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Trends in 160-Gb/s OTDM materials and circuits research and our on-going activities in UEC

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1. Introduction: this innovative research area, optical-TDM technology, from 20 years ago towards our near future

As an electromagnetic wave that could carry information between us, the inherent *advantage* of lightwave over wired- and wireless-microwave has been clear since 19th century, which is its ultrabroad bandwidth. After the 30-year-long research since the births of super-low-loss single-mode silica fibers (bandwidth> 50 THz) and super-small-sized reliable laser diodes (f= 200 THz= 2×10^{14} Hz @λ= 1.5 µm) in the 1970's, a wavelength-division-multiplexed lightwave can carry 10-Tb/s ultrahigh-bitrate data per one optical fiber whose diameter is only 125 µm [1]; The digital bitrate of 10 Tb/s potentially takes care of maximum 100,000 fiber-to-the-home (FTTH) subscribers.

The modern packet-network's design flexibility and consequently our information-communication technology between those broadband subscribers are, however, supposed to be strongly restricted by the electronics bottleneck; We still need optical-electronic-optical (o-e-o) signal conversion every signal-processing point, such as transceivers, routers, and buffers. Most of the volumes of 'optical' communication systems are still occupied by 'electronic' processors and o-e-o converters (Fig. 1(a)), whose speed seems to be inherently limited to 40-100 Gb/s (for keeping their power consumptions within a practically acceptable range). This speed limit of every electronic circuit is restricting the lightwave's potential bandwidth of 10-50 Tb/s.

A transition from electronic circuits (Fig. 1(a)) to optical circuits (Figs. 1(b) and Fig. 2) that make the best use of the lightwave's potential bandwidth has been one of the biggest targets for optical scientists and engineers. The first such motivation is traced back to the pioneering works done by Dr. Nicolaas Bloembergen in 1960's. From the 1960's through 80's, scientists searched varieties of optical materials and physics from their optically nonlinear susceptibilities ($\chi^{(2)}$ and $\chi^{(3)}$), so that optical signals could interact more strongly with each other [2]. The required optical powers for those optical interactions were, however, too strong to start engineering practical signal processors.

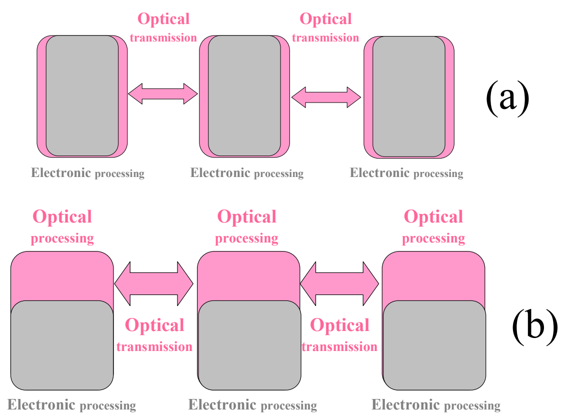


Fig. 1: Optical versus electronic circuit ratios in optical-network systems. (a) present, (b) future potential.

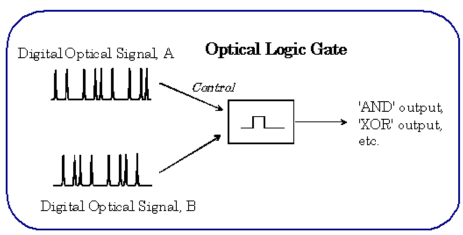


Fig. 2: Optical signal-processor unit

The first significant generation of ultrafast optical signal processors such as nonlinear optical loops (NOLM) and nonlinear directional couplers (NLDC) was intensively studied *since 20 years ago*, ie., mid 80's, with using either (a) optical-fiber waveguides [3] or (b) slightly off-resonant semiconductor waveguides [4] as more efficient optical- interaction media. In 2000, record-fast 640-Gb/s TDM transmission was demonstrated with using the NOLM scheme as an optical demultiplexer [5]. More recently, the typical interaction length of NOLM's has partially been improved from some hundreds meters down to a few meters by developing highly nonlinear fibers (HNLF) with or without photonic-crystal structures. Nevertheless, the optical powers required in these research-level processors are several orders of magnitude stronger than electronic alternatives.

The transition to the second-generation took place in mid 1990's, in which resonant semiconductor-waveguide devices started attracting attention because they can realize ultrafast responses, in addition to their inherently shorter interaction length and cm-sized integration capabilities [6, 7]. After major basic schemes were invented with semiconductor waveguides either in a resonantly absorptive regime or in an amplification regime, several groups of innovative applications research have been going on with semiconductor optical amplifiers (SOA's) as highly efficient, optical interaction media [6]. From mid 1990's, the concept, optical-TDM (OTDM) system, has globally been spread.

2. Basic schemes and more recent milestone achievements in the OTDM processor technology

Figure 3 shows one of the popular gate schemes, ie. an optical wavelength converter, in which an SOA is working as an all-optical interaction medium between two independent optical signals or waves, λ_1 and λ_2 [8]. When the optical pulsed data signal is input to the SOA, every pulse in the signal is efficiently amplified inside the SOA, the density of electron-hole pairs is strongly modulated, and then the effective refractive-index of the SOA waveguide is modulated (Fig. 4(a)). The electron-hole pairs are continuously injected from outside SOA with an electric dc bias current. When the continuous lightwave co-propagates with the optical pulses, the continuous wave probes the optically modulated refractive index, phase-modulated, and furthermore amplitude-modulated after the optical Mach-Zehnder interferometer (Fig. 3).

In more details, the rise time of the all-optical response curve is extremely fast due to the stimulated-emission process in the SOA. In contrast, the recovery time of the response curve before MZI is longer than 30 ps or even 200 ps (Fig. 4(b)) due to the semiconductor's intrinsic lifetime limited by spontaneous-emission and non-radiative-relaxation processes. After the MZI, the slow recovery component is dramatically filtered out, in principle (Fig. 4(b)). Thus, more generally speaking, this basic gate scheme consists of a "nonlinear photonic (ie., quantum-electronical) material" and a "linear lightwave circuit."

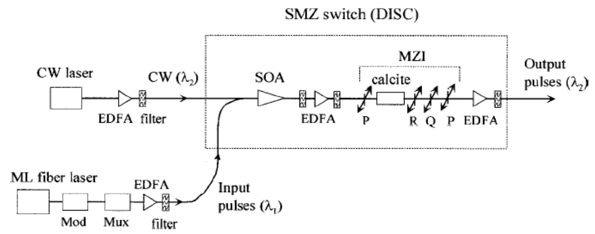


Fig. 3: All-optical gate scheme (SMZ-DISC)

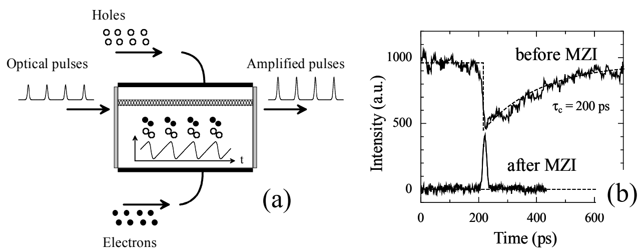


Fig. 4: Ultrafast, all-optical interaction
(a) inside SOA,

(b) measured response curves after SOA

Some of the milestone achievements with gate schemes similar to the SMZ-DISC were bit-error-free 160-Gb/s demultiplexing, 80-Gb/s 3R regeneration, and 160-Gb/s wavelength conversion (Fig. 5) from Japan around the centennial year 2000.

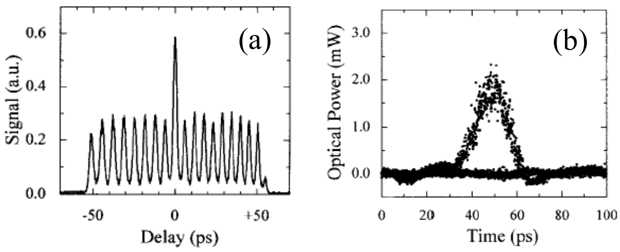


Fig. 5: Record-high-frequency 160-Gb/s waveforms after a DISC wavelength converter in 2000. (a) averaged with higher resolution, (b) sampled with lower resolution after demultiplexer.

More recently, the bitrate record of the wavelength conversion using a similar scheme has been pushed to 320 Gb/s by an European research group [11]. With these OTDM circuit technology, this European group and a few other groups have started experimentally building innovative, 160-Gb/s packet router systems, and successfully demonstrating their performance.

3. Homemade, all-optical gate circuits, 200-Gb/s signal generators, and signal monitoring systems in UEC

In UEC, we are studying the physics of, and upgrading the designs of, these all-optical gate circuits for expanding their capabilities. Because both optical and electronic equipments in such an ultrahigh-frequency region are basically *not* commercially available, we are developing core parts of optical-signal generators and monitoring systems, as well. The OTDM signals in Fig. 6 were generated by combining a 12.5-GHz synchronized mode-locked fiber laser, an optical pulse compressor, 16x optical multiplexers, and chromatic-dispersion compensators. Their waveforms were monitored by an optical cross-correlator, whose time resolution is improved to less than one picosecond with using an adiabatically compressed 0.5-ps pulsed probe.

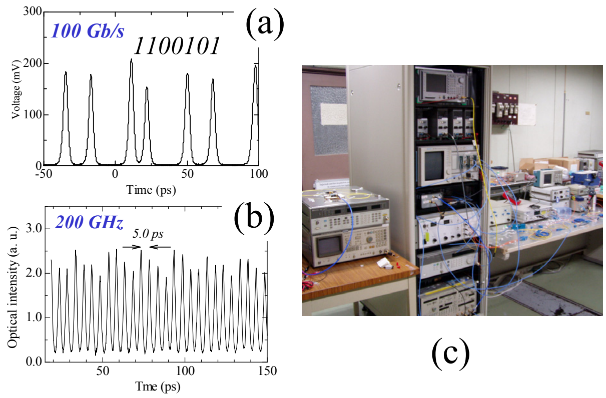
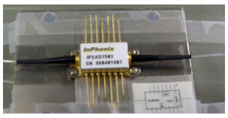


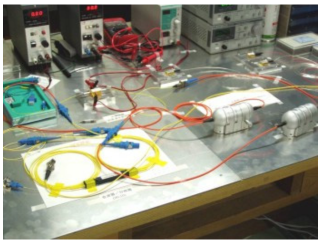
Fig. 6: Optical signal waveforms, generated and monitored by our homemade equipments

Makings of proto-type all-optical gate circuits are the most important fabrication activities of ours. Even though the future practical forms of those all-optical gates must be *integrated* ones in cm-unit size, we in UEC are currently fabricating fiber-cable-connected circuits in the following two groups of methods, instead, because of their larger research flexibility in upgrading designs, reliable monitoring techniques, and furthermore, try-and-errors. In the first group, we choose one of the fiber-pigtailed SOA modules which several venture companies are recently designing for use in these kinds of all-optical signal-processing research (Fig. 7). These SOA modules are easily installed in our optical circuits with standard optical connectors. This group of fabrication methods is used in our application-oriented activities.

In the second group, we customize some of those commercial SOA designs in collaboration with a few skilled vendors, receive those SOA's in the form of 'bare chips,' and then optically connect them to the other part of gate circuits, with spatially aligning two micro-lensed fibers under a microscope (Fig. 8). This group of SOA's is used in more materials-research-oriented activities in UEC.

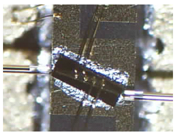


(a)

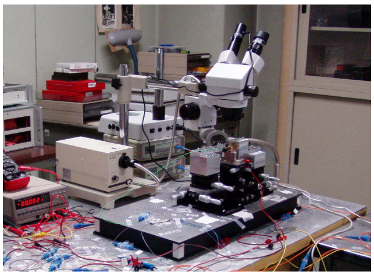


(b)

Fig. 7: All-optical gate unit (1)



(a)

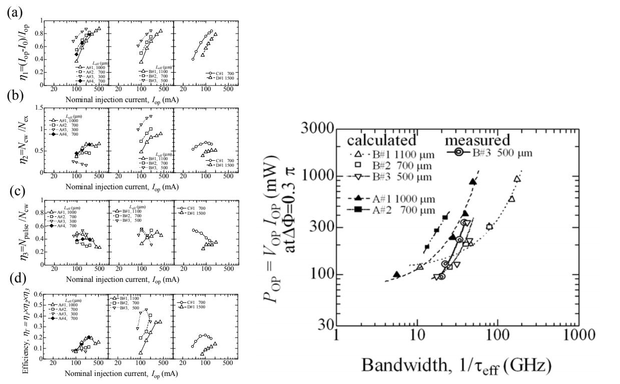


(b)

Fig. 8: All-optical gate unit (2)

4. Quantum conversion efficiency and consequent power consumption in the gates

As was earlier mentioned, the efficiency and power consumption of an all-optical gate scheme has always been one of the most important subjects. Regarding the SMZ-DISC scheme, however, systematic research had never been reported, to our knowledge. Recently, one of the authors (J. S.) and his co-workers have systematically characterized quantum-conversion efficiency of both commercial SOA's and custom-designed SOA's, and then modeled the bitrate-dependent electric dc power consumptions for those SOA's (Figs. 9 and 10) [12]. According to these characterizations and model of ours, the electric power consumption for this scheme of wavelength converter is 750 mW for 160Gb/s signals, and has nearly quadratic dependence on the bitrate, power consumption~ (bitrate)^2, in the bitrate region between 40 and 160 Gb/s. These research results must be useful for further designing SOA materials and structures, for use in all-optical signal processors.



(a) (b)

Fig. 9: Quantum efficiency (a) and bitrate-dependent power-consumption (b) of several types of SOA samples

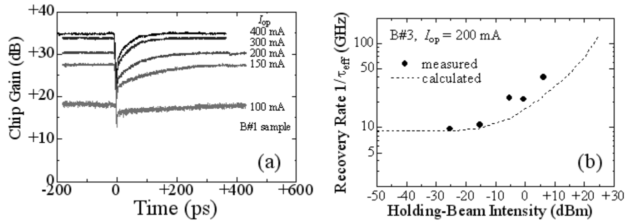


Fig. 10: Systematically measured relaxation time constants (a). The measured recovery rate matched well with the SOA model newly developed in our work.

Separately from SOA's including conventional bulk or QW active layers, we have started characterizing nonlinearly absorptive photonic-crystal/quantum-dot waveguide samples, in collaboration with two other research institutes. One of its latest results will be presented in the student session [13]. For our characterizing sub-picosecond responses of the self-assembled quantum dots in the 1.3-µm wavelength region, we have setup a 130-fs, 80-MHz large-frame parametric oscillator system as a reliable optical pulse source, whose wavelength is widely tunable from almost 1 µm to nearly 2 µm and handmade a pump-and-probe system (Fig. 11).

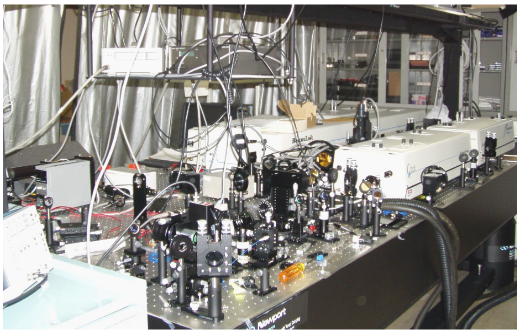
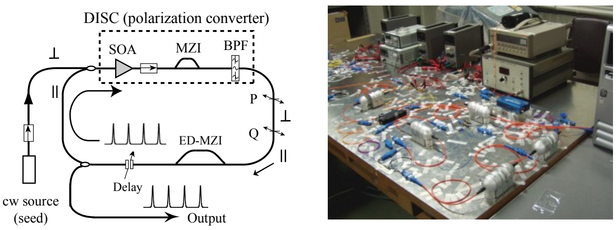


Fig. 11: 130-fs optical parametric oscillator system with a homemade pump-and-probe setup

Several other newly successful modeling works have also been done in UEC in 2005-2006, partially in collaboration with other groups [14].

5. Ultrafast, high-frequency, mode-locked optical clock source

In UEC, we are also pursuing anther practical application of the ultrafast SMZ-DISC gate, that we have named disc-loop-type pulse generator (Fig. 12) [15, 16].



(a) (b)

Fig. 12: originally proposed scheme [15] (a) and snap photo of our prototype setup in UEC [16] (b)

The originally expected principle of this new scheme [15] has recently been proved by our experimental evidences that (1) the output pulse width matches well with and linearly follows the MZI's delay time inside the SMZ-DISC gate, and that (2) it suddenly starts generating mode-locked pulses when the loop gain for pulse circulation exceeds 0dB (Fig. 13) [16]. Figure 14 shows successfully generated 2-ps, 40-GHz pulse trains, where the measured pulse width matched well with the MZI delay time of 2 ps.

More recent experimental activities in this research direction will be presented in the student session [17].

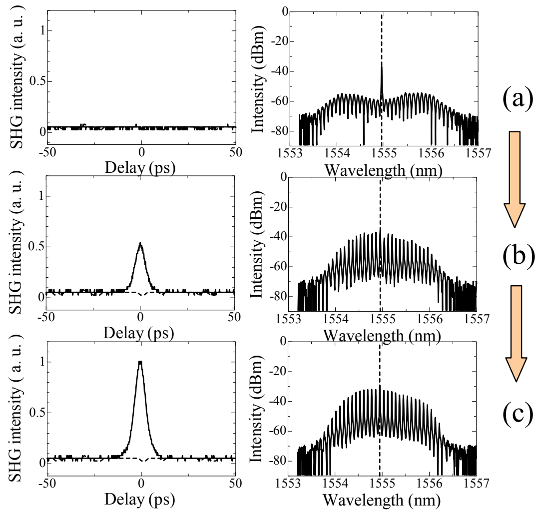
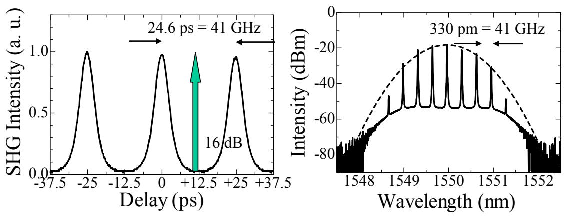


Fig. 13: Threshold behavior of the mode-locked pulse generation, observed with series of output waveforms (left) and optical spectra (right).



(a) (b)

Fig. 14: Measured auto-correlation trace (a) and optical comb spectrum (b) of 2-ps, 40-GHz mode-locked pulses [16]

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