If anybody likes to keep *this talk's slides*, please email me*!*

Roadmap of ultrafast energy-saving *optical* semiconductor devices to Year 2025

--- <speed, energy, size> estimates of optical Micro Processor Unit ---

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National Univ. of Electro-Communications (UEC)

Tokyo, Japan

42nd ssdm, Tokyo, Sept. 22, 2010

Contents

[1] Total energy consumptions in ICT technology

[2] Recent trends of optical-data-processing devices <speed, energy, size>

[3] All-Optical gates: from principles to new potentials <speed, energy, size>

[4] Crude estimates about "optical MPU" (long-term research)
(first time, too, to our knowledge)

Co-authors and Collaborations

[1] Energy consumptions in ICT-related systems

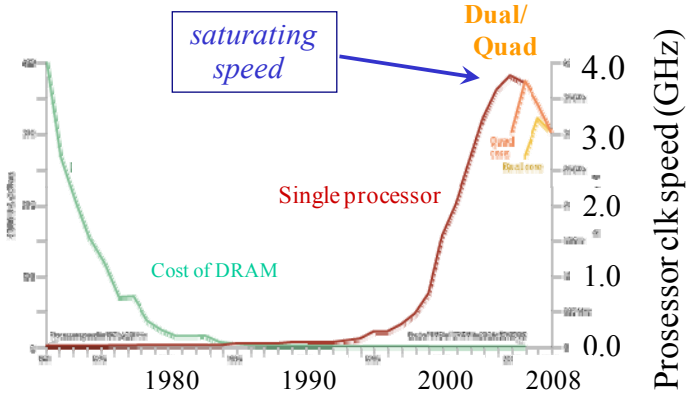
Conventional Technol.
(electronic MPU's)

Around 2005,
Clk freq. reached 3 GHz.
Nano-materials inside MPU's are nearly melt.
(37 years of Moore's law, IEEE 2008)

consequently

consequently

Nuclear Power-Station
1 GW / reactor

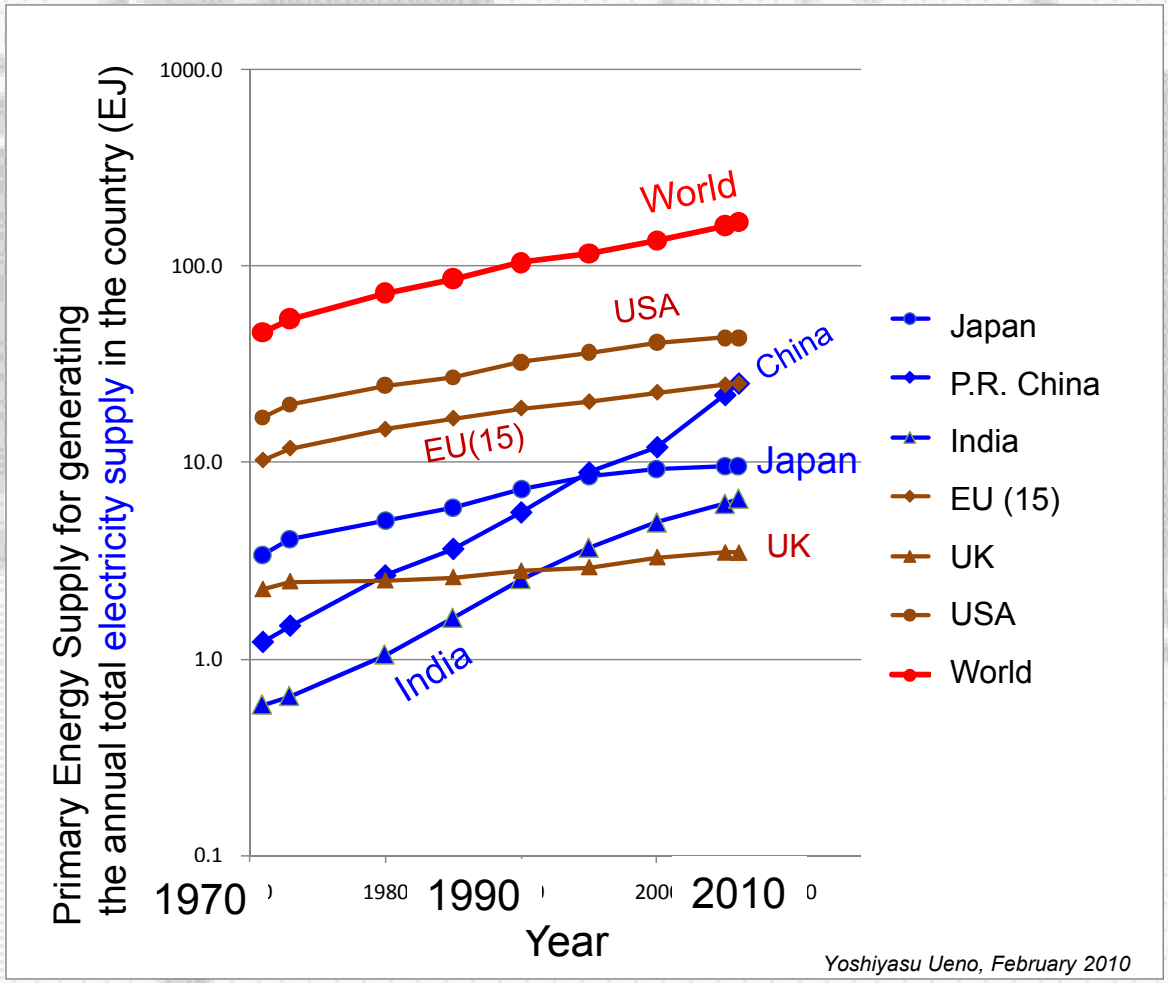


In **Data Centers** of Google, Microsoft, etc.
Clk freq.: 3 GHz, with similar MPU's
Heat-energy dissipation: 10 kW / sever rack
Data-center energy: 20 MW / data center

We need ultrafast & energy-saving
Optical Transistors
in future !

Electric-energy consumptions, 1970-2006

Primary energy supply, for electricity



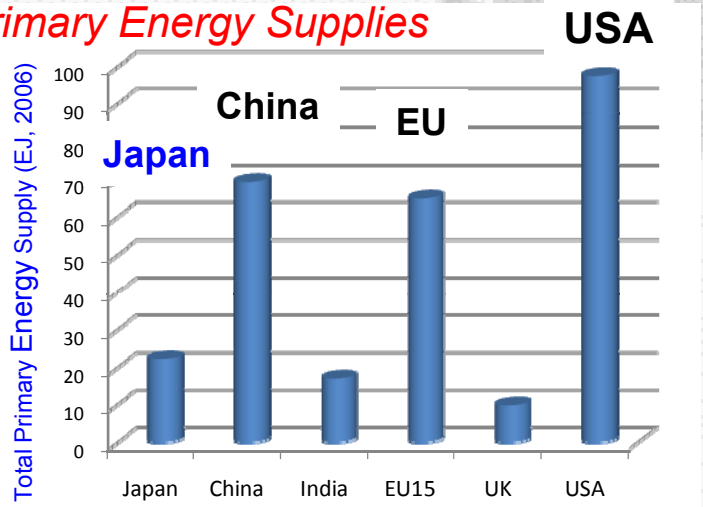
*1) Source: International Energy Agency (IEA), Paris,
Energy balances of OECD countries and non-OECD countries.

*2) 1 EJ= 1×10^{18} J.

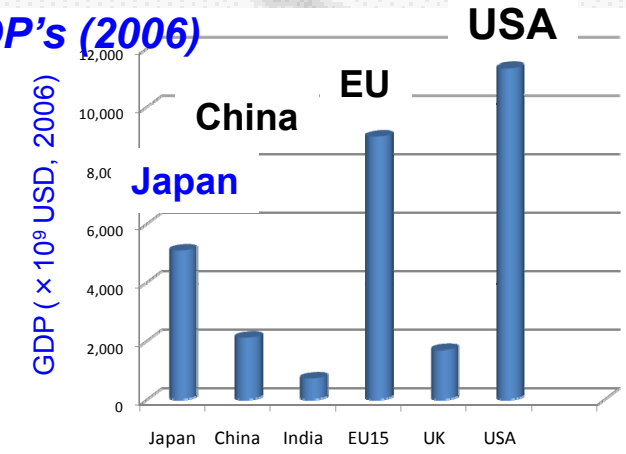
Macro-scopic:

Primary Energy Supplies (sum of electricity and non-electricity), 2006

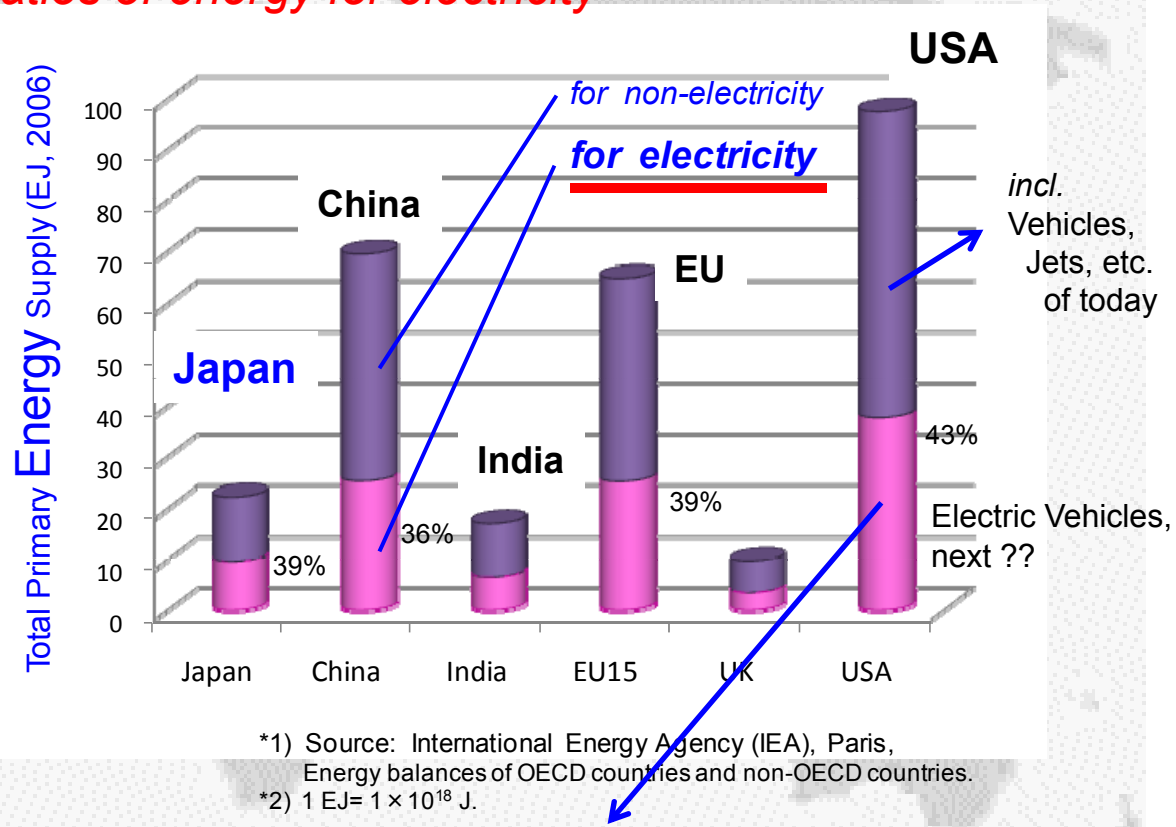
Primary Energy Supplies



GDP's (2006)



Ratios of energy for electricity



*1) Source: International Energy Agency (IEA), Paris, Energy balances of OECD countries and non-OECD countries.

*2) 1 EJ= 1×10^{18} J.

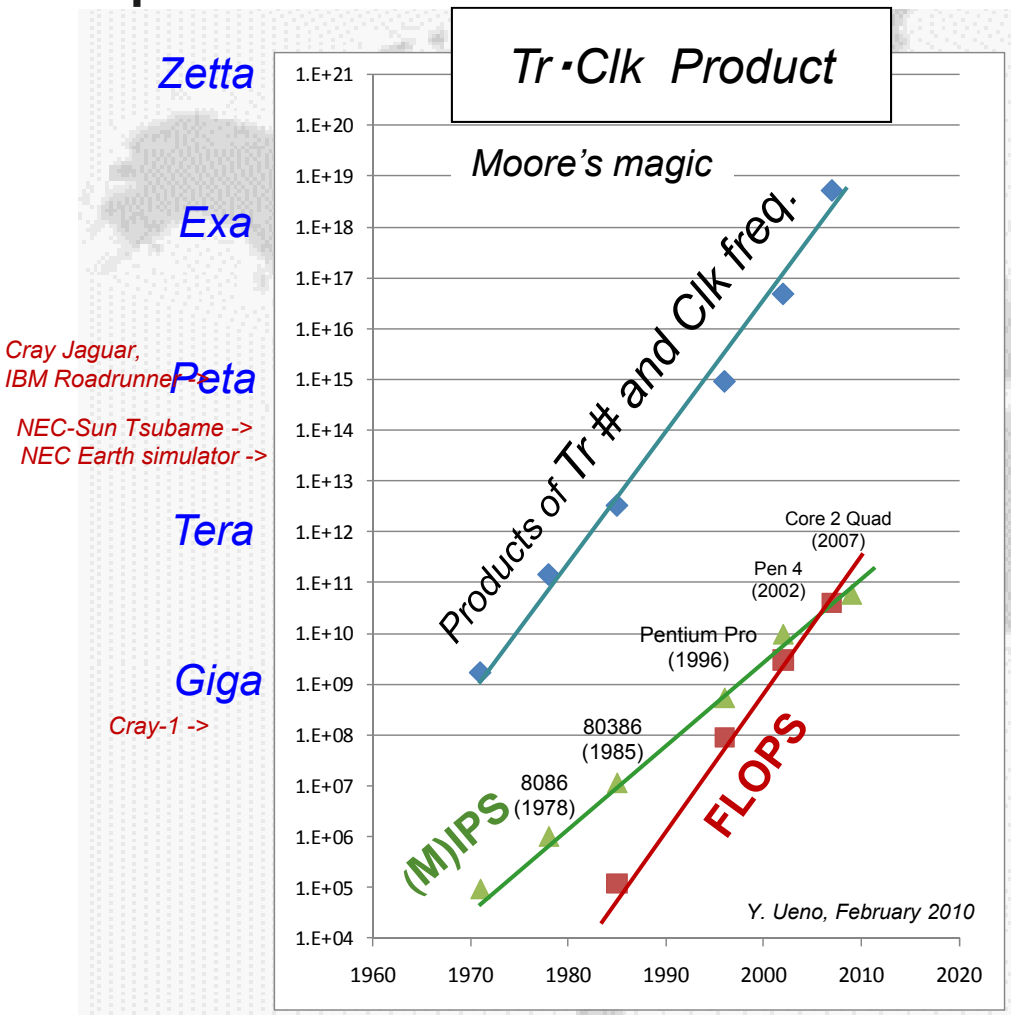
Data Centers in USA consuming 1.5% of all electricity (D. Miller, Stanford).

not very large?? → **1.5%** correspondes to **10 nuclear reactors**!!

→ We need energy-saving devices.

Micro-scopic:

one origin of ICT-energy consumptions



Sources: FLOPS from measured results, MIPS from wikipedia.

Tr-number times Clk-freq. has evolved by a factor of $10^6 \times 10^4 = 10^{10}$ (in 40 years)

Tr number: 10^6

Clk freq.: 10^4

- FLOPS speed has increased by 10^{10}.
- MIPS speed has increased by 10^4, only, without supported by Tr number. *(reasonable)*
- **Already relying** on parallel-processing MPU's and software. many-folded parallel-structures are probably pushing-up electric-energy consumptions (and costs). [hard to quantitatively characterize now, though.]

? for 2010-2050: Increasing demands are FLOPS-type demands, or, MIPS-type demands ??

- no. of Trs. times clk freq. 10x every 4 yrs.
- FLOPS 10x every 4 yrs.
- Instructions per sec. 10x every 7 yrs.

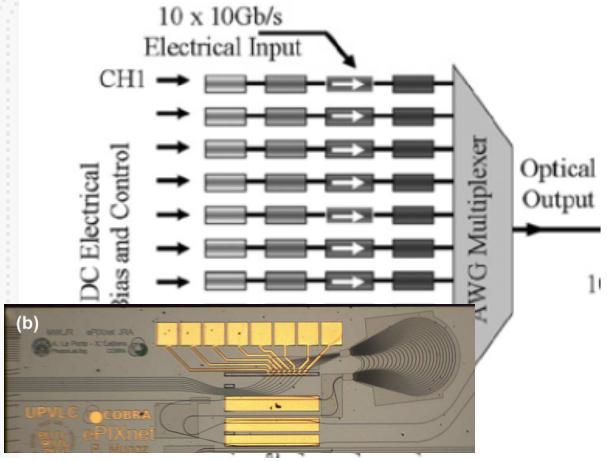
to move from electronics to optics: its famous weakness

Latest degrees of integrations for optical-processing devices

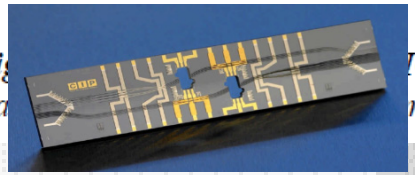
Number of devices on one chip= 200 (Infinera, 2006)

→ evolving steadily, driven by industrial demands,

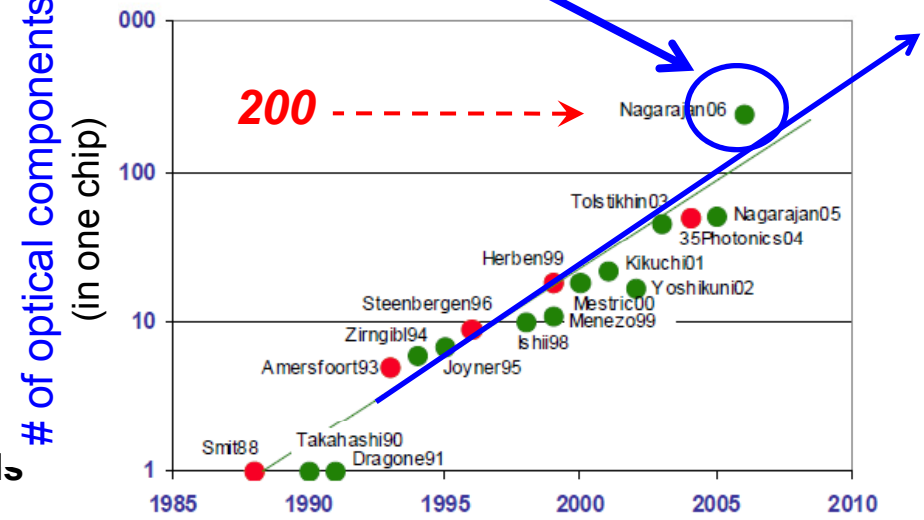
and approaching the number 2,300 in intel 4004 (1971).

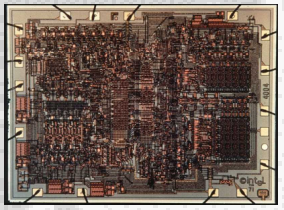


Eindhoven Univ. Technol., Netherlands



CIP Technologies, UK.





Electronic processor
Intel 4004 (1971)

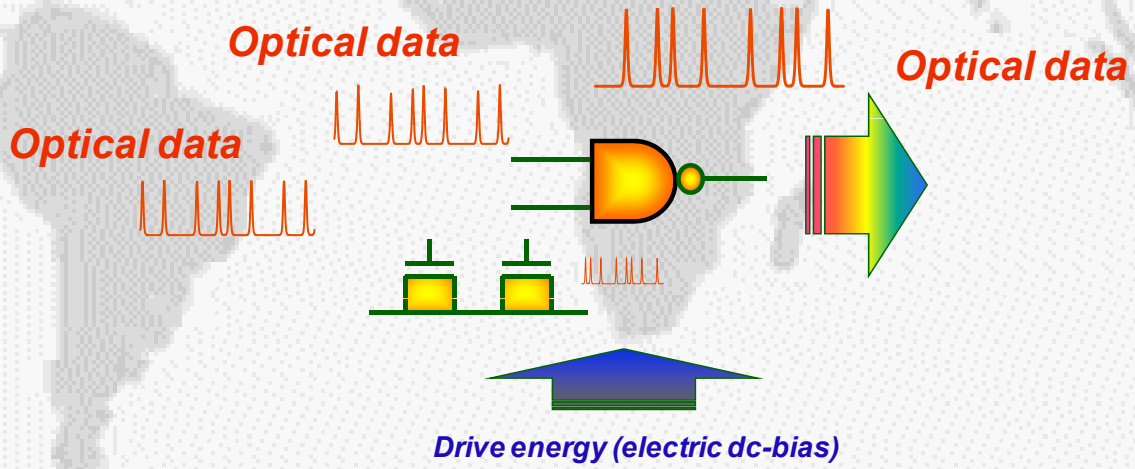
Fig. 2 Moore's law in Photonics: the development of WDM PIC complexity, measured as the number of components per chip.

source:
M.K. Smit (Eindhoven U. Technol.), IEEE-LEOS Annual 2008.

[2] Optical-data-processing “gates and memories”

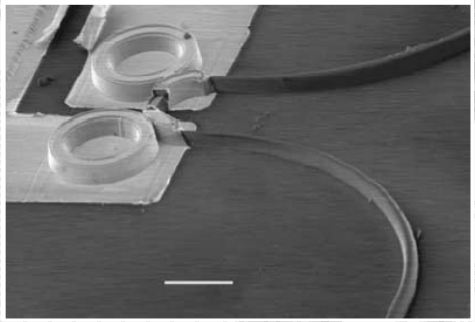
All-Optical circuits w/ gates & memories

Y. Ueno, UEC, 2010



[2] Optical-data-processing "gates and memories" <speed, energy, size>

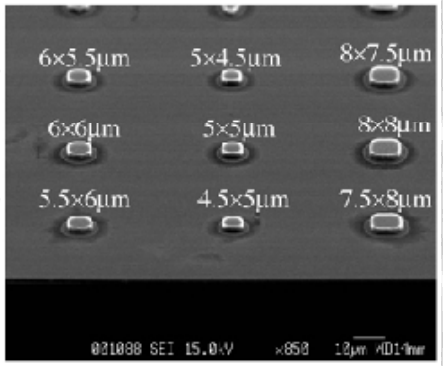
(2-1) Optical buffer memories (fundamental-research)



25Gb/s, 1pJ/bit, $(30\mu m)^2$

M.T. Hill (Smit Gr., Eindhoven),

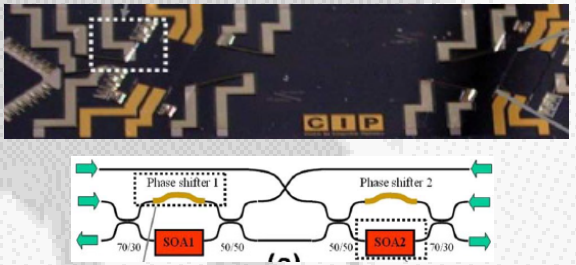
planar, ring-laser.



40-100Gb/s, 3pJ/bit, $(10\mu m)^2$

T. Katayama (Kawaguchi Gr.), 2009,

Vertical, VCSEL.



40-160Gb/s, L= few mm long

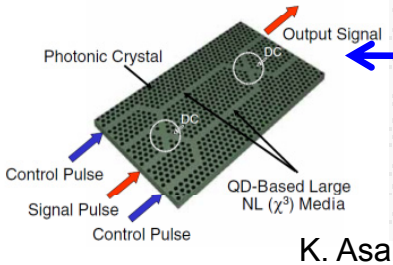
E. Kehayas (Dorren Gr., Eindhoven)

planar, coupled-gates.

photon-electron interactions

In bulk or MQW semiconductors

are used.



photonic-crystal gate

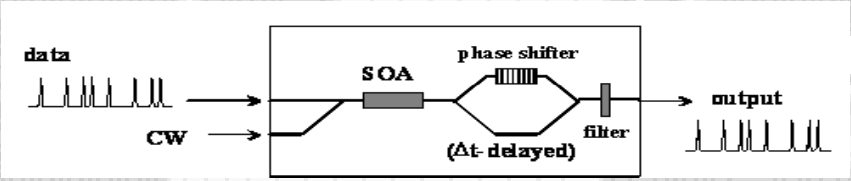
(FESTA, U. Tsukuba, AIST)

K. Asakawa et al., J. of Phys. 2006

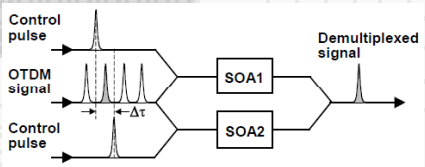
[2] Optical-data-processing "gates and memories" <speed, energy, size>

(2-2) All-optical gates (for practical signal-conversion, 2R/3R, demux, etc.)

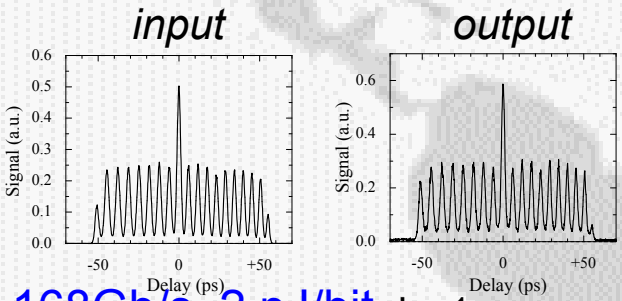
SMZ-DISC scheme, with non-linear cross-phase modulation XPM



original-SMZ scheme, with XPM



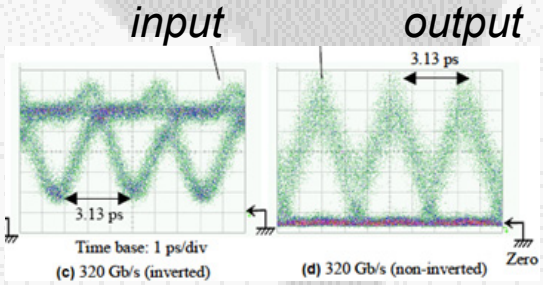
Gate, 2000年



168Gb/s, 2 pJ/bit, L≅ 1mm

S. Nakamura, Ueno, Tajima (NEC), wavelength-conversion

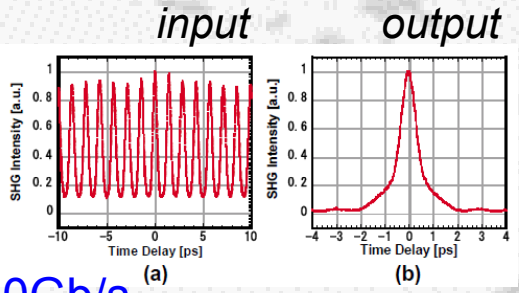
Gate, 2006年



320Gb/s, 2.5 pJ/bit, L≅ 1mm

Y. Liu (Eindhoven), wavelength-conv.

Gate, 2009年



640Gb/s

T. Hirooka (Tohoku U. & NEC), Demux.

[2] Optical-data-processing "gates and memories" <speed, energy, size>

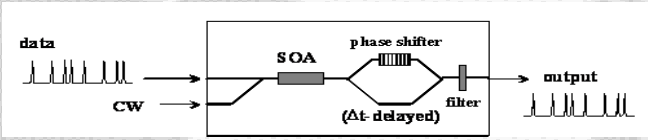
(2-2) All-optical gate (fundamental-research in our univ. UEC, Tokyo)

Converter, XOR, AND, 2R/3R, etc.

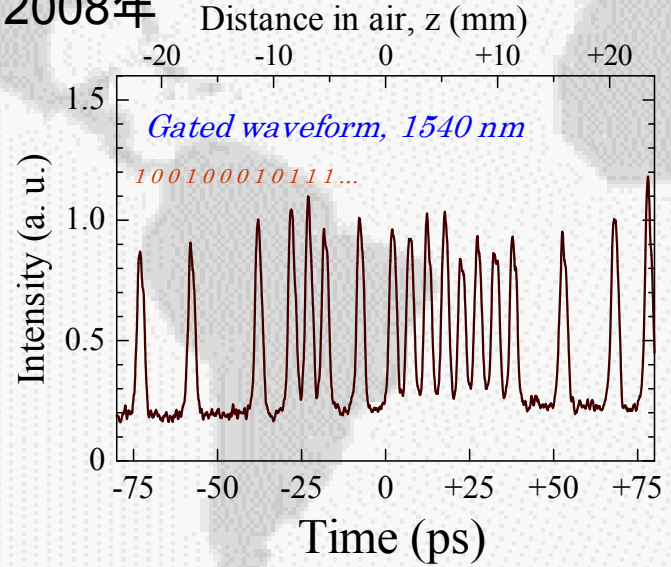
Flip-Flop (Eindhoven, Tsukuba)

Clock oscillator (UEC)

SMZ-DISC scheme (XPM) in our group



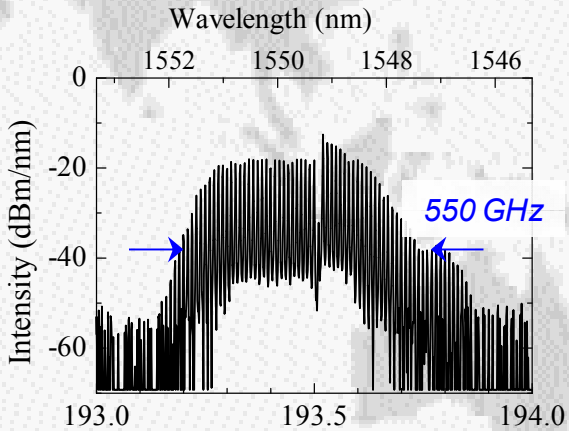
Gate, 2008年



200Gb/s, 3 pJ/bit, L≅ 1mm

Sakaguchi, et al. (Opt. Comm. 2009)

Oscillator, 2005-2008年



(160G-class)

Δ2ps/40GHz optical clock oscillator

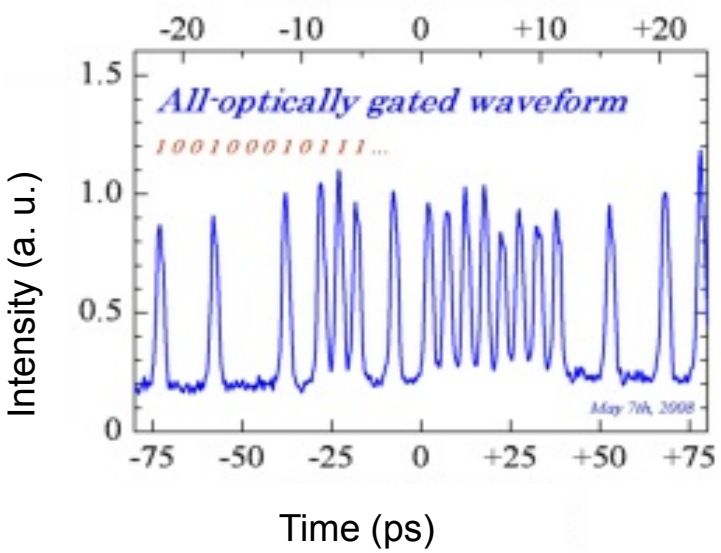
Suzuki, Nakamoto, et al. (CLEO2006, NANO2008)

200-Gb/s gated waveforms,
in the middle of our experimental studies

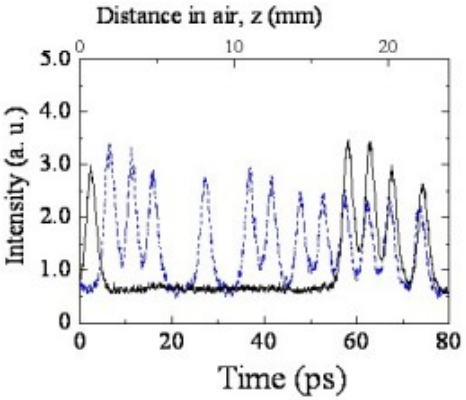
Jun Sakaguchi, et al., Opt. Comm. 2009.

good *!!*

Distance, z (mm)

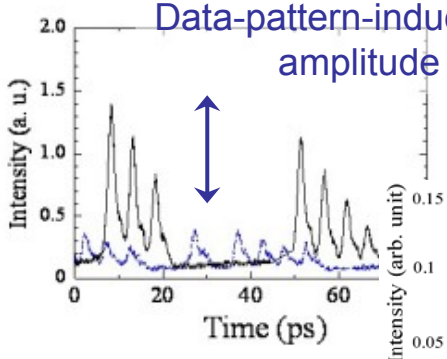


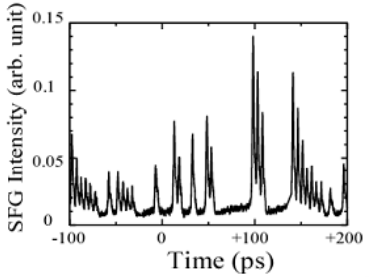
better
(accelerated)



badly gated
(too slow)

Data-pattern-induced
amplitude noise





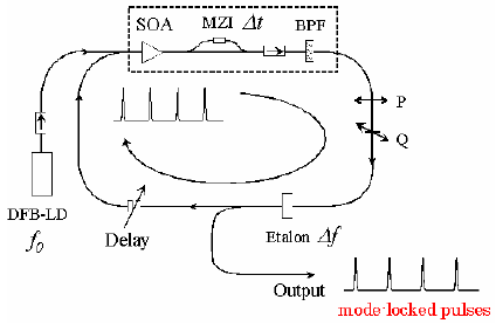
Clock oscillator (UEC)

COE-research: DISC-loop-type mode-locked pulse source

2-ps, 40-GHz pulse and comb generation, 2005-2006

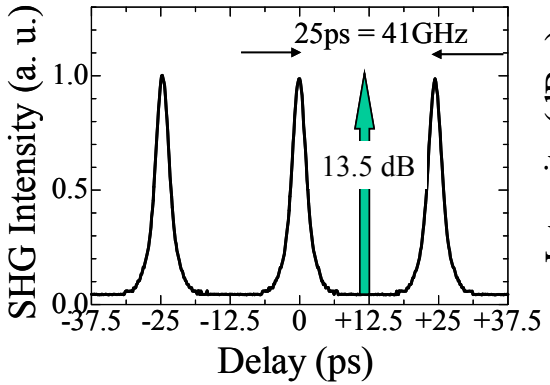
R. Suzuki, et al., CLEO, Long Beach, USA, May 2006.

DISC-type polarization converter

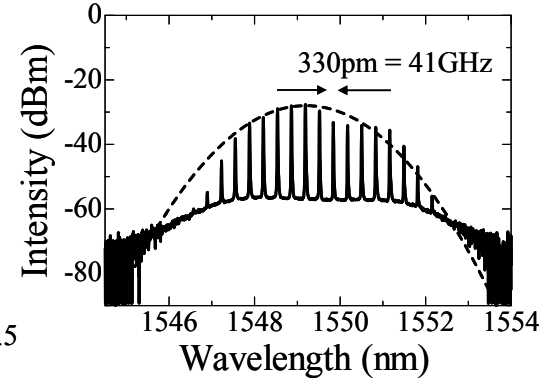


Original scheme from,
Y. Ueno, et al., Appl. Phys. Lett. Oct. 2001

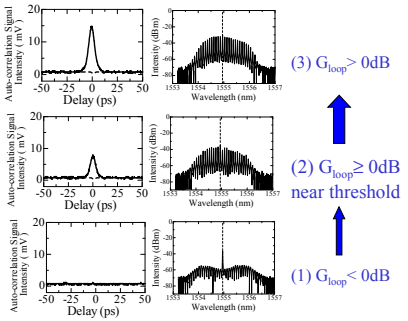
Auto-correlation trace



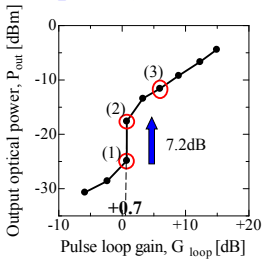
Optical-frequency-comb spectrum



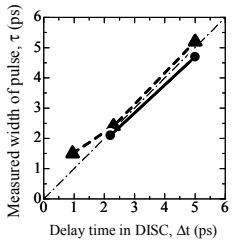
measured t-f product, Δt·Δf= 0.53
(1.2 times that of a Gaussian pulse)



Proof of principle (1), threshold behavior



Proof of principle (2), linearly controlled pulse widths



solid curve: 10 GHz
dashed curve: 40 GHz

fundamental research of “gates” → XOR, AND, 2R/3R, etc.
→ Flip-Flop (Eindhoven, Tsukuba)
→ Clock oscillator

Clock oscillator (UEC)

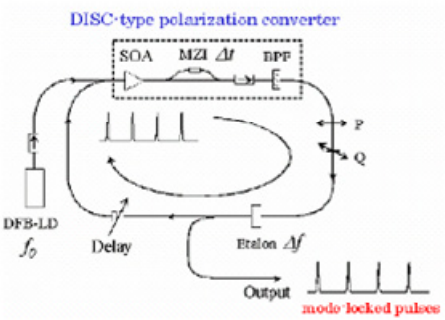
single-longitudinal-mode mode-locking, 2008

(with using high-Q etalon filter designed by JAE Japan)

precise, only-one-mode lasing

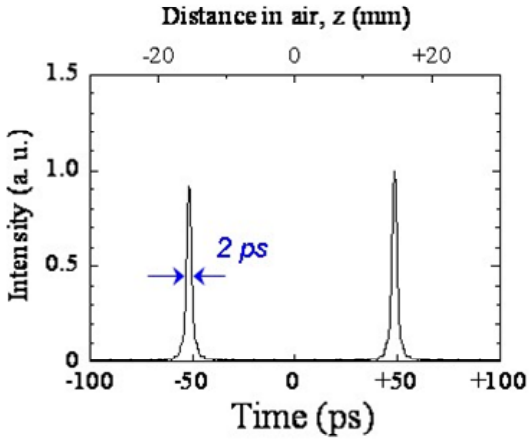
out of Δ10-MHz-spacing modes.

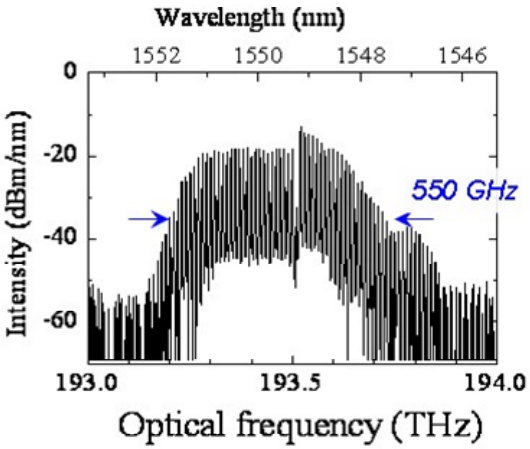
(Nakamoto, et al. OSA-NANO 2008)



Original scheme from,

Y. Ueno, et al., Appl. Phys. Lett. Oct. 2001





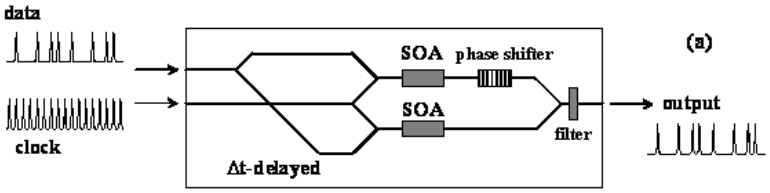
Original features of this scheme of ours:

- 500-GHz-BW comb, low power consumption, integration possibility (*presently*)
- precise optical frequency, f_{opt} (locked to external DFB source, f_{opt})
- precise repetition frequency, f_R (locked to dielectric etalon’s FSR, f_R)
- precise comb envelope shape, f_{BW} (locked to dielectric MZI delay time, Δt)

fairly-good

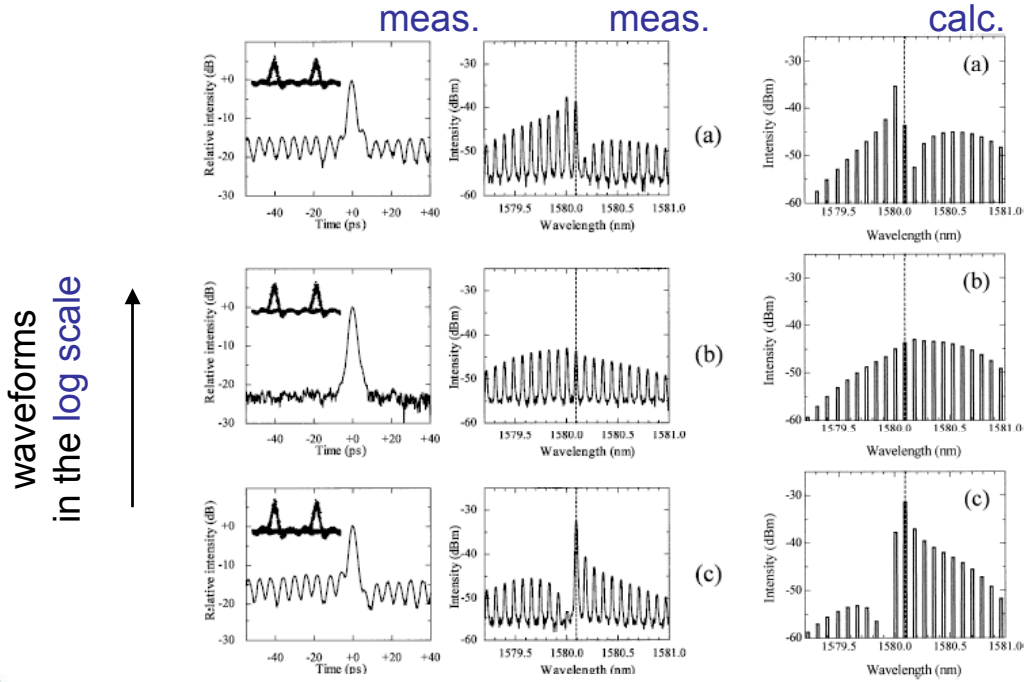
status of Modeling-research (optical gates)

Ueno et al., 2001-2002
ECOC, IE³ PTL, IEICE Trans.



from the hybrid-integrated SMZ device

Subject: about the useful correlation between
sensitive dependences of waveform and spectrum, on the optical phase bias, $\Delta\Phi_B$



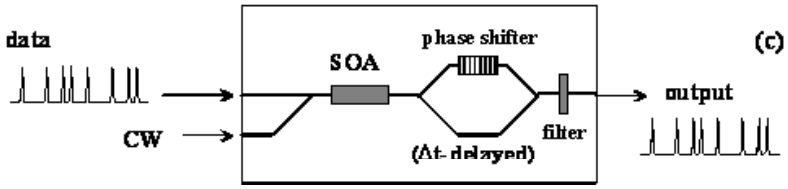
Conclusion:

we'll be able to feedback-control
the 160-Gb/s Demux
by monitoring the "supervisory" spectrum

fairly-good

status of Modeling-research (optical gates)

J. Sakaguchi et al., JJAP 2005 and 2008

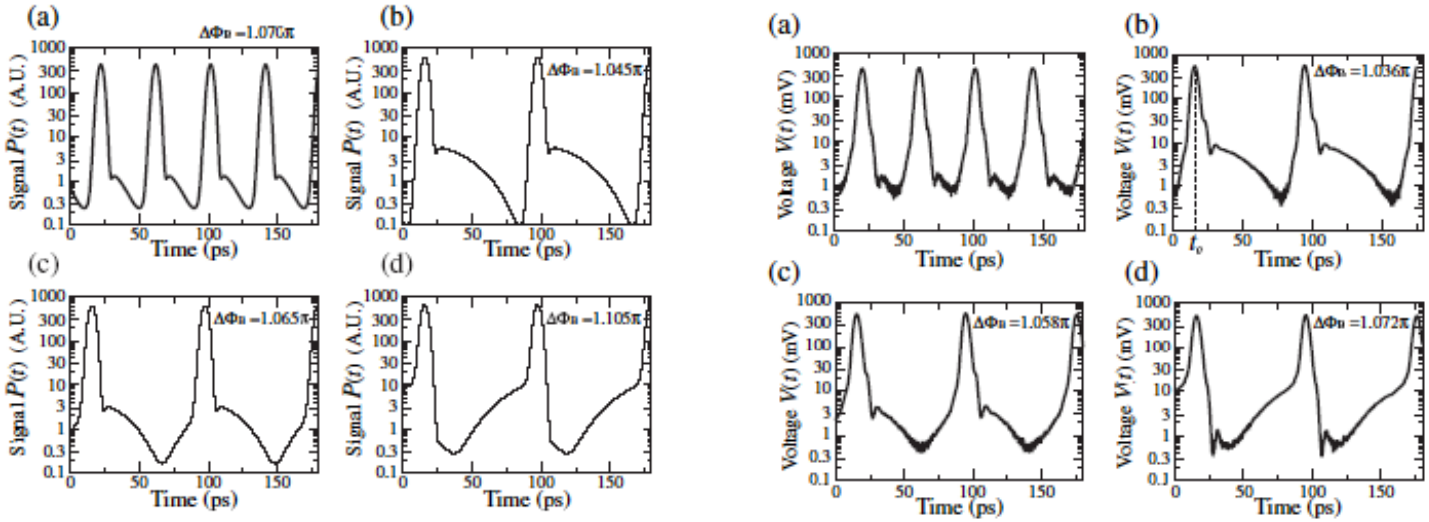


subject: about one generic issue for DATA conv. in the original DISC design

calculated

measured

waveforms in the log scale

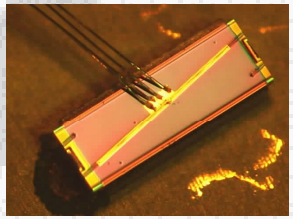


To solve this, within DISC scheme, we need a kind of imbalance factor between the two interferometer arms.

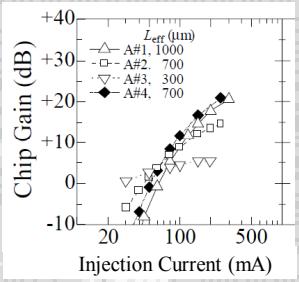
[3] Physics and potentials, of all-optical gates <speed, energy, size>

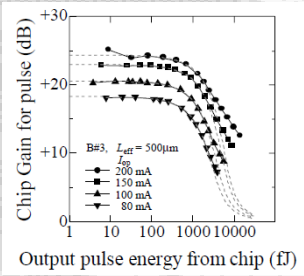
Quote: "All-optical semiconductor gate *seems* *too complicated*"

--- Prof. Guifang LI, CREOL/UCF, USA.



Inversion-population semiconductors (SOA's)



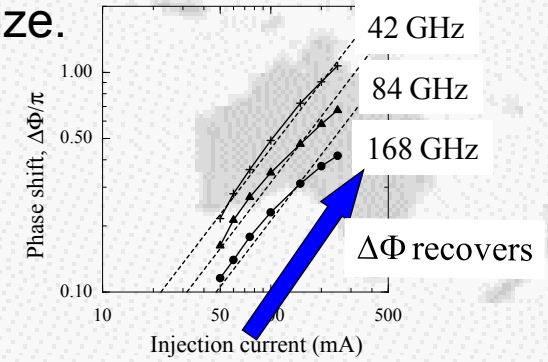


- nonlinear dependences → unsaturated gain G_0, gain-saturation energy P_{sat}, optical 3R/2R.

- **linear dependences (many ways)** → in gate speed, energy, size.

Ueno et al., JOSAB 2002

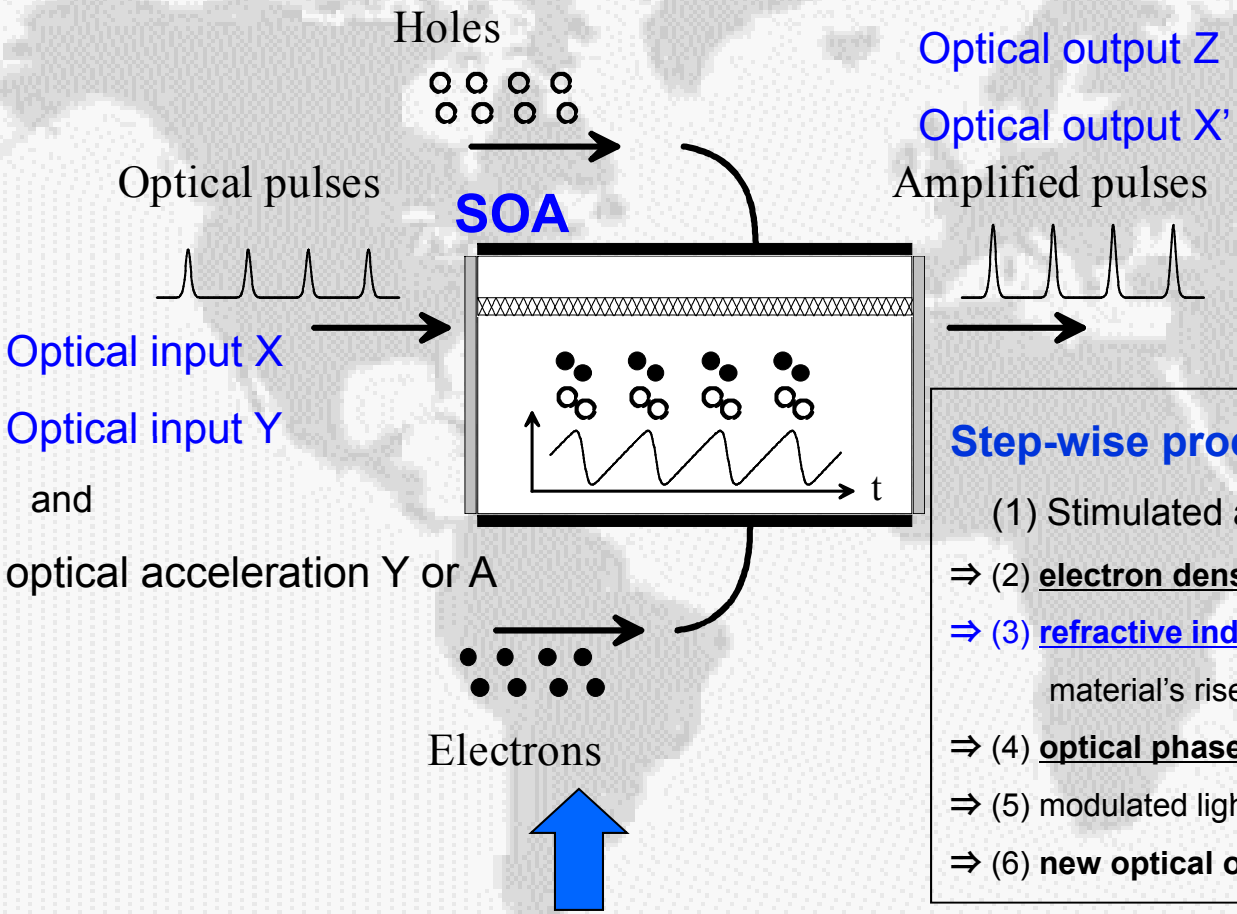
"not so complicated !!"



linear dependence

Physics : Refractive-index modulations, etc., due to excited-electron-hole-density modulations

K. Tajima (NEC 1993)
J. Sokoloff (Princeton 1993)



Excited electrons in conduction band

Excited holes in valence band

Step-wise processes in generating optical outputs, Z and X'.

(1) Stimulated amplification of optical inputs X and Y.

⇒ (2) **electron density** is modulated (in materials).

⇒ (3) **refractive index** is modulated (in materials).

material's rise time= 100 fs (fall time is slower).

⇒ (4) **optical phase** is modulated (in optical signal X or Y).

⇒ (5) modulated lights are **coherently combined**, before gate's output.

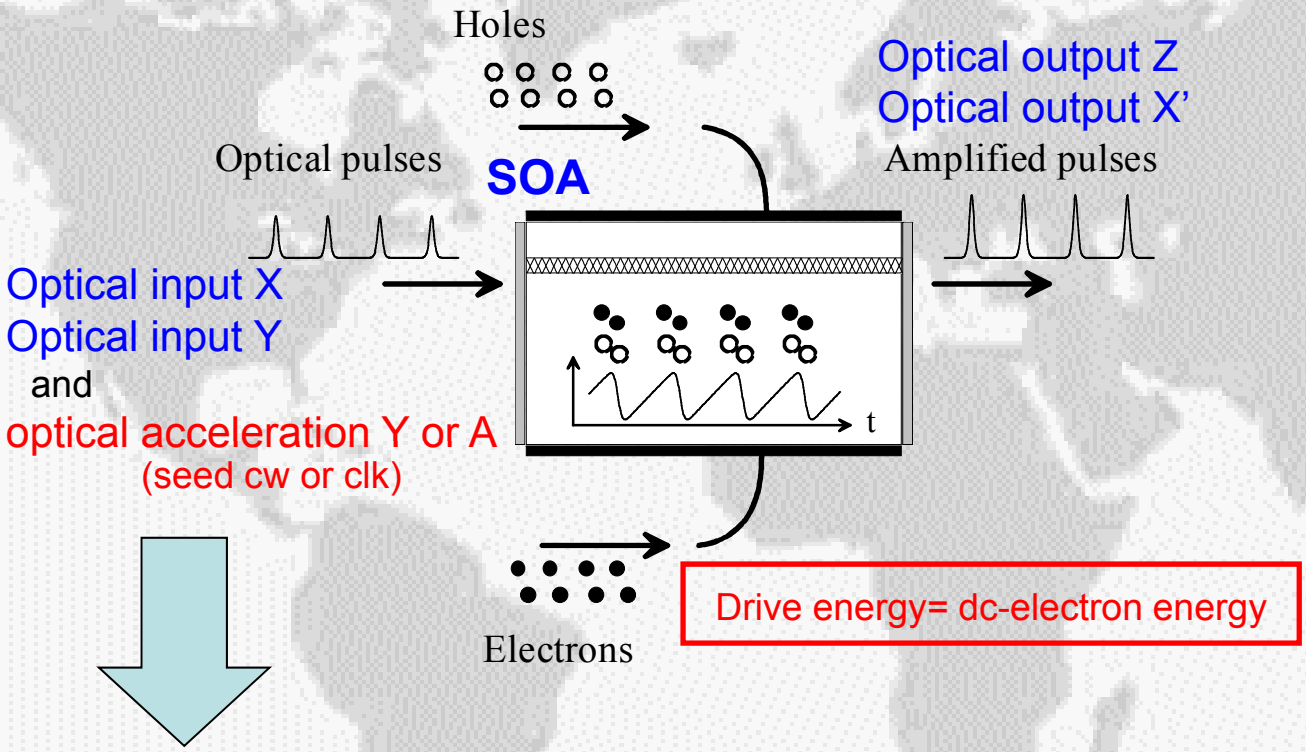
⇒ (6) **new optical outputs**, Z and X' are generated.

Drive energy= dc-electron-injection energy (dc-bias current)

Speed of gates

faster than material-relax. speed,
after optically accelerating the material

Origin: R. Manning (BT), EL 1994



- For gates, this acceleration is equivalent to "faster materials"
- Energy consumption is equivalent to them, as well.

experimentally recognized.

(Sakaguchi, et al., Opt. Express 2007)

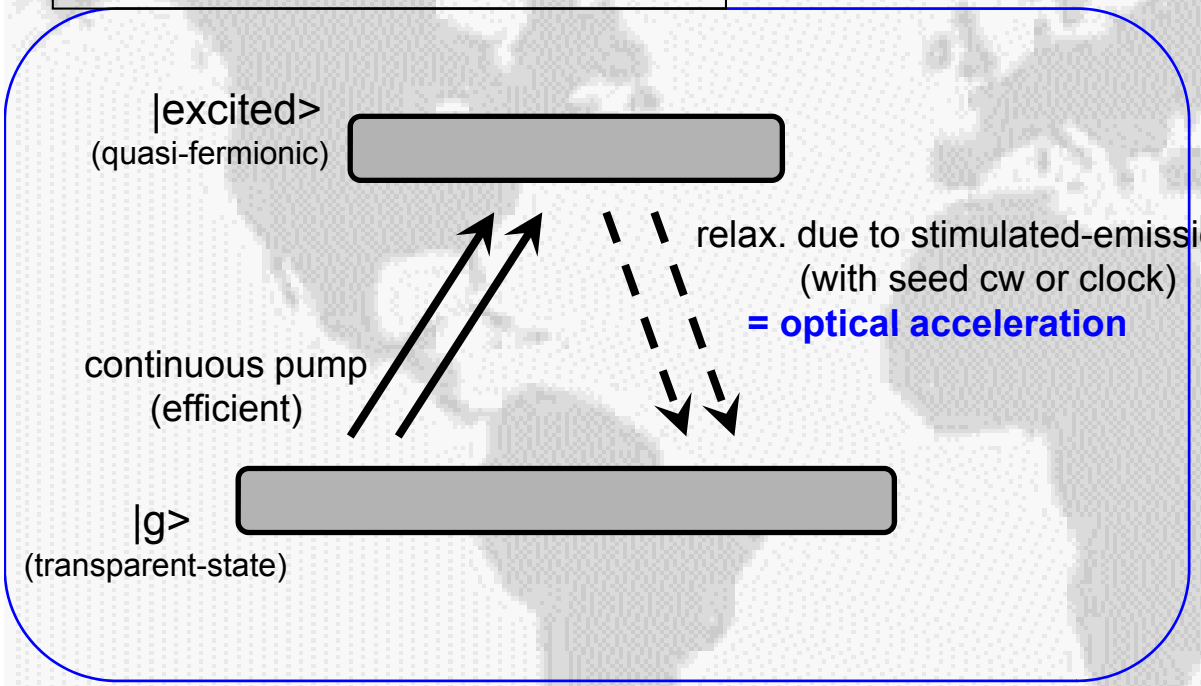
$$\frac{d}{dt}n_c = \frac{I_{op}}{qV} - \frac{\{G[n_c]-1\}}{V} \times \frac{|E_{accel}(t)| + |E_{data}(t)|^2}{\hbar\omega}$$

Speed of gates, more simply

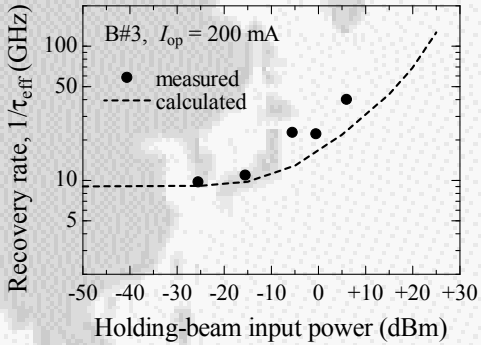
Sakaguchi, et al., Opt. Express 2007
Ueno et al., JOSAB 2002

Linear dependences after optical acceleration

Principle of acceleration (in SOA)

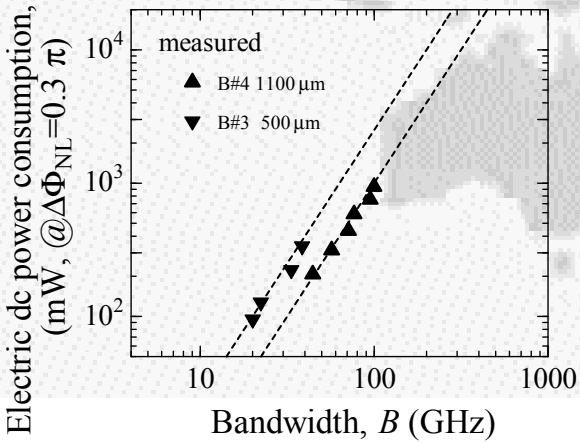


material level: **nonlinear** dependence



gate performance: **linear** dependences show-up.

energy per bit ∝ speed (due to Joule loss)
helpful for designs and experiments



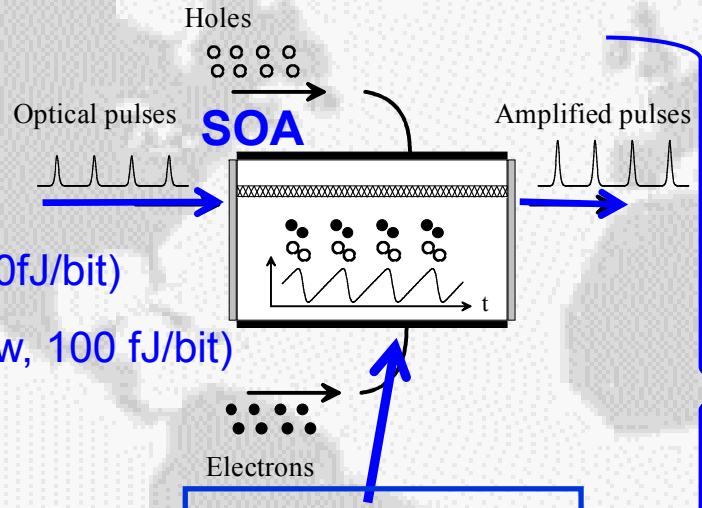
several other linearities::

optical phase mod. ∝ electron dens. mod.
optical phase mod. ∝ interaction length
optical phase mod. ∝ electron-photon overlap

Speed of gates → numbers at operating point (200Gb/s)

w/ nonlinear pol. rot.
S. Nakamura et al., Appl. Phys. Lett. 2001
J. Sakaguchi et al., Opt. Comm. May 2009

Principle of gate = electron-pump

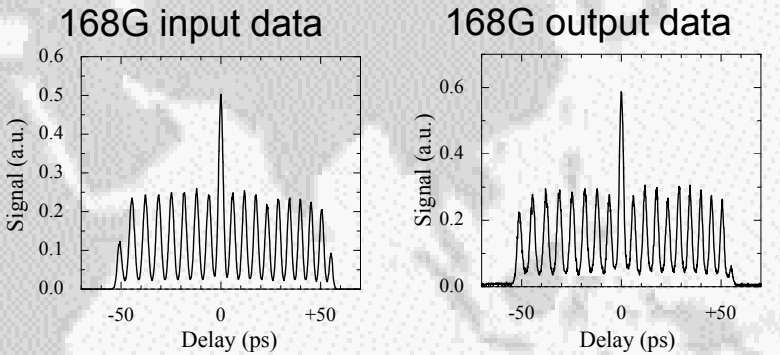


optical input (30fJ/bit)

acceleration (cw, 100 fJ/bit)

dc-electron energy

168G wavelength conversion (2000)



material > 60ps → gate recovery < 6ps

- electron consumption= 1×10^7 electrons/bit
- electric-energy consumption= 3 pJ/bit

nearly-regardless of material's speed (in this regime)

Energy-efficiency of gates → new potentials in near-future (--2025)

Other institutes: packet-routing, buffer memories, integrated 2R-subsystem.

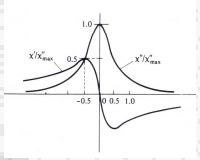
300 pJ/bit
30 pJ/bit
(previously)

Our group (UEC): following directions (for energy-saving)

- blue-shift filter → Nielsen et al., Opt. Express 2006
- nonlinear-polarization rotation → Sakaguchi et al., Opt. Comm. 2009

3 pJ/bit
(present)

- spectral-synthesis scheme → going-on (Nishida et al., IEEE-LEOS 2009)
  (UEC-NICT collaboration, FY2007-)
- (non-deg. ->) degenerate-scheme → going-on
  [free from polarization-insensitivity requirements]



0.3 pJ/bit
(near future)

not yet started but, from near-future

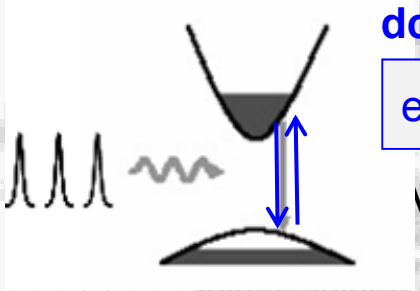
- QW-band-engineering, for enhancing refractive-index mod.
  (e.g., ACQW)

further

- efficient pump (optical)
- low-dim., surface plasmon, nano-photo

100-fJ to 30-fJ
(far future)

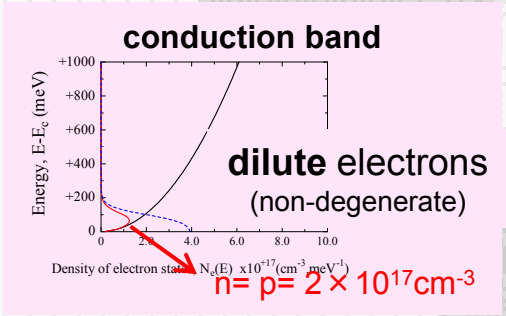
Size of gates → interaction L, new potentials in near-future (--2025)



dc-electron pump (at present)

energy supply of 3 pJ/bit, that is, 1×10^7/bit of electrons, in interaction length= 1 mm

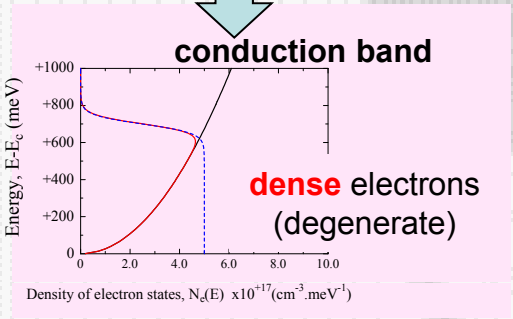
Volume density of excited electrons > 2×10^{18}cm^{-3} ?



exeprimentally: stock= relatively dilute (2×10^{17}cm^{-3}) !

Sakaguchi et al., Optics Express 2007 through present

→→ flow (modulation)= less efficient (at present)

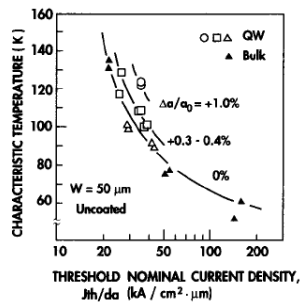


one of new potentials

10-times more electron density (2×10^{18}cm^{-3}),

→ 10-times shorter gate length (L= 100 μm)

(Hetero-barrier energy seems not enough, at present)



Characterstic temperatures
(AlGaInP/GaInP laser, 1993)

volume density of excited electrons (cm^{-3})

Plasmonics (very lossy) — ***Al*** ***Au, Ag, Cu***

Spintronics *"half-metal"* — ***Mn: GaAs***

$Ti:Al_2O_3$, Nd: YAG

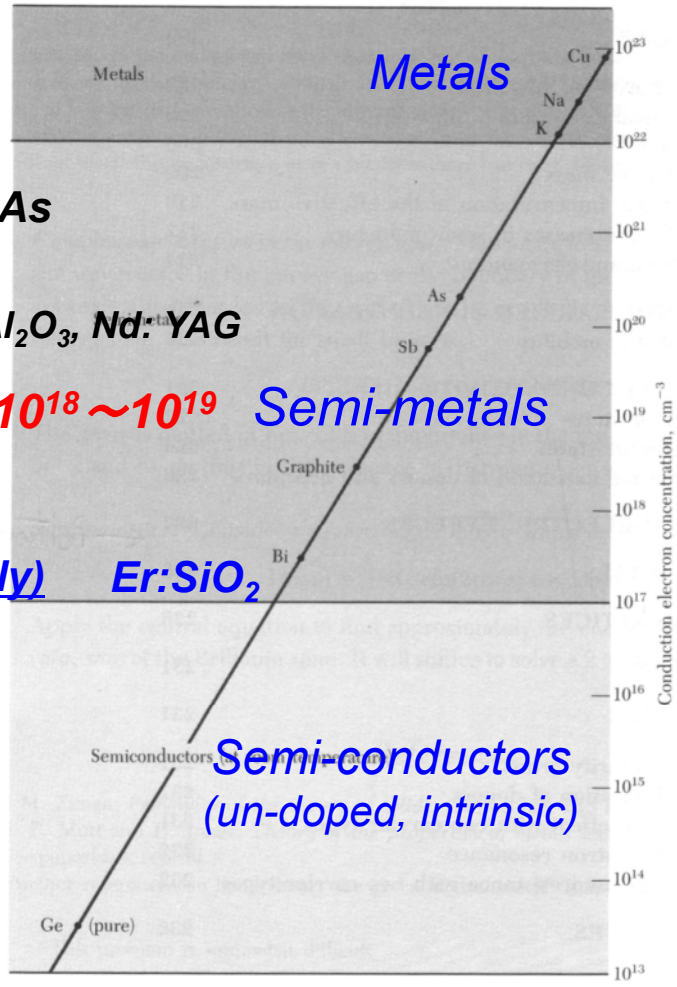
super-dense electrons in III-V, 10^{18} ~ 10^{19}

III-V in all-optical gates (presently)

unexpectedly dilute, 2×10^{17}

$Er:SiO_2$

background levels



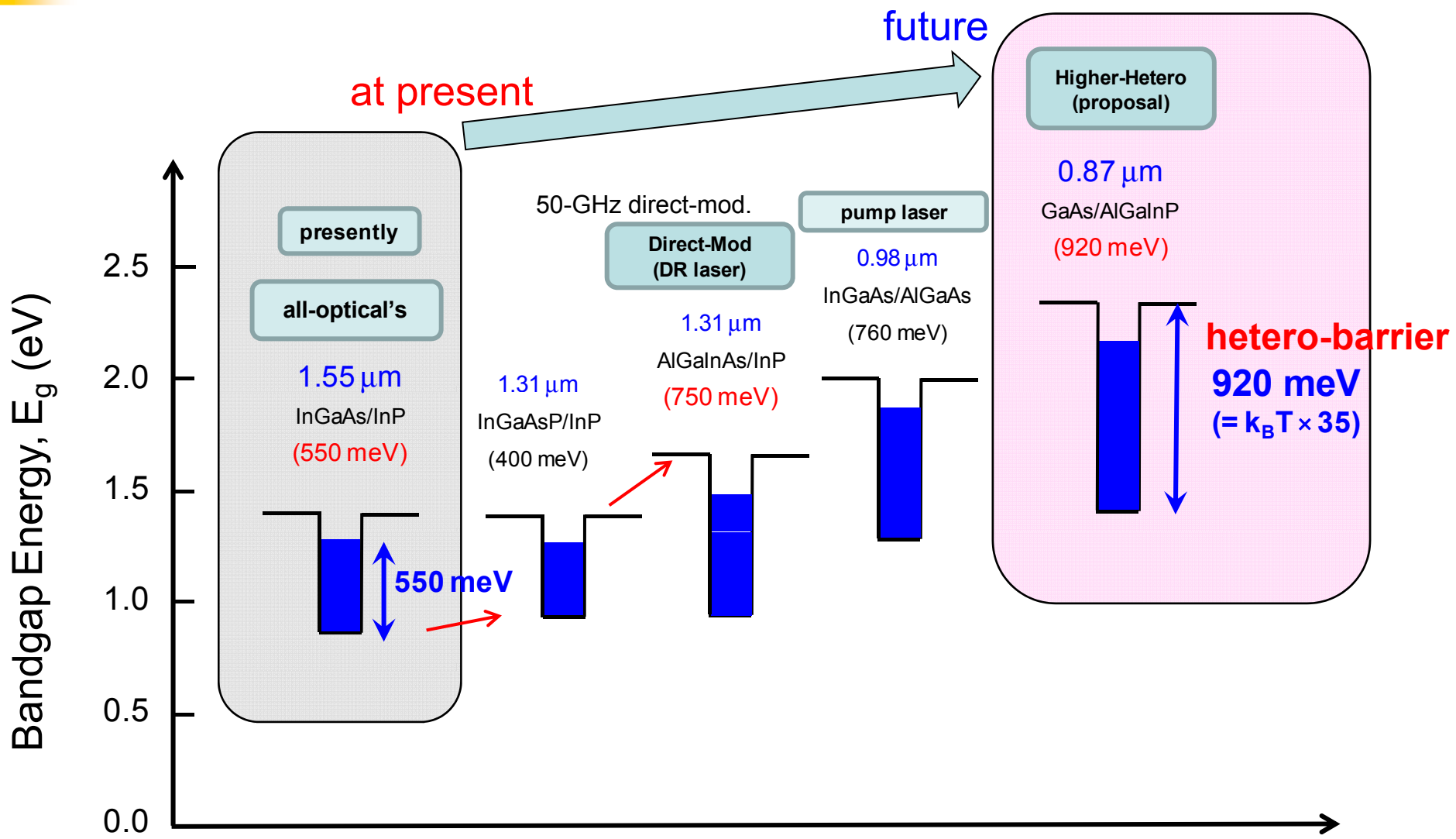
volume density
1E22
1E20
1E18
1E16
1E14

Semi-metals

Figure 1 Carrier concentrations for metals, semimetals, and semiconductors. Th range may be extended upward by increasing the impurity concentration, and t extended downward to merge eventually with the insulator range.

partially after **Charles Kittel,**
Introduction to Solid State Phys.,
1953-1996

Super-high-density electron-confinement, with new hetero-barrier systems



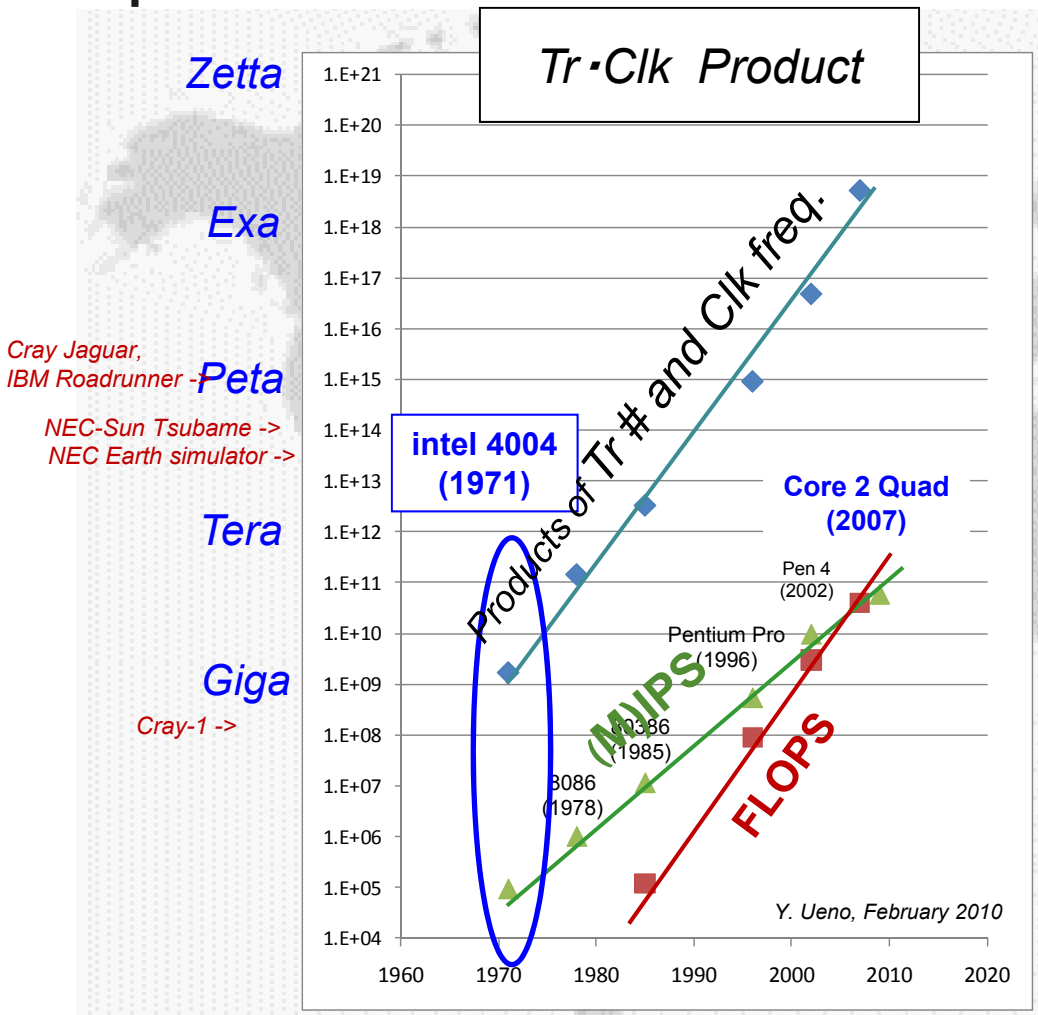
[4] Optical micro-processor, near Year 2025

near-future <speed=300G, energy=0.3pJ/bit, size(interaction)= 100μm>

	Electronic	Optical processor	
Specification	intel 4004	Present	Near Future
Demo Year	Year 1971	Year 2000-2010	Year 2025
Speed	500 kb/s	200-300 Gb/s	300 Gb/s
Energy (per bit)		3-10 pJ /bit/gate	0.3 pJ /bit/gate
Size (per gate)	70×70 μm^2	1,000×3,000 μm^2	500×500 μm^2 (w/ 100-μm interaction)
Number of gates (per chip)	2,300 transisters	several	2,300 gates (6 chips on 3-inch wafer)
Energy dissipation (per chip)			200 Watt

Optical processor 4004

Relative performance of optical-processor 4004



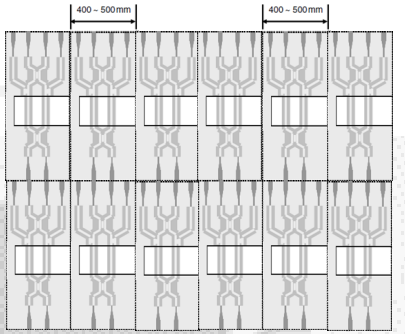
出典：FLOPSは市販PC計測結果、MIPSはwikipedia資料。

Earlier statements:

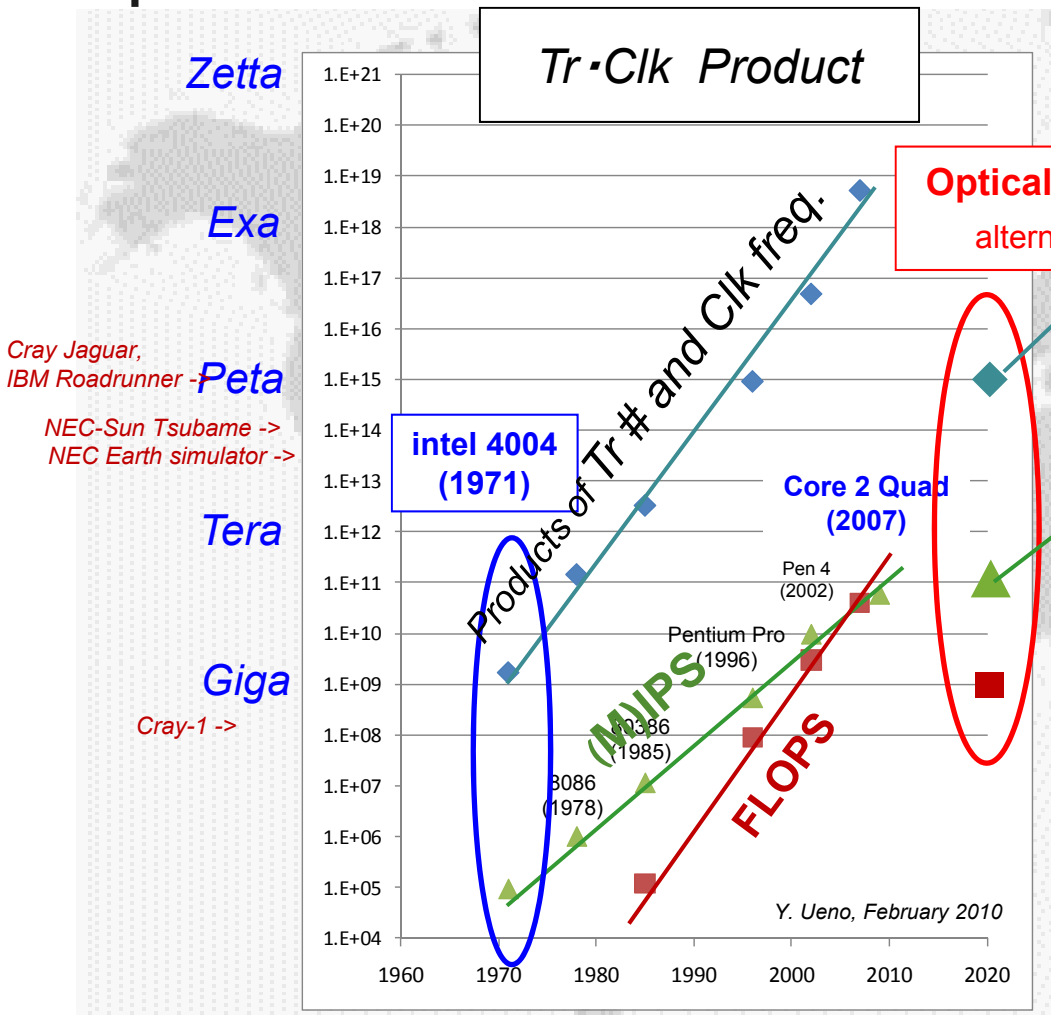
- already relying on parallel-processing structures, which are probably pushing-up their electric-energy consumptions.
- Increasing demands in 2010-2050 are FLOPS-type demands or MIPS-type demands??

◆ no. of Trs. times clk freq. 10x every 4 yrs.
■ FLOPS 10x every 4 yrs.
▲ Instructions per sec. 10x every 7 yrs.

Relative performance of optical-processor 4004



number-integration



Optical processor (estim.)
alternative to Moore's law

Tr・Clk matches to Pentium Pro(1996)

(M)IPS matches to Core 2 quad (2007).

FLOPS will be weak.

Power consumption: 200 Watts

◆ no. of Trs. times clk freq. 10x every 4 yrs.
■ FLOPS 10x every 4 yrs.
▲ Instructions per sec. 10x every 7 yrs.

出典：FLOPSは市販PC計測結果、MIPSはwikipedia資料。

sample-spec. numbers of optical-80386

250 × 250μm² o-Tr's on 6" GaAs wafer

			e-80386	e-Core2_quad	optical 80386	
			(32bit)	(32bit/64bit)	(32bit)	
			1985	2007	2025	
		unit				
1	Clk	Hz	1.20E+07	2.60E+09	3.00E+11	
2	Tr		275,000	2,000,000,000	275,000	
	Clk*Tr		3.30E+12	5.20E+18	8.25E+16	
	Clk*Tr (relative)		6.35E-07	1.00E+00	1.59E-02	
3	Flops		1.2E+05	4.0E+10	-	
4	(M)IPS, measured and estimated		1.10E+07	6.00E+10	2.75E+11	
	(M)IPS (relative)		1.83E-04	1.00E+00	4.58E+00	
5	power consumption	Watt	3	80	2.00E+04	20 kW
6	energy / instruction	J	2.73E-07	1.33E-09	7.27E-08	
	energy / instruction	fJ	2.73E+08	1.33E+06	7.27E+07	
	energy / instruction (relative)			1	5.45E+01	
7	energy / clk	J	2.50E-07	3.08E-08	6.67E-08	
	energy / clk	fJ	2.50E+08	3.08E+07	6.67E+07	
	energy / clk (relative)			1	2.17E+00	

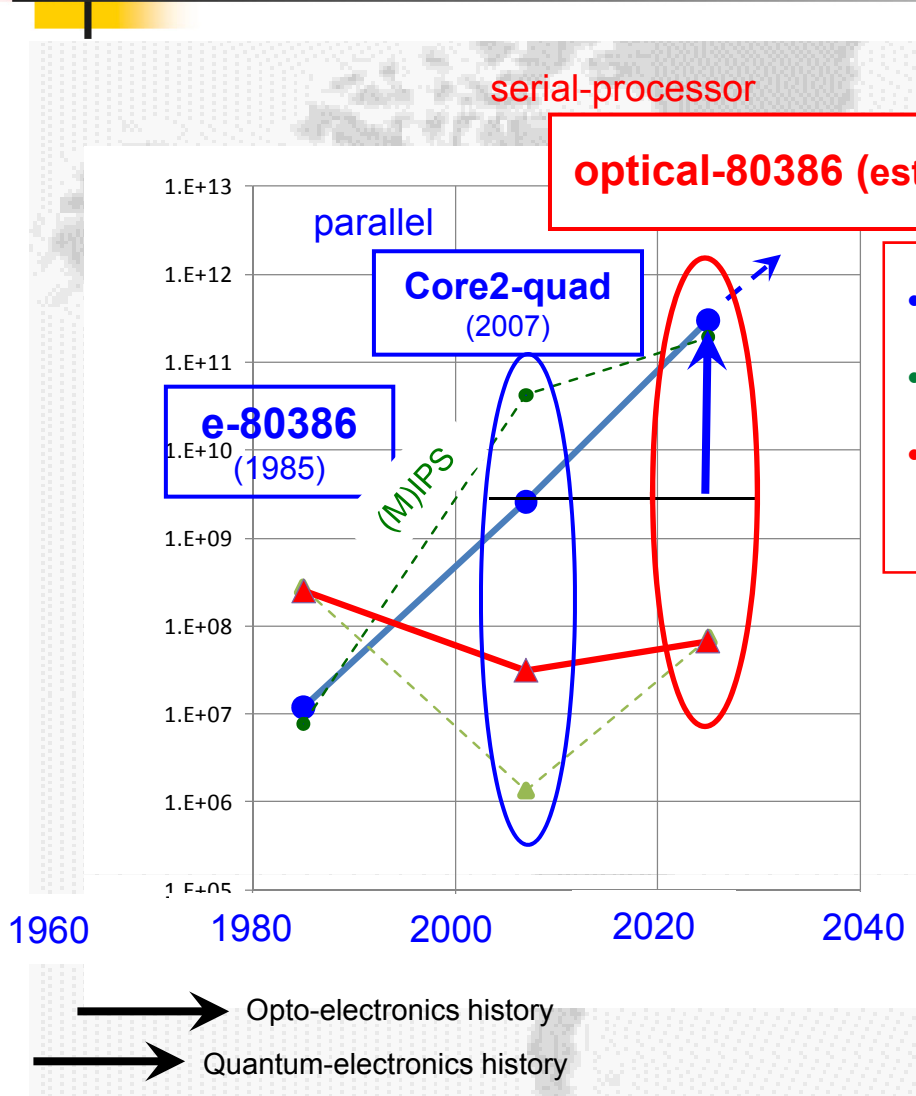
optical-processor 80386 (with 300,000 gates)

advantage of serial-processor

latency, synchro issues → 1/100 or less

programming costs, risks → 1/100 or less

→→ technical efficiency → 100x / 15 yrs



- Clk: 100x
- MIPS: increases
- energy per clock: comparable (70 nJ/clk)

(all relative to Core2-quad)

Possible to integrate??

$250 \times 250 \mu m^2$ o-Tr's

on 6" GaAs wafer

⇒ **275,000** Tr's (=80386)

Previously,

Tr number × Clk: 100x / 8 yrs

FLOPS 100x / 8 yrs

MIPS 100x / 15 yrs

If anybody likes to keep *this talk's slides*, please email me*!*

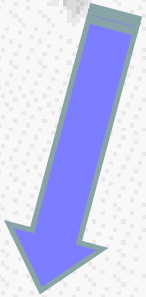
Summary (ssdm 2010)

- Impacts of ICT-related energy consumptions
  e.g.: energy supply to Data centers in USA: 10 nuclear reactors
  heat energy from one server rack: 20-kW level.
  many-folded parallel-data-processes will *the best for all* applications, thru. 2050 ***?***

- <speed, energy, size> of all-optical gates, at present: <200G, 3 pJ/bit, length, 1 mm>

- <speed, energy, size>, 2nd or 3rd generation: <300G, 0.3 pJ, 250 μm^2>

- in Materials Research (semi-classical quantum):
  optical acceleration (incl. gate scheme),
  electron-photon interaction (little studied),
  higher-density excitations (w/ larger hetero-barrier).



- optical-4004: MIPS, comparable to Core2 quad. Electric energy, 200W.
- optical-80386: 300,000 gates. Energy per clk, comparable to Core2 quad.
  (this will probably save energy and costs, for a group of serial-process-oriented tasks.)

an alternative to 40-year-long Moore's law

Thanks to Co-authors and Collaborations

Co-authors:

Jun Sakaguchi, PhD course, UEC

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Takashi Ohira, master course, UEC

Ryoichi Nakamoto, master course, UEC

Fellran Salleras, postdoc, UEC (from **ETH**, Laussanne)

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and several more.

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Kiyoshi Asakawa, **NIMS (Univ. Tsukuba)**

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