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Ultrafast SOA-based SMZ-type All-Optical Regenerators and Wavelength Convertors

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1. SMZ-type all-optical switches

Several types of picosecond-to-femtosecond-class all-optical switchings at repetition frequencies from 10 GHz to over 100 GHz have been successfully achieved in the last 4-5 years with using semiconductor waveguide devices, in spite of the relatively long carrier relaxation times (50 ps to 1 ns) of conventional bulk-semiconductor materials. Such ultrahigh-speed switchings are possible with specific switch structures, i.e. Symmetric-Mach-Zehnder (SMZ)-type switch structures [1-3], because the slow carrier-relaxation-induced decay components can be completely cancelled out at an optical interference (between two-split mutually-delayed signal components) inside these switches. Both the rise and fall times of their switching windows can basically be shortened with the width of optical input control pulses.

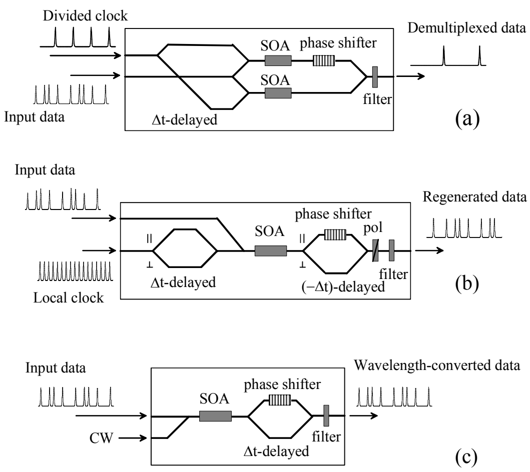

Fig. 1 Three configurations of SMZ-type all-optical switches. (a) original SMZ switch [1] for demultiplexing, (b) PD-SMZ switch [2] for regeneration, and (c) SMZ-DISC [3] for wavelength conversion.

Figure 1 shows three configurations of SMZ-type all-optical switches where semiconductor optical amplifiers (SOA's) are used for significantly reducing the optical control pulse energy. In case of the all-optical demultiplexing (a), divided-clock pulses control the switch, form switching windows at the divided-clock frequency, and extract one TDM channel out of the high-frequency data pulses. Error-free demultiplexing of 336 Gb/s has recently been achieved with a divided-clock frequency of 10.5 GHz [4]. In case of regeneration (b) in contrast, each of the high-frequency data pulses controls the switch, forms a switching window, and allows only a corresponding clock pulse to go through. Consequently, the clean clock pulses are encoded by the data pulses, i.e., the data pulses are 'regenerated.' In case of wavelength conversion (c), each of the input data pulses controls the switch, forms a corresponding switching window, and allows only the CW component within each window to go through. When the window width is optimized, data pulses at the CW wavelength are newly generated.

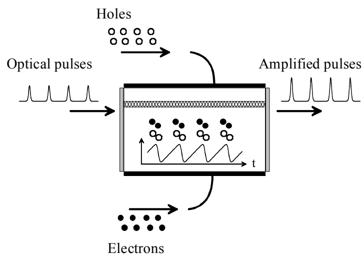

Fig. 2 Nonlinear refractive-index changes are induced by stimulated amplification in the SOA's.

The driving force of these all-optical switchings is the nonlinear refractive-index change inside the SOA's (Fig. 2). Each time a control pulse is amplified in an SOA, the carrier density drops almost instantaneously, which causes the refractive index to jump up due to the bandfilling effect. As a result of this ultrafast refractive-index change and an optical interference, the switch forms a window whose width is determined by a specific delay time Δt that is indicated respectively in Fig. 1 [1-3].

2. All-optical regeneration (Optical 3R)

We have achieved penalty-free error-free input-polarization-insensitive regeneration at 84 Gb/s [5], where each of the 84-Gb/s input data pulses controlled the SOA inside the PD-SMZ switch and consequently encoded each of the synchronized 84-GHz clock pulses. To date, we have demonstrated two types of regenerative properties. The one is regeneration in time, due to the rectangular-like shape of the switching window [1]; the bit-error-rate tolerance against the input timing jitter has been measured to be approximately 2.3 ps [5]. The other property is regeneration in amplitude due to the sinusoidal transfer function of the interferometer; the intentionally-incorporated amplitude noise in the input [Fig. 3(b)] was removed in the output [Fig. 3(c)]. The magnitude of the nonlinear phase shift was measured to be slightly less than π (0.6π). This measurement was done by systematically observing the output waveforms as a function of the interferometer phase bias [Fig. 3(d)].

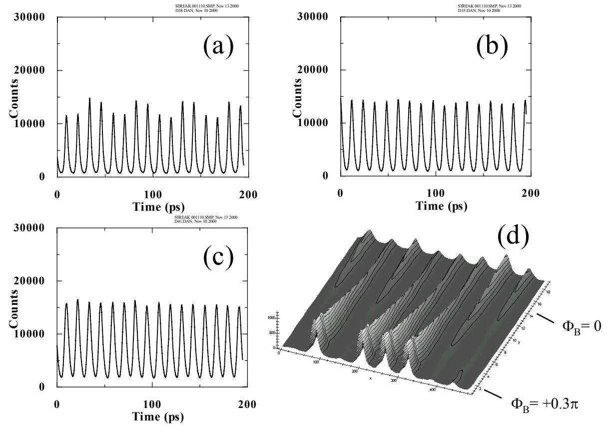

Fig. 3 All-optical regeneration at 84 Gb/s. (a) Input random pulses, (b) local clock pulses, (c) output random pulses, and (d) waveforms as a function of the interferometer phase bias.

3. Wavelength conversion

Error-free wavelength conversion has been achieved at up to 168 Gb/s [6], which is the highest pseudo-random-switching frequency ever reported to the authors' knowledge. The output pulse width was measured to be 2.0 ps with using an autocorrelator [Fig. 4(b)], which matched well with our Δt design. The nonlinear phase shift involved in the conversion was measured to be approximately 0.2π from the output XPM spectrum [Fig. 4(d)] and also from a method similar to that in Fig. 3(d).

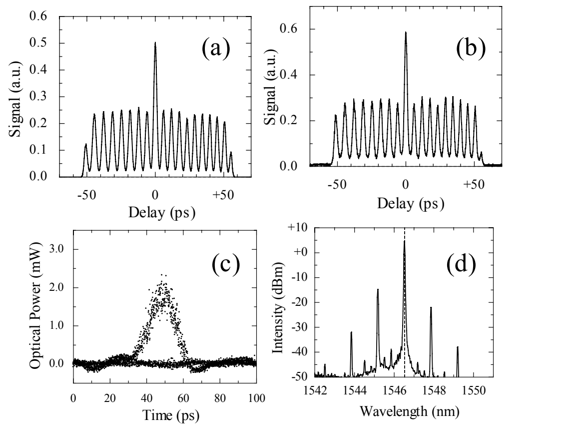

Fig. 4 Wavelength conversion at 168 Gb/s. Autocorrelation trace for the input random pulses (a), that of the output random pulses (b), the output eye diagram after demultiplexing to 10.5 Gb/s (c), and the XPM spectrum (temporarily with all-one input pulses).

4. Nonlinear phase shifts at ultrahigh frequencies

One of the central issues in the ultrahigh-frequency switchings is the decrease in the nonlinear phase shift with the repetition frequency. We analyzed fundamental properties of the nonlinear phase shift in the 40-to-160-GHz range, in a pump-probe regime and under not random but regular (periodical) switching conditions in the first place [7]. We have found that the nonlinear phase shift decreases almost linearly with the frequency and also that the phase shift is recovered linearly with the injection current to the SOA (Fig. 5). Because conventionally designed SOA's have been used in the above-mentioned experiments, the results in Fig. 5 have suggested that new SOA designs and new materials will enable us to explore higher switching frequencies.

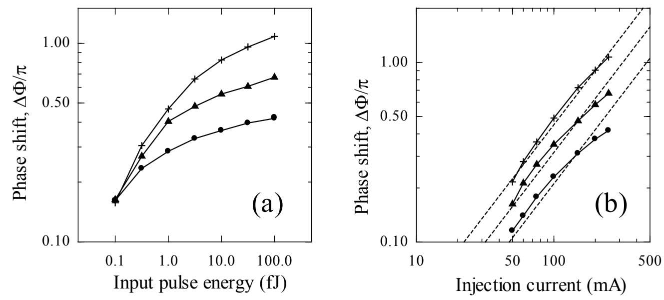

Fig. 5 Measured nonlinear phase shifts as functions of the input pulse energy and the injection current to the SOA. The input pulse frequencies were 168 GHz (circles), 84 GHz (triangles), and 42 GHz (crosses).

5. Conclusion

We have shown our recent results of the all-optical regeneration and the wavelength conversion. The SOA-induced nonlinear phase shifts at ultrahigh repetition frequencies were discussed in details.

Acknowledgments

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