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Observation of Small Sub-Pulses Out of the Delayed-Interference Signal-Wavelength Converter

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The generation of small sub-pulses in the delayed-interference signal-wavelength converter (DISC), which has been studied for use in future 160-Gb/s optical time division multiplexing–wavelength division multiplexing (OTDM–WDM) communication systems, was recently predicted as a potential problem. In this work, we have experimentally verified the generation of such pulses and its mechanism. In the experiments we used 3.8-ps-long 1.56-μm input pulses with repetition frequencies from 12.5 to 25.0 GHz and a cross-correlation monitoring system with a time resolution of approximately 2 ps.
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Several types of all-optical gates based on the semiconductor optical amplifier (SOA) have been studied with the goal of realizing ultrafast, compact, low-power-consumption signal processors for use in future optical time division multiplexing–wavelength division multiplexing (OTDM–WDM) networks and systems. Notably, 168-Gb/s error-free wavelength conversion[1,2] and 40-Gb/s error-free ultra-long-distance 2R transmission[3] have been demonstrated using the delayed-interference signal-wavelength converter (DISC).[4,5]

Recent modeling research regarding the DISC, however, has revealed a potential issue concerning its fundamental operating principle: when we minimize the pattern-induced amplitude noise from the DISC, it can instead potentially generate small 'sub-pulses' between the RZ-formatted output pulses.[6,7] This modeling research suggests that such generation was a factor in the experiments mentioned above.

In this work, to model the DISC operation and clarify the origin of the large amplitude noise in the 168-Gb/s converted eye reported in ref. 1, we sought to experimentally verify whether these sub-pulses exist.

Figure 1 shows our experimental setup, where a commercially available SOA module (InPhenix, IPSAD1503, drive current = 250 mA) was used. The Mach–Zehnder interferometer (MZI) contained a calcite crystal (DGD, $\Delta t = 5$ ps). We input continuous wave (cw) light ($\lambda_2 = 1548$ nm, $+8.9$ dBm) from the DFB LD to the SOA and aligned its polarization at the SOA input facet to either the transverse electric (TE) or transverse magnetic (TM) axis of the SOA. At the input of the calcite crystal, the cw light was polarized to 45° off the principal axis using quarter-wave plate Q_0 and polarizer P_0, and equally divided into fast and slow components. The optical phase bias $\Delta\Phi_B$ between the divided cw components passing through the MZI was tuned by rotating quarter-wave plate Q_1 and polarizer P_1. To accurately control the polarization state and obtain high extinction ratios, pigtailed-cartridge-type rotatable low-loss crystal polarizers and waveplates (Optoquest) were used in this work.

The 25- and 12.5-GHz continuous input pulses ($\lambda_1 = 1560$ nm) were generated with a mode-locked fiber-ring laser (Pritel, UOC-3) and an optical multiplexer. The width of the pulses sent to the DISC was broadened from 2.2 to 3.8 ps with a 100-m-long single-mode fiber to suppress carrier-heating-related phenomena inside the SOA. The polarization of the pulses was set parallel to that of the cw light; i.e., the TE or TM direction of the SOA. The nonlinear phase shifts in the SOA caused by the input pulses were estimated to be 0.5π (for 25 GHz) and 0.8π (for 12.5 GHz) through cross phase modulation (XPM) spectrum measurements.[5] To observe wavelength-converted output waveforms from the DISC with a very short time resolution, we used a cross-correlator (Femtochrome Research, FR-103XL) into which the 2.2-ps, 12.5-GHz pulses were injected as probe pulses.

The mechanism of DISC operation has been modeled based on a rate equation of the carrier density in the SOA:

$$\frac{d}{dt}\overline{n_c(t)} = \frac{I_{op}}{qV} - \frac{\overline{n_c(t)}}{\tau_c} - \frac{1}{V}\left(G(\overline{n_c(t)}) - 1\right) \times \frac{|E_{pulse}(t)|^2 + |E_{CW}|^2}{\hbar\omega}. \tag{1}$$

Here, $\overline{n_c(t)}$ is the excess carrier density averaged over the interaction length, I_{OP} is the injection current, τ_c is the carrier lifetime, $E_{pulse}(t)$ and E_{CW} are the input light amplitudes, and G is the SOA gain. The DISC-gate simulation method in this work was developed using this equation, as described in ref. 5. It has been pointed out that when $\overline{n_c(t)}$ recovers exponentially with t between pulsed inputs, sub-pulses appear in the DISC output.[6,7]

Figure 2(a) shows a typical cross-correlation trace $V(t)$ of the 25-GHz DISC output that we measured after maximizing the extinction ratio by adjusting the Q_1 and P_1 angles in the MZI. As shown in Fig. 2(a), the extinction ratio was limited to 25 dB by small sub-pulse-like components between the output pulses. Then, to observe the waveform of the remaining components in more detail, we dropped the pulse frequency from 25 to 12.5 GHz and carefully optimized the waveplate angles once again. At this frequency, the extinction ratio was limited to about 18 dB by several types of relatively large sub-pulse components depending on the Q_1 and P_1 settings [Figs. 2(b) to 2(d)]. In particular, the sub-pulse waveform in Fig. 2(d) appeared to be time-inverted with respect to that in Fig. 2(b). After we repeatedly observed the dependence of the waveform on the waveplate angles, we estimated the relative phase bias $\Delta\Phi_B$ (indicated in each figure) from the waveplate angles by using the Jones-matrix analysis. (ΔQ and ΔP are the relative angles of Q_1 and P_1 measured from the positions where $\Delta\Phi_B = \pi$.)

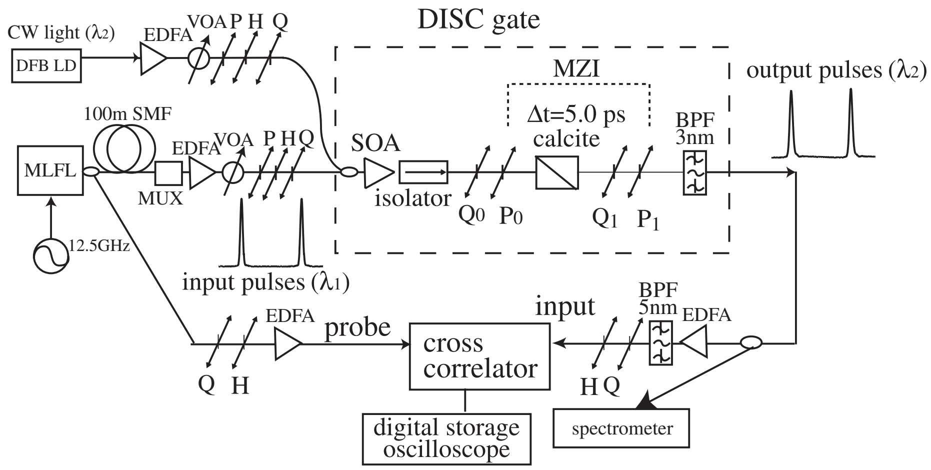

Fig. 1. Setup of the DISC-gate experiment. VOA: variable optical attenuator, MZI: Mach–Zehnder interferometer, SOA: semiconductor optical amplifier, Q: quarter-wave plate, H: half-wave plate, P: polarizer.

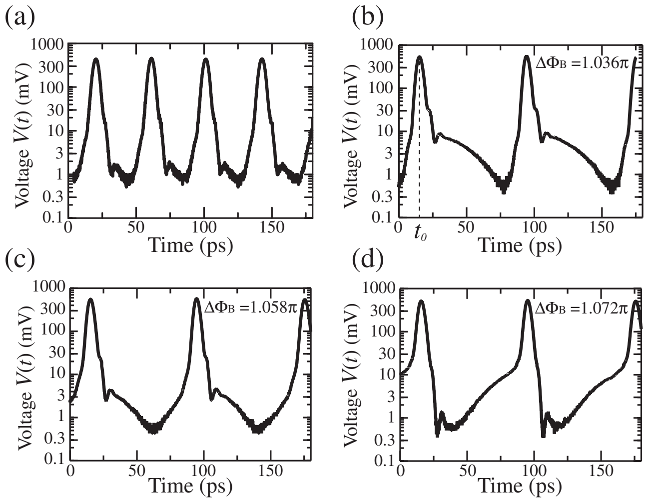

Fig. 2. Measured cross-correlation traces of the DISC output with different Q_1 and P_1 settings: (a) with +12.3-dBm, 25-GHz input pulses, (b)–(d) with +13.5-dBm, 12.5-GHz input pulses [(b) $\Delta Q = -3^\circ$, $\Delta P = -1^\circ$, (c) $\Delta Q = -6^\circ$, $\Delta P = -4^\circ$, (d) $\Delta Q = -8^\circ$, $\Delta P = -6^\circ$]. Phase bias $\Delta\Phi_B$ was calculated from ΔQ and ΔP in each case.

For comparison, according to the above-mentioned simulation method, we calculated the sub-pulse waveforms. The SOA parameter values used in the calculation were separately determined from measured gain-saturation behaviors, cross-gain-modulated output waveforms, and cross-phase-modulated output spectra. These parameter values are summarized in Table I. According to the calculated results, the relative peak intensities of the sub-pulse-like components were −25 dB in Fig. 3(a) and −20 dB in Fig. 3(b).

The measured waveforms in Figs. 2(a) to 2(d) match the respective calculated waveforms in Figs. 3(a) to 3(d) fairly well. For a more systematic comparison of the measured and calculated results, though, we studied how the relative intensities of the sub-pulse-like components behave as a function of the optical interference phase bias $\Delta\Phi_B$ (Fig. 4). The relative intensity was taken at three timing positions ($t = t_0 + 15$, $t_0 + 40$, and $t_0 + 65$ ps, where t_0 is the primary pulse's position). The calculated optimum phase-bias values $|\Delta\Phi_B - \pi|$ in Fig. 4(b) were slightly larger than the measured ones in Fig. 4(a). For instance, the maximum extinction at $t_0 + 40$ ps (dashed curve) was obtained with an optimum $\Delta\Phi_B$ of 1.08π in Fig. 4(b), while in Fig. 4(a) the maximum extinction at $t_0 + 40$ ps (dashed curve) was observed with an optimum $\Delta\Phi_B$ of 1.06π. This small mismatch was probably due to a slight imbalance in the

Table I. Parameters used in the DISC-gate simulation.

Parameter	Description	Value: Fig. 3(a)	Value: Figs. 3(b)–3(d)
f	Pulse frequency (GHz)	25	12.5
t_{pulse}	Input pulse width (FWHM) (ps)	3.8	3.8
	Input pulse energy to the SOA module (fJ)	680	1790
P_{cw}	Input cw power to the SOA module (mW)	8	8
	SOA input coupling loss (dB)	2	2
G_0	SOA small-signal gain (chip) (dB)	23.4	23.4
P_{sat}	SOA saturation energy (fJ)	1080	1080
τ_c	SOA carrier lifetime (ps)	200	200
$\Delta\Phi_{max}$	Phase shift at complete carrier depletion	$+6\pi$	$+6\pi$
Δt	Delay time in the MZI (ps)	5.0	5.0
t_{probe}	Cross-correlator probe width (FWHM) (ps)	2.2	2.2

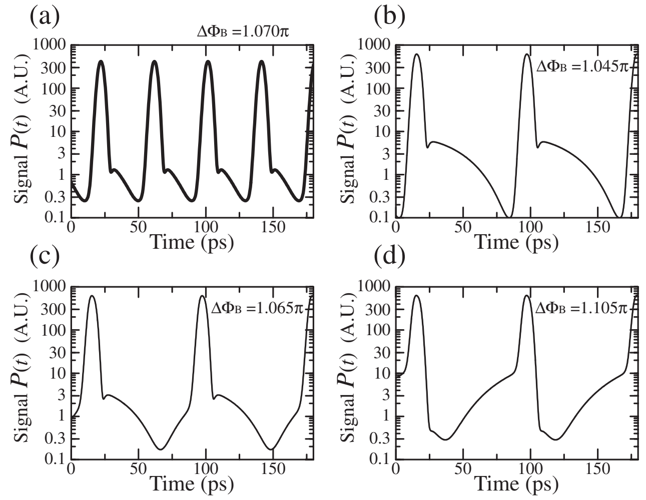

Fig. 3. Calculated cross-correlation traces of the DISC output: (a) with 25-GHz input pulses, (b)–(d) with 12.5-GHz pulses. [(b) $\Delta\Phi_B = 1.045\pi$, (c) $\Delta\Phi_B = 1.065\pi$, (d) $\Delta\Phi_B = 1.105\pi$]. Other parameters are summarized in Table I.

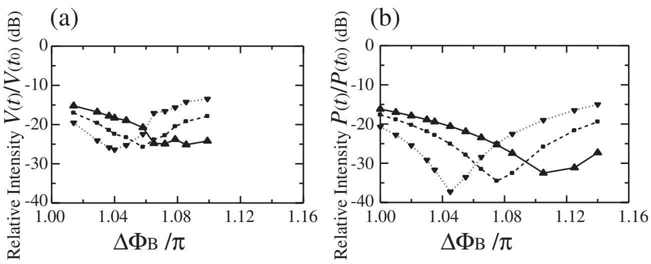

Fig. 4. Relative intensities of sub-pulse-like components in 12.5-GHz DISC output: (a) from experimental results, (b) from calculation. These were obtained at three timing positions: $t = t_0 + 15$ ps (solid), $t_0 + 40$ ps (dashed), and $t_0 + 65$ ps (dotted).

optical intensities between the fast and slow interference components and the remaining carrier-heating-induced phenomena in the SOA. Except for the small mismatch, the calculated relative intensities in Fig. 4(b) behaved in a manner very similar to those of the measured ones in Fig. 4(a).

Thus, as shown by Figs. 2 through 4, we observed a good match between the measured and calculated waveforms and phase-bias dependence. According to these results, we believe that we have experimentally verified the previously predicted sub-pulse generation from the DISC gate.

The sub-pulses of the DISC may cause a serious problem when we convert patterned data signals. Figure 5(a) shows a

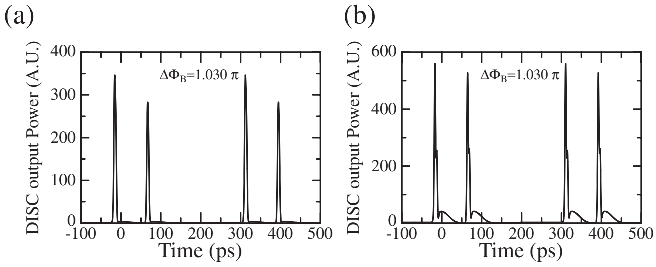

Fig. 5. Calculated cross-correlation traces of the DISC output for "1100"-patterned input pulses: (a) $\tau_c = 200$ ps, (b) $\tau_c = 80$ ps. Other parameters are the same as those used for Fig. 3.

calculated DISC output waveform for "1100" input pulses with $\tau_c = 200$ ps, and Fig. 5(b) shows a result with a smaller τ_c of 80 ps. The calculated results in Fig. 5 along with the measured results in Fig. 2 indicate that we face an unfortunate trade-off between the sub-pulse formation and the pattern-induced amplitude noise: when the effective carrier recovery time is relatively long, the sub-pulse intensity is small (Fig. 2) and the pattern-induced noise is relatively large [Fig. 5(a)]; however, if we accelerate the carrier recovery with stronger cw input light, which works as a holding beam, the sub-pulse intensity increases and the pattern-induced noise is suppressed [Fig. 5(b)].

We observed that the DISC output contained small sub-pulses in addition to the wavelength-converted output pulses. The measured dependence of the sub-pulse waveform on the MZI setting was well reproduced numerically with our DISC model. We also showed, according to our DISC model, that a trade-off exists between the magnitudes of these sub-pulses and the pattern-induced amplitude noise. These results suggest that part of the DISC structure should be improved to overcome this trade-off. Our on-going research activities on ways to improve the DISC structure will be presented elsewhere.

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