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

Takehiro Nishida[1], Satoshi Shinada[2] , Naoya Wada[2] , Takeru Yamaji[1], and Yoshiyasu Ueno[1]

1. *Univ. of Electro-Communications (UEC), Dept. of Electronic Engineering, 1-5-1, Chofugaoka, Chofu-shi, Tokyo 182-8585 Japan, Phone: +81-42-443-5207, e-mail: nishida@ultrafast.ee.uec.ac.jp*
2. *National Institute of Information and Communications Technology (NICT), 4-2-1, Nukuikita, Koganei-shi, Tokyo 184-8795, Japan*

Abstract

When using ultrahigh-speed optical data pulses whose pulse duration is shorter than 2 ps, approximately, the signal waveforms after our all-optical gate in the conventional delayed-interference (DI) scheme is supposed to be strongly distorted, due to the previously reported second-slowest gain-recovery component from the semiconductor optical amplifier (SOA) inside our all-optical gate. In this talk, 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 bandpass 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 based on MEMS mirrors which independently controls both the phase and intensity of spectrum[3]. With respect to pulse shaping technique, by using an integrated optical pulse shaper which was configured with arrayed-waveguide gratings (AWGs) including phase and/or amplitude modulators, pulse waveform shaping from sech^2 pulses to square pulses was demonstrated [4], and dispersion compensation was investigated[5].

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[6,7]. (Further, other ultrafast optical materials tend to contain more than one time constant, for instance, *quantum-dot* switches [8], *intersubband transition* semiconductors[9].) Therefore, one of the present authors (Y. Ueno) and co-workers had 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[10].

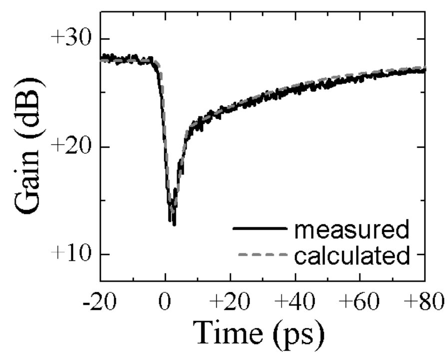

Fig. 1. Measured (solid) and calculated (dashed) SOA gain recoveries of a standard SOA (which differs from the SOA in Sections 2 and 3), after it amplified a 1.25-GHz, 2.1-ps, 8-fJ input pulse. The first- and second-slowest recovery time constants were 54 ps and 6.5 ps, respectively.

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.

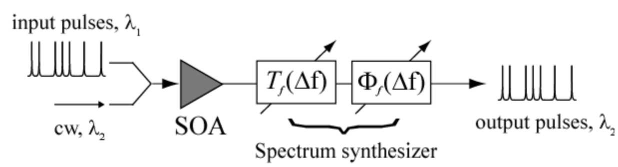

Fig. 2. The new scheme of our all-optical gate which contains an optical spectrum's phase-and-amplitude synthesizer[10].

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 selected 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 modulated cw light by SOA was equally divided into the fast and slow components by rotating a quarter-wave plate (Q_0) and a polarizer (P_0) located before the calcite crystal. 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[11], 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. 10, by controlling the VBS basically according to this scheme's recipe.

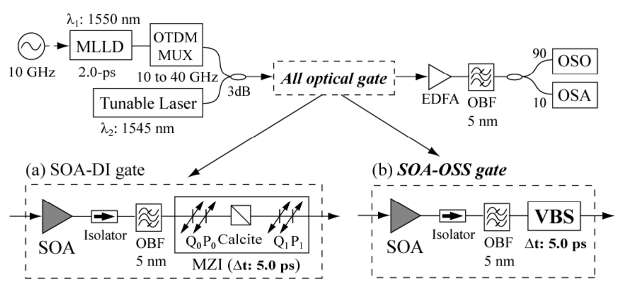

Fig. 3. Experimental setups of the two alternative all-optical gate schemes.

(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.

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 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

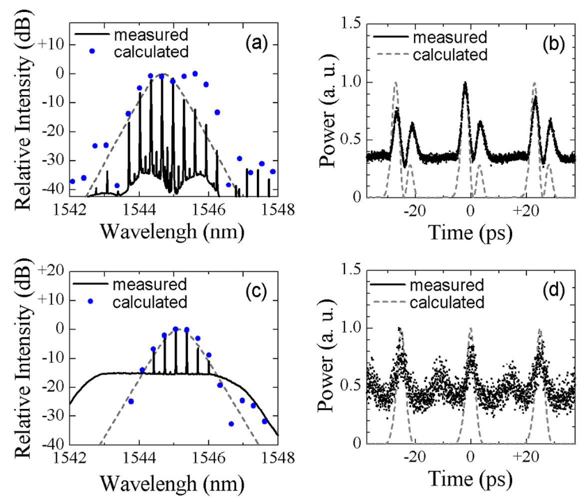

Fig. 4. Measured (solid) and calculated (dotted, dashed) optical spectra and waveforms at the output of all-optical gates with 2.0-ps, 40-GHz, 41-fJ clock input pulses.

(a), (b): with the DI scheme (i.e., without spectrum synthesis).
(c), (d): with the OSS scheme (i.e., with theoretical designed synthesis scheme).

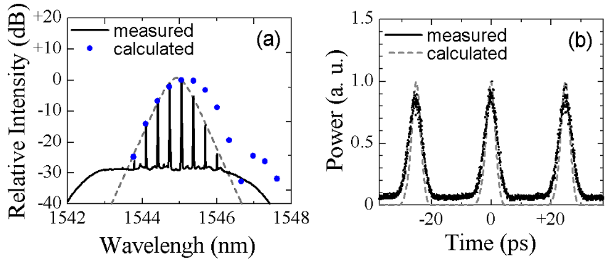

Fig. 5. Measured (solid) and calculated (dotted and dashed) optical spectra (a) and waveforms (b) at the gate's output after empirically adjusting the intensity of the first, second, and third red-spectrum components from those in Fig. 4. (c) and (d).

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.

Acknowledgements

We thank Mr. Takeshi Makino and Mr. Hiroyuki Sumimoto of NICT for technical supports. We also thank Mr. Sungchol Park and Mr. Takuya Yoda of Optoquest, Co., Ltd. for valuable discussion and technical supports for the proto-type sample of VBS.

References

[1] Y. Ueno, S. Nakamura, and K. Tajima, "Nonlinear phase shifts induced by semiconductor optical amplifiers with control pulses at repetition frequencies in the 40–160-GHz range for use in ultrahigh-speed all-optical signal processing," J. Opt. Soc. Am. B **19**, 2002, 2573.

[2] Y. Liu, E. Tangdiongga, Z. Li, H. de Waardt, A. M. J. Koonen, G. D. Khoe, X. Shu, I. Bennion, and H. J. S. Dorren, "Error-Free 320-Gb/s All-Optical Wavelength Conversion Using a Single Semiconductor Optical Amplifier," IEEE J. Lightwave Technol. **25**, 2007, 103.

[3] J. Leuthold, D.M. Marom, S. Cabot, J.J. Jaques, R. Ryf, and C.R. Giles, "All-Optical Wavelength Conversion Using a Pulse Reformatting Optical Filter," IEEE J. Lightwave Technol. **22**, 2004, 186.

[4] M.J.R. Heck, P. Muñoz, B.W. Tilma, E.A.J.M. Bente, Y. Barbarin, Y.S. Oei, R. Ntzel, and M.K. Smit, "Design, Fabrication and Characterization of an InP-Based Tunable Integrated Optical Pulse Shaper," IEEE J. Quantum Electron. **44**, 2008, 370.

[5] K. Takiguchi, T. Kominato, H. Takahashi, T. Shibata, and K. Okamoto, "Flexible pulse waveform generation using a slica waveguide based spectrum synthesis circuit," OFC 2004, Los Angels, USA, TuI5.

[6] J. Mørk, and A. Mecozzi, "Theory of the ultrafast optical response of active semiconductor waveguides," J. Opt. Soc. Am. B **13**, 1996, 1803.

[7] J. Mørk, T. W. Berg, M. L. Nielsen, and A. V. Uskov, "The Role of Fast Carrier Dynamics in SOA Based Devices," IEICE Trans. Electron. **E87-C**, 2004, 1126.

[8] H. Nakamura, Y. Sugimoto, K. Kanamoto, N. Ikeda, Y. Tanaka, Y. Nakamura, S. Ohkouchi, Y. Watanabe, K. Inoue, H. Ishikawa, and K. Asakawa, "Ultra-fast photonic crystal/quantum dot all-optical switch for future photonic networks," Optics Express, **12**, 2004, 6606.

[9] H. Yoshida, T. Simoyama A.V. Gopal, J. Kasai, T. Mozume, and H. Ishikawa, "Ultrafast All-Optical Switching and Modulation Using Intersubband Transitions in Coupled Quantum Well Structures," IEICE Trans. Electron. **E87-C**, 2004, 1134.

[10] Y. Ueno, R. Nakamoto, J. Sakaguchi, and R. Suzuki, "Optical-spectrum-synthesizer design within an all-optical semiconductor gate to reduce waveform distortion induced by carrier-cooling relaxation at sub-Teraherz frequencies," Optics Express **14**, 2006, 12655.

[11] S. Anzai, M. Mieno, Y. Komai, N. Wada, T. Yoda, T. Miyazaki, and K. Kodate, "Amplitude, Phase, and Bandwidth Tunable High-resolution Optical Spectrum Shaper and its Application for Optical Communication Systems," OFC/NFOEC 2008, San Diego, USA, JthA25.