IEEE LEOS Annual Meeting (LEOS 2003), Invited Talk
Tucson, Arizona, October 26-30, 2003, vol. 1, pp. 380-381.

All-Optical Signal Processing for over-100-Gb/s Optical-TDM Networks

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Abstract: Recent semiconductor-based ultrafast signal processing results are reviewed. After results regarding demultiplexing, 3R gating, and related topics are introduced, several scaling rules that could govern the SOAs in such gating modes are given.

1. Current OTDM Component Technology

The large and ultrafast optical nonlinearity of millimeter-size semiconductor optical amplifiers (SOAs) has led to the study of several types of gate functions at ultrahigh bit-rates beyond 40 Gb/s. Among these functions, **optical demultiplexing** has been the most successfully demonstrated with 336 Gb/s RZ signals [1]. The slow-recovery-induced phenomena that accompany the ultrafast nonlinear response inside each SOA do not slow down the gating speed, because their effects on the optical signals are dramatically removed by an optical interferometer incorporated in each ultrafast gate structure (e.g., SMZ, TOAD, PD-SMZ, UNI, or DISC).

Despite the use of optical interference, their stability will not be a problem in the building of network systems. Integrated gates have shown excellent stability. Even when ultrafast gating with large extinction ratios is required in long terms, the **optical interference** will precisely be stabilized with low-cost slow optoelectronics inside each gate module (Fig. 1) [2].

One gate function that has attracted considerable attention from both OTDM and 40-Gb/s researchers is **optical 3R gating**. Its noise-tolerant, jitter-tolerant regenerative properties have been observed experimentally with 40- to 80-Gb/s signals by several research teams (Fig. 2) [3-6]. 3R regenerative gating with 160-Gb/s signals is currently a particularly attractive research goal.

All-optical **wavelength conversion** for cross-connecting OTDM signals has also been demonstrated with one of the above gate structures. To date, error-free wavelength conversion of 168-Gb/s signals has been reported [7]. Importantly, all-optical gates in the wavelength-conversion mode, as well as those in the 3R-gating mode, are driven with ultrafast-line-rate RZ signals, in good contrast to those gates in the demultiplexing mode. The experimental demonstration of 168-Gb/s conversion, consequently, is considered a milestone along the way to 160-Gb/s 3R gating.

2. Possible Scaling Rules for nonlinear SOAs in the Ultrahigh-Frequency Gating Mode

The modeling and designs of SOAs *for amplification purposes* have been well established in the past decade. In contrast, those *for ultrafast gating* remain on-going subjects. Several types of straightforward scaling rules that could govern such SOAs were proposed only recently, where the gating mechanism was modeled as simply as possible for deriving such rules. The simplest gating mode, i.e., the ‘periodical’ gating mode as is used in demultiplexing, was assumed there as well. Systematically measured data in the frequency range from 40 through 160 GHz have been reasonably representative of two of these scaling rules; the driving force for the gating, i.e., the magnitude of the nonlinear response in an SOA, follows the rule,

$$\Delta\Phi \propto f^{-1} \times I_{op}, \qquad (1)$$

where f is the gating frequency and I_{op} is the injection current to the SOA (Fig. 3) [8].

3. Scaling Rules for 160-Gb/s optical-3R Gating

Because all-optical gates in the 3R-gating mode are driven by line-rate random signals, the slow recovery time constant of SOAs inside these gates must be of the order of the bit separation (6 ps for 160-Gb/s gating). Two alternative research directions for accelerating the SOA recovery have attracted attention. Recent results from sub-band-transition nanostructures suggest that less-than-one-picosecond-recovery SOAs will appear in the future [9, 10]. For conventional SOAs, a remarkable acceleration of the recovery time has been reported, where the SOA is pumped with a specifically designed light [11, 12]. We should emphasize, however, that the tolerance of optical 3R gating to input timing jitter will be *lost* if the SOA recovery is accelerated to that of the fiber nonlinearity. Thus, the SOA recovery time is clearly an important gate-design subject.

For the optical 3R gating mode, no scaling rule has been established. The experimentally observed 3R properties (noise suppression and jitter tolerance) have been numerically demonstrated only very recently using the latest 3R gating model (Fig. 4) [13]. A possible frequency-scaling rule derived from the latest model will be presented at the talk. Scaling rules that can be derived from such modeling will be helpful for drawing roadmaps for various types of on-going research aimed at 160-Gb/s signaling in the near future, and towards higher bit-rates beyond that.

References: [1] S. Nakamura et al., OFC 2002, Anaheim, Postdeadline paper FD3, [2] Y. Ueno et al., IEEE Photon. Technol. Lett. **14** (2002) 1692, [3] A. E. Kelly et al., Electron. Lett. **35** (1999) 1477, [4] Y. Ueno et al., ECOC 2001, Amsterdam, the Netherlands, Th.F.2.1, [5] B. Dagens et al., OFC 2003, Atlanta, ThX1, [6] M. Tsurusawa et al., OFC 2003, Atlanta, ThX3, [7] S. Nakamura et al., IEEE Photon. Technol. Lett. **13** (2001) 1091, [8] Y. Ueno et al., J. Opt. Soc. Am. **B19** (2002) 2573, [9] T. Akiyama et al., Electron. Lett. **37** (2001) 129, [10] I. Waki et al., FST 2003, Makuhari, Japan, WB-2, [11] M. Tsurusawa et al., Jpn. J. Appl. Phys. **41** (2002) 1199, [12] T.P. Hessler et al., Appl. Phys. Lett. **81** (2002) 3119, [13] Y. Ueno, submitted to Opt. Comm.

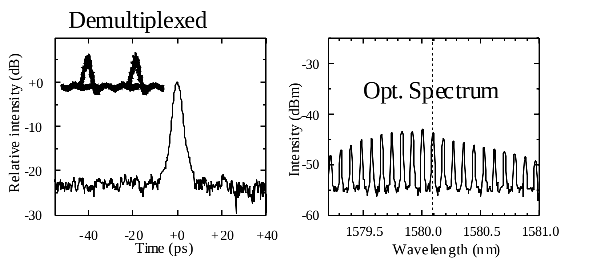

Fig. 1: Interference control scheme demonstrated in the 16:1 168-Gb/s demultiplexing [2].

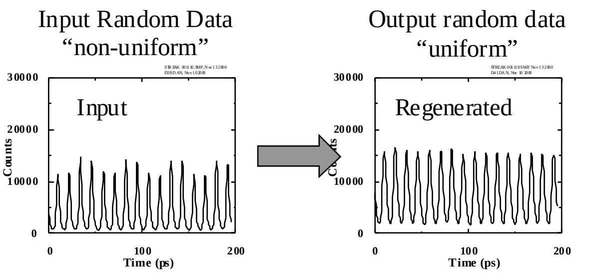

Fig. 2: Optical 3R gating with 84-Gb/s pseudorandom signals, observed with streak camera [4].

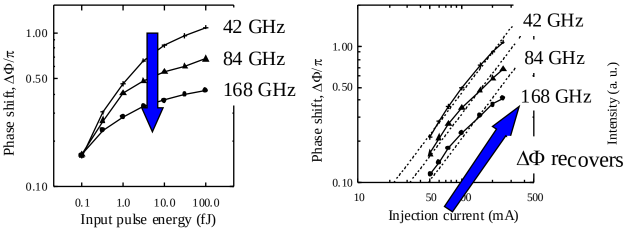

Fig. 3: Observed scaling rules in the SOA's nonlinear response in the frequency range from 42 to 168 GHz [8].

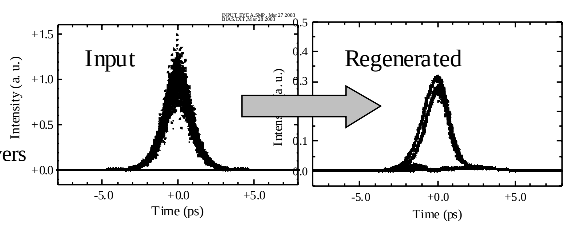

Fig. 4: Calculated noise-suppression property from the latest 3R gating model [13].