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Ultrafast distortion-free semiconductor-based all-optical gate that contains optical-spectrum's phase-and-amplitude synthesizer

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Abstract: We have experimentally verified that our original all-optical-gate scheme removes waveform distortion that is otherwise strongly induced by such active-material's second-slowest relaxation component.

1. Introduction

All-optical wavelength converters based on semiconductor optical amplifiers (SOAs) are promising devices for future high-capacity optical time division multiplexing-wavelength division multiplexing (OTDM-WDM) networks, due to their ultrahigh response, low power consumption, and integration potential[1]. 320-Gb/s wavelength conversion with the delayed-interference (DI) scheme using a detuned optical band-pass filter (OBF) at the SOA output has recently been demonstrated[2], and 40-Gb/s wavelength conversion has been achieved by a pulse reformatting optical filter which independently controls both the intensity and phase of spectrum[3].

For ultrahigh-speed signal processing above 320 GHz with on-off keying (OOK), pulse width shorter than 1 ps is necessary. It has been reported that under ultra-short control pulses the gated output waveforms with the DI scheme is distorted since the SOA gain recovery has second-slowest and first-slowest components (Fig. 1) due to carrier temperature relaxation and electron-hole recombination respectively[4,5]. (Further, other ultrafast optical materials tend to contain more than one time constant, for instance, *quantum-dot* switches[6], *intersubband transition* semiconductors[7].) Therefore, Ueno *et al.* has numerically demonstrated a particular optical-spectrum-synthesizer (OSS) design with the expanded DI scheme (Fig. 2), by which the gated waveform distortion has successfully been removed[8].

In this work, we have experimentally verified that the new gate scheme with one of standard SOA's removes the otherwise very strong waveform distortion. Assuming bit-rates faster than 160-Gb/s in next research steps, 2.0-ps, 40-GHz input pulses were used in this work.

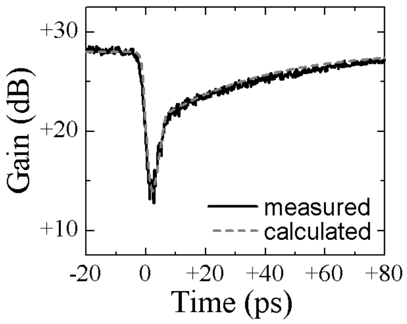

Fig. 1. Measured (solid) and calculated (dashed) SOA gain recoveries of a standard SOA (which differs from the SOA in Sections 2 and 3), after it amplified a 1.25-GHz, 2.1-ps, 8-fJ input pulse. The first- and second-slowest recovery time constants were 54 ps and 6.5 ps, respectively.

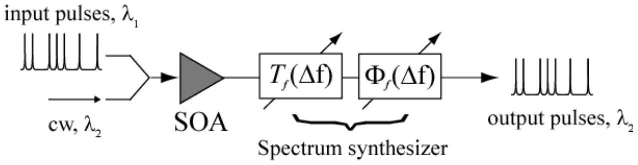

Fig. 2. The new scheme of our all-optical gate which contains an optical spectrum's phase-and-amplitude synthesizer[8].

2. Experimental setup

Our experimental setup is shown in Fig. 3. A mode-locked laser diode (MLLD) generated 2.0-ps 1550-nm optical clock pulses at a repetition rate of 10-GHz. The 10-GHz pulses train was multiplexed up to 40-GHz through OTDM-MUX. These 40-GHz clock pulses were injected into an SOA module together with 1545-nm cw light generated by a tunable laser-diode. The injection current for the SOA was set to 100 mA. The fiber-to-fiber gain of the SOA was +12 dB. The first- and second-slowest recovery time constants were measured, respectively, to be 30 and 5 ps. The average powers of clock pulses and of cw light at the input of SOA module were +2.2 dBm (41 fJ) and –4.9 dBm, respectively. At the output of SOA, the cross-gain modulated (XGM) and cross-phase-modulated (XPM) cw light inside SOA was se-

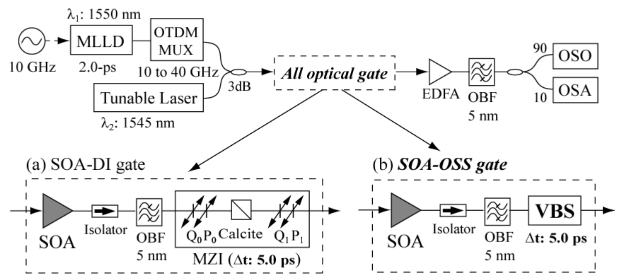

Fig. 3. Experimental setups of the two alternative all-optical gate schemes.

(a) the conventional delayed-interference (DI) gate.
(b) the optical-spectrum-synthesizer (OSS) gate in Fig. 2.

SOA: semiconductor optical amplifier, OBF: optical band-pass filter, Q: quarter-wave plate, P: polarizer, OSO: optical sampling oscilloscope, OSA: optical spectrum analyzer, VBS: variable bandwidth spectrum shaper.

lected by a 5 nm bandwidth optical filter. The optical wavelength converter with the conventional DI scheme consisted of a SOA, an OBF, and a Mach-Zehnder Interferometer (MZI). The MZI contained a birefringent calcite crystal whose relative delay time (Δt) was 5.0 ps. The optical phase bias between the fast component and the slow component was adjusted by rotating the Q_1 and P_1 located after the calcite

In this work, we used a proto-type sample of the variable bandwidth spectrum shaper (VBS[9], Optoquest Co., Ltd.), one of the commercially-available, compact, high-resolution OSSes. The maximum intensity-extinction ratio was +22 dB, the maximum phase quantity was 2 π, and the spectral resolution was from 9.7 GHz to 11.8 GHz. We have tried to verify the validity of the new gate scheme in Ref. 8, by controlling the VBS basically according to this scheme's recipe.

3. Experimental results

Fig. 4 (a) and (b) show the 40-GHz gated output spectrum and waveform of the MZI. The spectral envelope was close to the calculated dashed curve of a transform-limited 3.6-ps hyperbolic secant pulse in Fig. 4 (a). The inconsistency of the red-spectrum components between the measured results and calculated results (dotted) was outstanding compared with that of the blue-spectrum components. At the present time, it is not clear what causes this inconsistency. We observed the measured waveform with strong distortion induced second-slowest relaxation components in Fig. 4 (b). The floor level noise between pulses was part of the background noise level due to amplified spontaneous emission from an EDFA in front of the OSO. Particular shape of the measured waveforms with distortion in Fig. 4 (b) (i.e., there was the main strong pulse next to the satellite weak pulse) was approximately consistent with the calculated results.

Fig. 4 (c) and (d) show the 40-GHz gated output spectrum and waveform of VBS with the intensity and phase profile based on our original numerical model[8]. The spectral envelope approximately matched the calculated dashed curve for a

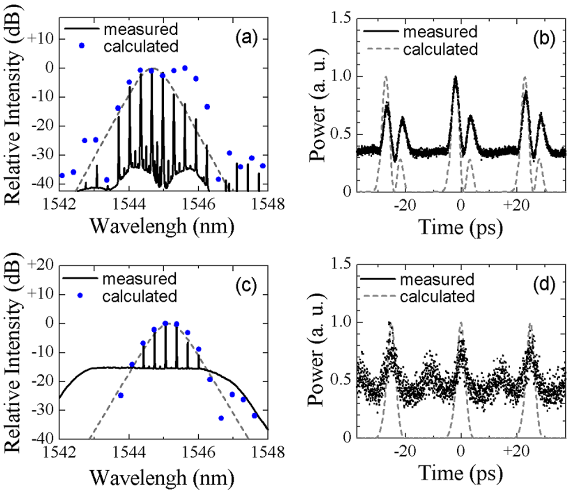

Fig. 4. Measured (solid) and calculated (dotted, dashed) optical spectra and waveforms at the output of all-optical gates with 2.0-ps, 40-GHz, 41-fJ clock input pulses.
(a), (b): with the DI scheme (i.e., without spectrum synthesis).
(c), (d): with the OSS scheme (i.e., with theoretical designed synthesis scheme).

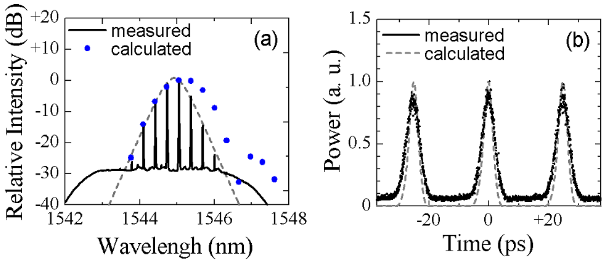

Fig. 5. Measured (solid) and calculated (dotted and dashed) optical spectra (a) and waveforms (b) at the gate's output after empirically adjusting the intensity of the first, second, and third red-spectrum components from those in Fig. 4. (c) and (d).

transform-limited 3.3-ps sech^2 pulse in Fig. 3 (c). We observed the satellite pulses between the main pulses of the measured waveform in Fig. 4 (d).

The waveform and spectrum of the VBS output measured after empirically adjusting the intensity of the first, second, and third red-spectrum components from the case of Fig. 4 (c) and (d) are shown in Fig. 5. We observed the output waveform without distortion in Fig. 5 (a). The pulse duration and the extinction ratio were estimated 5.0-ps and 10 dB, respectively. The spectral envelope approximately matched the calculated dashed curve for a transform-limited 4.4-ps pulse in Fig. 5 (b), which suggests that the output pulses contains little chirping, or we speculated that the pulse width was broadened due to the limited resolution (< 800 fs) of the OSO we used.

4. Conclusions

We experimentally verified that the strong waveform distortion induced by the second-slowest relaxation time constant of semiconductor materials in general is clearly removed by our switching the all-optical gate scheme from the conventional one to the new one. We needed to slightly adjust both real and imaginary parts of the spectral profile, but the magnitudes of these adjustments were relatively small. The reason of this need is presently under study between our model and proto-type OSS. Even though relatively short 2-ps pulses with intentionally lower rate (40 GHz) without binary codes were used in this experimental work, this new scheme will work for more realistic 160-Gb/s pseudorandom data pulses, as well, where the ratio of pulse's width to its spacing ranges from 0.15 to 0.20.

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