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

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Abstract: Evolution in energy efficiency of many-core parallel processors through year 2025 looks unclear, because the serial speed of new electronic cores has stopped to evolve. With reviewing application-research activities in opto-electronics, instead, the author estimates what possibilities the still-crude 100-times-faster serial processors (e.g. 200-Gb/s) will contribute through year 2025.

1. Introduction

In the last 40 years (since this ssdm conference started in 1969), our world has changed dramatically. Until 10 years ago, semiconductor devices, systems, and their heat dissipations used to be *not* consuming *nor* influencing visible portions of the total primary energy supply (TPES, from crude oil, coal, natural gas, nuclear powers, and others) of us, the mankind. Now in USA, data centers are consuming 1.5% of its nation-wide electric-energy supply [1], which corresponds to all outputs from 10 nuclear power reactors. In USA, the amount of primary energy supply (40 EJ/year= 40×10^{18} J/year) for generating the nation-wide electric energy occupies almost 40% of USA's TPES (100 EJ/year) [2]. Figure 1(a) shows the unexpectedly steady increases over the last 40 years, in primary energy supplies for generating electricity in the world and selected countries including the above number (40 EJ/year) from USA, according to the statistics in [2].

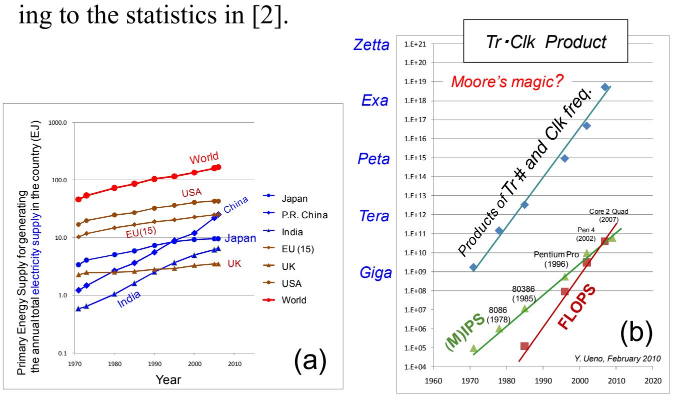

Fig. 1. 40-year-long increases in international-level energy supplies (a) and indexes of micro-processor performance (b).

The primary energy supply for generating world-wide electricity reached 170 EJ/year. Silicon and other semiconductor materials are playing (or about to play) roles in almost all electricity-consuming systems such as computers, communication systems, back-lights of displays, and now room lights. Many of the biggest impacts to our world in the last 40 and coming 40 years will be strongly influenced by semiconductor materials industry and particularly by the performance of micro-processors.

Instead of the number of transistors which appears to follow the Gordon Moore's law [3], Fig. 1(b) in this work shows the product of clock frequency and transistor number (Tr·Clk), measured floating-point operations per second (FLOPS), and measured instructions per second ((M)IPS) of micro-processors in the last 40 years since its birth in 1971. This figure suggests that the big growth of the order of 10^{10} in FLOPS is proportional *not* to Tr but to the product Tr·Clk. It suggests next that a factor of 10^4 (among the factor 10^{10}) came from growth in Clk, while another, much larger factor of 10^6 came from the Moore's law (growth in Tr).

The larger growth factor (10^6) from Tr than that (10^4) from Clk is symbolic; nearly 40 years we had already relied on and will rely with coming many-core processors on even furthermore-folded parallel-processing architectures which consist of command-level, intra-core-level, intra-processor-level, intra-sever level, and intra-network level, rather than the transistor speed. Many network applications will tolerate with more-folded parallel architectures, such as video streaming where time delays between packet arrivals and machine loads in packet reconstruction procedures are accepted somehow. Other applications may not tolerate, however [4]. For such *intolerant* applications, it could be difficult for skilled programmers to keep the time-to-output efficiency in all tasks, and/or to enhance the system performance per unit energy in the coming 40 years.

In the above majority R&D direction with developing much more cores, the time-domain speed of transistors seem to completely stop to grow beyond 3 GHz. The coming big challenges are located still in the new few generations of ultra-fine lithography, and newly in the increasing microwave losses along the intra-processor microwave-guided connections, instead of new challenges in transistors. The microwave-connection-loss issue is inherent and will be enhanced more by the still expanding parallel architectures.

An ultimately alternative direction has been widely recognized to be the extremely-quantum signal-processing system (called as quantum computer) since nearly 20 years ago. It is believed, however, to take care of an extremely limited range of existing signal-processing applications.

2. 300-GHz optical gates and memories for network systems

It seems safer for us in coming 40 years to have an option other than the above two directions (furthermore parallel architecture with the fixed speed and quantum computer). We probably have one option, in fact; Scientifically near the middle point of the above two directions, a group of international research institutes have been studying the third direction, that is, optical-signal-processing devices and materials [5-12].

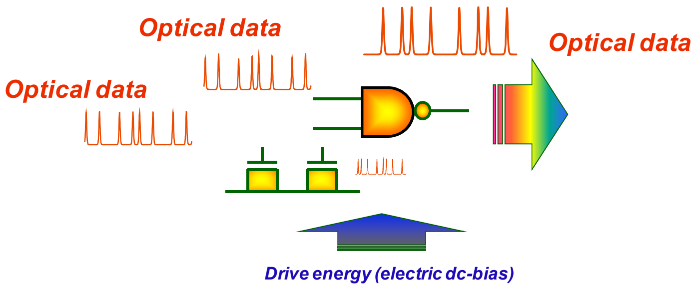

Fig. 2. Fundamental elements of optical processors are optical logic gates and optical buffer memories [5-12].

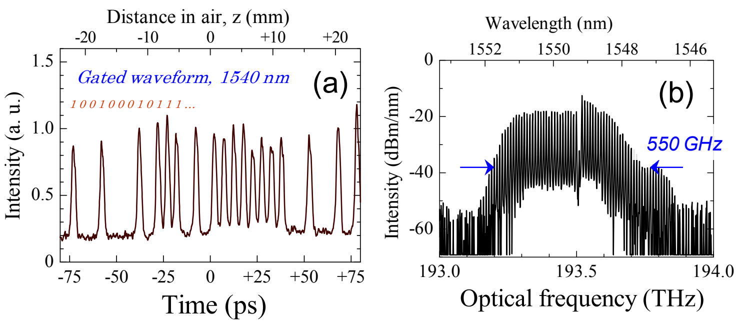

Fig. 3. 200-Gb/s data waveform generated by our III-V semiconductor optical gate (a)[10] and the 550-GHz bandwidth of clock generated with a similar optical-gate scheme [7].

This group of institutes including us (UEC) has been trying to develop optical de-multiplexers, optical wavelength converters, optical 3R repeaters, synchronized optical clock sources, optical buffers, etc. so that they work in the near-future optical communication systems. The typical optical data speed has reached 200-to-300 Gb/s [6, 8, 10]. The electric-dc-bias energy consumption has been improved dramatically to less than 10 pJ/bit [9], from those 10-to-20 years ago. The sizes of elementary gates and buffers are, in contrast, apparently much behind (larger than) modern electronic processors; The presently typical sizes are about 500×500 μm.

3. 300-GHz optical gates and memories for optical processor in year 2025

Most previous and on-going research goals have been limited to within optical-communication-node systems and are not yet expanded to an optical-processor vision, mostly because of their spatial sizes and partially because of their electric-bias-energy levels which still look behind electronic processors. Nontheless, because of the above-mentioned present status of electronic processors, we have very recently started estimating the potential performance of optical processors in year 2025, taking into account potential progresses in bias-energy consumption and size, from material physics viewpoints (i.e., semi-classically-quantum opto-electronics with III-V semiconductors). Depending upon the pros and cons of optical-porocessor's potential performance, the group of parallel-intolerent signal-processing applications will be specified better, hopefully in collaboration with computer specialists. This type of activities will support R&D of all-optical devices for use in ultrafast network-node systems, as well.

In this invited talk, we will present an outline of the above-mentioned estimations towards optical processors. Any sudden ideas, weird ideas, or fundamental questions are always welcome during and after the talk.

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