams

We can easily generate large arrays of light beams from one source. Diffractive optics has done this for at least 30 years.

Free-space beam arrays have the same time delay to ps levels over millions of pixels.
Free-space arrays of beams

Aligning an entire array of light beams is not much more difficult than aligning one beam. Just add array orientation and overall array dilation.
Free-space arrays of beams

If necessary, servo the alignment in free-space arrays which we can do, even in physically demanding situations.

Think of the servo-ing of the optics in a CD or DVD player.

We could imagine such servo-ing for longer distance links such as between boards or cabinets.
Free-space arrays of beams

For shorter distances, for example, between chips, we could simply make rigid optics, essentially a small rectangular rod of plastic incorporating any lenses.
2D arrays of 1024 free-space channels

E.g., 10 x 10 micron optical “pads”

either packed closely

or spaced out, and using lenslet arrays

A “straw-man” low-energy system approach

Key additional technologies
Integration – at least hybrid
- a silicon photonics optical “interposer” especially with additional materials e.g., germanium, III-Vs
- detectors beside transistors or in the photonics “interposer” layer on top

Improved optical couplers, including
- optical vias
- waveguide arrays
- free-space couplers

“Straw man” system concept exploiting
- tightly integrated optoelectronics
- efficient beam couplers
- free-space communications with 1000’s to 10,000’s of channels

A “straw-man” low-energy system approach

A major opportunity for nanophotonics beam and mode couplers with %’s of loss, not dB’s of loss

“Straw man” system concept exploiting
- tightly integrated optoelectronics
- efficient beam couplers
- free-space communications with 1000’s to 10,000’s of channels

A “straw-man” low-energy system approach

Goal – 10 fJ/bit (total system energy) up to 10 m distance

Note that this “straw man” system predicts that

even with ~19 dB total system loss

10fJ/bit is achievable

Note 10 fJ/bit implies only

10 mW power for 1 Tb/s interconnect bandwidth

“Straw man” system concept exploiting
- tightly integrated optoelectronics
- efficient beam couplers
- free-space communications with 1000’s to 10,000’s of channels

The bad news

Time-multiplexing is not the solution for low energy

We may need to change to synchronous systems

We may need to change the way we use optics

introducing highly parallel free-space systems

We need to invest in new technologies
The good news

We don’t need any new physics

The mechanisms we already have are more than good enough
The good news

We know what technology we need

- Integrate low-capacitance (e.g., ~1 fF) detectors close to transistors
- Implement low-energy modulators
- Implement array optics
- Improve couplers

We would want to implement much of this technology anyway
The good news

We have orders of magnitude of possible improvement

We really can eliminate the pJ/bit circuit energies

Free-space optics really does allow 1000s – 10000s of channels

We could change from 1 – 10 pJ/bit to 10 – 100 fJ/bit (total energy) for all interconnects from 1 cm to 10 m
The good news

There is no other competitive solution

Optics is the only way to increase bandwidth and reduce energy for off-chip interconnects
References and slides

Major references

On energy, systems, and device physics


On waves and channels for optical communication


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