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Ultrafast, low-energy-consumption, semiconductor-based, all-optical devices

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***Abstract*— The relatively-low electric-energy-consumption level (3 pJ/bit) of the most fundamental all-optical semiconductor gate device (i.e., signal-wavlength converter), with respect to its ultrafast response speed in the 200-Gb/s range, are briefly reviewed.**

I. INTRODUCTION

It was December 1901 when Mr. Guglielmo Marconi and his colleagues finally succeeded in their transmit-and-receiving the mankind-first, wireless signals across the Atlantic Ocean. After our research activities in the materials, devices, and system schemes in the last 100 years since then, the world-wide demands in network systems' capacities are continuously rising up. For instance, the number of optical-fiber-link subscribers in Japan has exceeded that of DSL in 2007 (Fig. 1(a) [1]). In both Korea and Japan, the numbers of optical-fiber-link subscribers per 100 inhabitants have reached nearly ten [2]. The network capacities between wireless base stations have been strengthened by optical-fiber links on an every week basis.

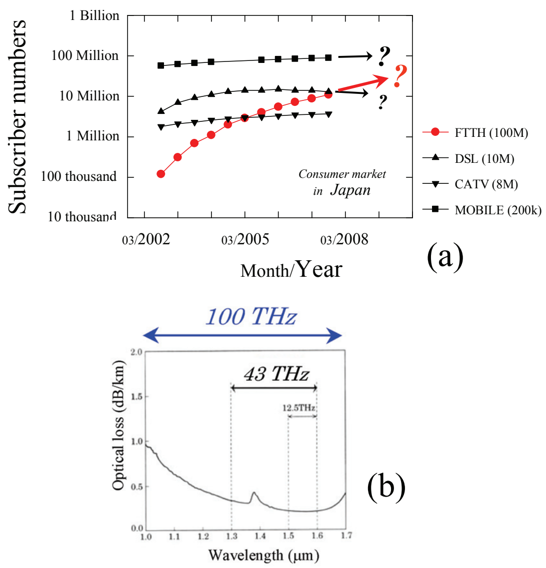

Fig. 1: Broadband subscriber numbers in Japan (a), in contrast to the bandwidth of our 'optical wires' (b).

One of the two most important origins of these up-to-date broadband optical-communication technology is the transparency bandwidth throughout 125-μm-diamieter silica fiber cables developed well in the last 40 years. This transparency bandwidth approaches *100 THz (10^{14} Hz)* in the optical frequency domain (Fig. 1(b), even though that of the most conventional C-band is limited to only 4 THz by the Er-ion-doped fiber amp's gain bandwidth). The other important origin is electronic signal processors developed in these 40 years since Intel Corporation had released the mankind-first signal processor, Intel 4004 in 1971, whose signal's bit-rate was 500 kb/s (Fig. 2(a)). Recently, in contrast, the 10-Gb/s electric signal's waveforms such as the one we are generating in our lab. (Fig. 2(b)) is not special at all.

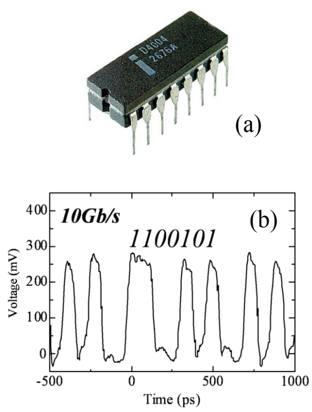

Fig. 2: the first, 500-kb/s processor, Intel 4004 in 1971 (a), in contrast to the recent microwave signal's waveform (b).

As the electronic signal-processing speed has been accelerated from classical 10 Mb/s to beyond 1 Gb/s, *however*, the energy-consumption rate per one-bit gate operation has more rapidly been increased as a matter of fact. This is recognized as one of the simplest reasons why the nearly-40-year-long continuous growth in the popular CPU clock frequency has recently been stalled near 3 GHz [3], and now dual-core and even quad-core processors have been developed. In other words, silicon materials inside such CPU chips of today could otherwise become chemically unreliable due to its own huge heat-energy dissipation, since the speed acceleration deteriorates the energy consumption rate per one-bit gate operation. In a similar manner, the electric energy consumed 24 hours a day by millions of IP router processors has started to appear as a bigger and bigger issue, simply because opto-electronic devices' bit-rates are regularly much faster than those of standard signal processors or CPU's. One of the symbolic examples would be Cisco's high-end router released in 2006 [4], which consumes 1-MW electricity (and another 1 MW for air-conditioning its machine room), for taking care of total 92-Tb/s through-put signals in its 40-Gb/s baseline bit-rate. These numbers indicate that this router's signal processors consume total 10 nJ per one-bit IP-routing process.

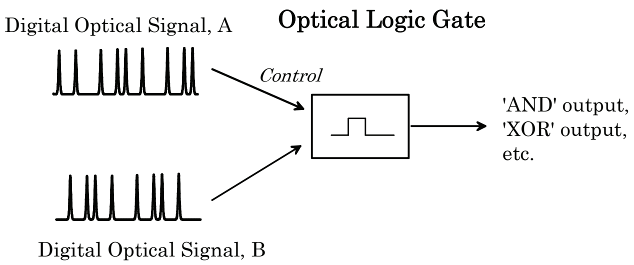

Fig. 3: Fundamental scheme of an all-optical gate.

Table I: Diversity in the types of all-optical gate operation [6-19], since early 1990's through present

Bit rate	Logic function	Year	Reference
640 Gb/s	Demultiplexing	2007	[6]
640 Gb/s	Clock extraction	2007	[7]
320 Gb/s	Wavelength conversion	2006	[8]
200 Gb/s	Wavelength conversion	2009	[9]
160 Gb/s	Wavelength conversion	2005	[10]
160 Gb/s	Wavelength conversion	2000	[11, 12]
100 Gb/s	AND gate	1998	[13]
80 Gb/s	3R regeneration	1999-2001	[14, 15]
10-40 Gb/s	Add-Drop, 3R, λ-conv, etc.	1990's	[16]
1 Gb/s	Shift register	1996	[17]
1 Gb/s	Random number generation	1999	[18]
1 Gb/s	Regenerative-loop memory	1998	[19]

Table II: One of future directions, optical signal processor

Specification	Electronic Intel 4004	Optical signal processors: Present research level	Near-Future level
Year	Year 1971	Year 2000-2010	Year 2010-2025
Speed	500 kb/s	200-300 Gb/s	300-600 Gb/s
Energy consumption per bit		3-10 pJ /bit/gate	0.1 pJ /bit/gate
Foot-print size	70×70 μm^2	1,000×3,000 μm^2	200×200 μm^2
Number of gates	2,300 transisters	few per chip	3,000 gates per chip
Energy dissipation			100 Watt per chip

II. *ALL-OPTICAL* SIGNAL PROCESSORS IN THE NEAR FUTURE

After the long-running R&D activities for developing faster electronic processors in the last 10-20 years, their highest speed seems to be limited to 40-100 Gb/s [5], physically due to signal processors' heat dissipation (60 pJ/bit in Ref. 5), microwave signal's connection losses, and moreover their propagation losses in these ultrahigh-frequency ranges. This microwave devices' bottleneck in *speed and energy consumption* has been believed to be broken-through in the future, by our technological "*transition*" from electronic to all-optical signal processors with III-V semiconductor materials (instead of silicon). Even though the global R&D activities for all-optical signal processors such as the one in Fig. 3 are staying in pre-competitive stages up to now, varieties of all-optical gate operations have experimentally been proposed and studied in some details by world-wide research institutes in the last decade (Table I). The bit rate of optical signals in these pioneering experiments has ranged in nearly three orders of magnitudes, i.e., from 1 Gb/s up to 640 Gb/s. Furthermore, as long as the energy of optical one-bit signal that all-optically controls (i.e., drives) these gates in bit-wise manners is concerned, its (optical) energy consumption has been staying in a very low range, that is, in the order of 100 fJ per one-bit signal pulse, throughout the experiments in Table 1. (In some of them, some of the present authors had directly been involved in.)

In Table II in this work, the present authors have proposed a set of possible specifications of "optical signal processors" in the near future, with paying attention to more fundamental all-optical gates in the recent research level in Table I. High-density integrated optical signal processors in bit rates between 300 and 600 Gb/s in years 2010-2025 will be realistic in front of us researchers, in the following manners.

Regarding the density of optical integration, assuming the foot-print size will be reduced to 200×200 μm^2 by combining independently on-going nano-photonics research near us such as the monolithically integrated photonic-bandgap-circuit technology [20-21] together with the growing planar-lightwave-circuit (PLC) technology in industrial institutes [22], one optical processor chip will start containing as many gates (about 3,000) as that in the first electronic signal processor, Intel 4004 (2,300). One of the other challenging parts indicated in Table II is the *electric* energy consumption, which must be in the order of 0.1 per one-bit gate operation so that the total energy consumption per one chip does not exceed 100 Watt, even with such ultrafast gate-operation times per second. This degree of reduction in energy consumption seems to be *realistic* in the near future.

Taking into account such optical signal processor vision for our future, we in this work will outline some of our recent results, where we've independently paid attention to the dependence of the *electric* energy consumption of our all-optical gate on its speed in the following Sections. III and IV.

III. OUR ALL-OPTICAL SEMICONDUCTOR GATE EXPERIMENTS IN THE 200-GB/S BIT-RATE RANGE

Figure 4 shows few quick views from our all-optical gate-operation experiments in 2006-2008 [9, 23]. Fig. 4(a) shows one of the simplest structures of our all-optical semiconductor gates (i.e., delayed-interference signal-wavelength converter (DISC) [8-12]), (b)-(c) show microscope photos of semiconductor-optical-amp (SOA) chips whose lengths are ranging from 500 to 1,100 μm, and (d) shows a schematic view of the most important, ultrafast photon-electron interaction mechanism that physically drives the gate.

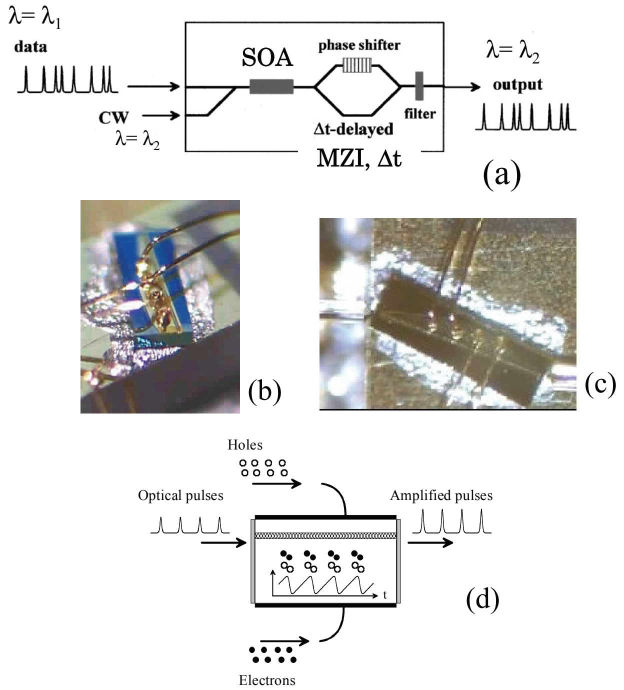

Fig. 4: All-optical gate-operation experiments in our lab. (a) device structure, (b) SOA chips, (c) material physics.

Fig. 5(a) and 5(c) show typical waveforms of our 200-Gb/s, 4,992-bit-long optical input data signal, measured with an all-optical cross-correlator with using a conventional inorganic nonlinear-optics crystal (FR-103XL, Femtochrome Research, Inc., USA). Our experimental set up is shown in Fig. 5(b). The uniform input data signal was generated with a 12.5-GHz synchronously-and-harmonically mode-locked fiber-ring laser (Ultrafast Optical Clock, Pritel, Inc., USA), dispersion-decreasing adiabatic-soliton-compression fibers (Pritel, Inc.), commercial $LiNbO_3$ e-o modulators, research-level electro-absorption modulators, a 12.5-Gb/s electronic pulse-pattern generator (Anritsu Corp.), four stages (two commercial and two home-made) of low-dispersion low-loss 1:2 optical multiplexers, a home-made high-precision sub-harmonically-synchronized optically sampled monitoring system, and several of low-dispersion Er-doped fiber amps. The pattern length of the microwave 12.5-Gb/s baseline data signal was set to 312, so that the waveform-monitoring system synchronizes to the data pattern in the 312:1 sub-harmonic frequency (40 MHz). In the meantime, the pattern length of the 200-Gb/s data signal reached 4,992 after being separated with intentionally-long de-correlation time-delay cables and then all-optically multiplexed by a factor of 16 from the 12.5-Gb/s signal, with the four stages of multiplexers.

In the following experiments, several types of semi-customized nonlinear SOA chips from EU, USA, and Japan were carefully diagnosed-and-selected, and then precisely coupled to the in-coming and out-going optical signals with our lensed-optical-fiber cables (Namiki Precision Jewel Co., Ltd., Japan, partially seen at the respective semiconductor-waveguide facets in Fig. 4(c)) [23]. Several types of Mach-Zehnder interferometer parts for use inside the DISC gate were built with using AR-coated bi-refringent calcite crystals as fixed short-time delays in the order of a few picoseconds, and several polarized optics combined in the commercially available low-loss cassettes-in-cartridge manners (Optoquest Co., Ltd., Saitama, Japan).

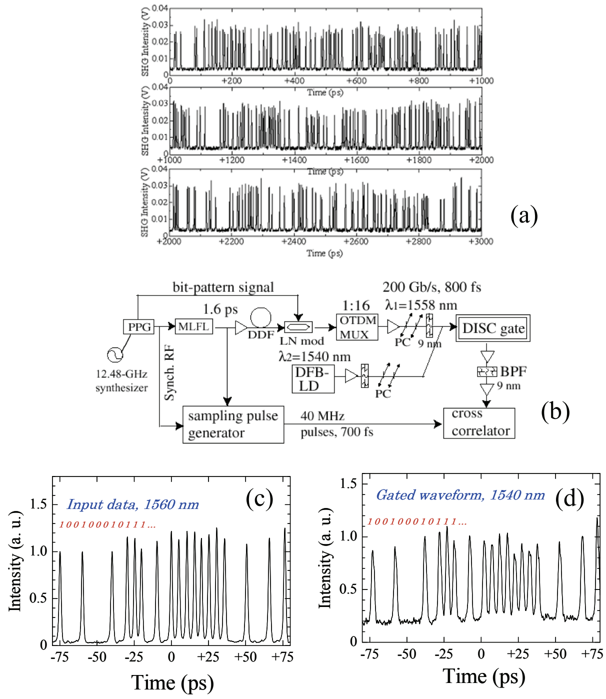

Fig. 5: Our 200-Gb/s experiments in May 2008 [9].

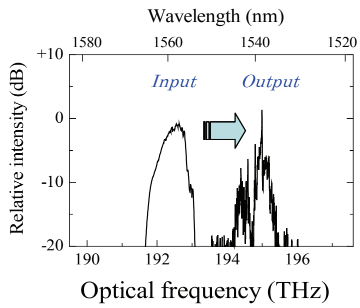

Fig. 6: Spectra before and after the wavelength conversion in a wavelength range, 1520-1580 nm (i.e, in an optical-frequency range, 190-198 THz) [9].

Fig. 5(d) shows one of the typical 200-Gb/s optical output data signals carrying the same binary-code pattern '10010010111', taken from the output port of the wavelength-converter gate in Fig. 4(a). According to its principles of operation [12], each of the output data signal pulses was generated after each of the 200-Gb/s λ_1 (1558 nm) input data signal pulses in Fig. 5(a) all-optically gated the co-propagating λ_2 (1540 nm) cw light. The ultra-short width of the output data-signal pulses approximately matched to that of the input data-signal pulses. (In fact, the width of our output pulses was more identical to that of the input pulses, than those previously reported in Ref. 8.)

Figure 6 shows of optical data signals' spectra before and after the wavelength conversion in the optical frequency scale, as well as in the conventional wavelength scale. As is shown in the figure, the center wavelength (center optical frequency) of the optical data signal was converted from $\lambda_1 = 1558\ nm$ ($f_1 = 192.4\ THz$) to $\lambda_2 = 1540\ nm$ ($f_2 = 194.7\ THz$). The frequency components of the respective spectra were broadened to both sides of the center component, due to the digital modulation. Consequently, the width of our frequency spectra was in the order of the bit-rate (200 GHz) in a manner similar to Return-to-Zero (RZ)-format experiments done in much lower bit-rates. *[It should be noted that the reason why the envelope of our measured λ_1 spectrum looks smoother was because this spectrum was averaged in time over inherently instable optical-frequency position of our 12.5-GHz mode-locked pulses. The λ_2 spectrum looks less smooth in contrast, because the stability of optical-frequency position of the converted signal was dramatically improved after 're-generated' from a highly stable DFB-laser light.]*

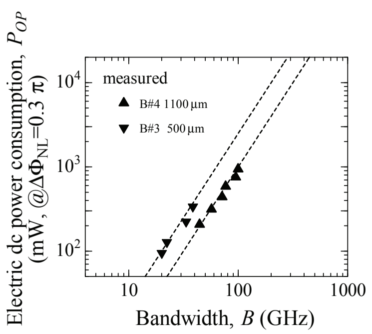

Fig. 7: Measured dependence of electric power consumption on the wavelength-converter's bit-rate [23].

IV. DC-ELECTRIC ENERGY CONSUMPTION RATE WHICH SCALES LINEARLY WITH BIT-RATE

Almost all of the authors in previous experiments since early 1990's [6-19] had diagnosed the *optical* energy consumption, that is, the energy of optical input data pulse which were all-optically driving their all-optical gates. As was mentioned in Sec. II, this amount of energy has been very small, in the order of 100 fJ per one-bit gate operation. It should be noted here these all-optical gates continuously consume-and-dissipate *several times larger* electric energy, for electronically biasing the SOA with a direct current (in the order of 100-500 mA) across the electric potential between its anode and cathode (about 1.0 Volt). Typical amounts of the dc-bias currents had been described in almost all of the above-mentioned mile-stone reports. Any scientific behaviors of the amount of dc-electric energy consumption had, *howeve*r, never been systematically studied until very recently, to the authors' knowledge.

Figure 7 shows two series of dependences of the dc-electric power consumption in our all-optical SOA-DISC gate on its effective gate speed [23]. These results have indicated unexpectedly simple, *bi-linear dependence* of the power consumption on the gate speed, in the range from 20 through 100 Gb/s. Consequently, they indicated *linear dependence* of the energy consumption per one-bit operation on the gate speed. The measured numbers were only 5 pJ/bit in 50-Gb/s, 10 pJ/bit in 100-Gb/s, and 20 pJ/bit (extrapolated) in the 200-Gb/s bit-rate. Throughout the experiments in Fig. 7, we accelerated the gate speed with the conventional optical-acceleration scheme (i.e., holding-beam scheme [24]).

Table III: Electric energy consumption per one-bit operation

Bit rate	after conventional acceleation	after effective acceleration	Reference
200 Gb/s	20 pJ/bit/gate (extrapolated)	3 pJ/bit/gate	[9, 23]
100 Gb/s	10 pJ/bit/gate		[23]
50 Gb/s	5 pJ/bit/gate		[23]

Table IV: The active density numbers in the ultra-hight-purity crystalline semiconductor materials in our experiments

Item	Value (typical)	Reference
Injected electron's energy consumption per one-bit operation	3 pJ/bit	[9]
Volume density of heat-energy dissipation	50 MW/cm^3	[9]
Injected electron's number consumption per one-bit operation	2×10^7 electrons/bit	[9]
Surface density of injected electron's current	40 kA/cm^2	[9]
Surface density of propagating optical signal's average power	2 MW/cm^2	[9]
Volume density of (unintentionally doped) impurity atoms	< 1 × 10^{16} cm^{-3}	
Volume densities of excited electrons and holes	0.3 to 3.0 × 10^{17} cm^{-3}	
Volume densities of group-III and group-V atoms	2.0 × 10^{22} cm^{-3}	
Three-dimensional device size (width, thickness, and length)	300×100×1,100 µm^3	[9]

We are expecting that the energy consumption in the order of 20 pJ/bit in the recent research level will be dramatically reduced in step-wise manners in the near future (Tables II and III). More recently, in fact, energy consumption of about 5 pJ/bit was sufficient in the experiments in Refs. 8 and 10, where they effectively accelerated the gate with a blue-shifted band-pass-filtering scheme [25]. In our 200-Gb/s experiments, 3 pJ/bit was sufficient where we accelerated the gate with a nonlinear-polarization-rotation scheme [9].

The ultrafast (in speed), very energy-efficient (in energy consumption), and compact-size nature of the all-optical gates are originated from their high-purity high-density nature of the crystalline semiconductor materials inside the SOA's. In Table IV, we summarized the densities of optical, electronic, and thermal properties in those semiconductor materials under their carefully designed working conditions.

V. OTHER NEW APPLICATIONS OF ALL-OPTICAL GATES

We must be able to extend our fundamental gate to varieties of new devices including flip-flop buffer memories [6-21]. Figure 8 shows another example, i.e., a mode-locked-pulse laser that consists of the gate in Fig. 4, a positive feedback loop, and an external cw laser. The width of its coherent, controllable, optical-frequency-comb spectrum has extended to 550 GHz at present [26-27]. In the future, this scheme will reduce the sizes of optical-frequency-comb-based *optical-metrology equipments*, from NIM-rack sizes to personally portable sizes, for use in our biological, continental, under-ground, submarine, and even cosmic research fields.

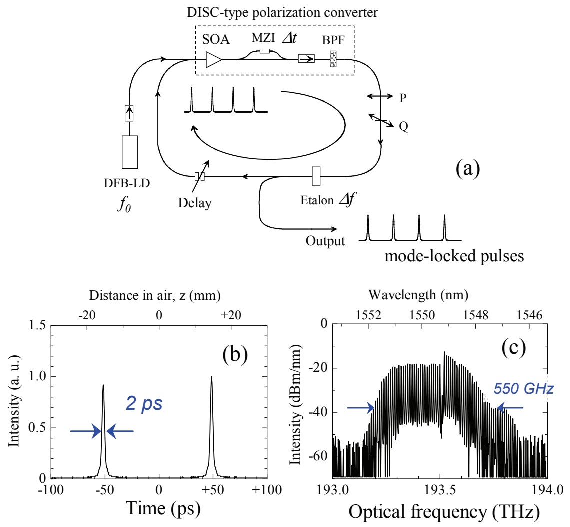

Fig. 8: Mode-locked pulse generation [26, 27].

VI. CONCLUSION

With referring to one of our future vision (Table II) and the recent 200-Gb/s gate research results (Sec. III), the electric-energy-consumption level of all-optical gates has been decreased to 3 pJ/bit (Sec. IV). This level seems to be one-to-two orders of magnitude smaller than those of electronic devices in the respective speed ranges ([5] in Sec. I).

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