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Ultrafast 168 GHz 1.5 ps 1 fJ Symmetric-Mach-Zehnder-Type All-Optical Semiconductor Switch

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We report on the ultrahigh-repetition all-optical switching of a semiconductor-optical-amplifier-based symmetric-Mach-Zehnder-type switch. Record high 168 GHz, 1.5-ps-wide, 10-dB-extinction switch windows were observed. This repetition rate is ten times higher than the semiconductor optical amplifier's cutoff frequency. The control optical pulse energy used was a record low 1 fJ (average power $= 170\,\mu$W). Clearly isolated 168 GHz components were also observed in the output pulses' optical spectrum, which was in contrast to the continuum-like spectrum of the input pulses.

KEYWORDS: repetition, ultrafast, all-optical, symmetric, Mach-Zehnder, semiconductor optical amplifier, switch window, extinction

Ultrafast all-optical semiconductor switches (including demultiplexers, wavelength converters, regenerators, logic gates, and soliton-preserving modulators) have been intensively studied in an effort to increase the time-division-multiplexing (TDM) bit rate of each wavelength-division-multiplexed (WDM) channel from 10 to 40 Gbps to 160 Gbps and even higher (possibly more than 1 Tbps in the future). Such high-speed TDM rates will not only increase a network's throughput but also dramatically improve its flexibility. Among these ultrafast switches, the symmetric-Mach-Zehnder (SMZ)-type switch,[1,2] composed of semiconductor waveguides and an interferometer, has shown a 200 fs switch response time using relatively low-power 3 pJ 130 fs optical control pulses.[3] The switch worked as an all-optical demultiplexer; it switched one pulse out of a 1.5 THz optical pulse sequence. In principle, the control pulse energy requirement can be reduced to less than 100 fJ by operating the semiconductor switch in an optical amplification mode incorporating semiconductor optical amplifiers (SOAs), instead of in an absorption mode as in ref. 3. The response time of SOA-based SMZ switches is 0.67–1 ps.[4,5] This response time suggests that the SOA-based switch will still be able to demultiplex Tbps-class optical signals. Demultiplexing of 80 to 168 Gbps signals has been reported using SOA-based SMZ switches.[6,7]

The SMZ switch can also function as an all-optical wavelength converter,[8,9] regenerator,[10,11] logic gate,[12] and soliton-preserving modulator.[13] For these functions, in contrast to demultiplexing, the switch is required to be not only ultrafast in response time but in repetition rate as well. This is because an SMZ switch used in such applications must operate at a repetition rate which equals the input signal rate (160 GHz or higher). The repetition rates of the SMZ-type switches reported previously, however, were limited to 100 GHz,[12] in which a 5 ps switch window was all-optically formed by 100 fJ control pulses.

In this work we report on a demonstration of 168-GHz-repetition regular switching. This repetition rate is ten times higher than the carrier cutoff frequency of the SOA used in the experiment. The switch all-optically opened 1.5 ps switch windows that have a high extinction. The control pulse energy used in our experiment was a record low 1 fJ (average power $= 170\,\mu$W).

Figure 1 shows our experimental setup. We used a simplified SMZ switch: a delayed-interference signal-wavelength converter (DISC).[9,14] The DISC's switch mechanism is identical to that of the SMZ switch. The DISC is composed of three parts: an SOA, a passive Mach-Zehnder (MZ) interferometer, and a band-pass filter. In the DISC switch configuration, each input λ_1 pulse controls the switch and all-optically forms a switch window with respect to the copropagating λ_2 continuous-wave (CW) light. The width of the switch window is determined by the MZ delay time Δt (between the two-split λ_2 components). The transmittance of the switch window is determined by the gain and the nonlinear phase shift given to the λ_2 light. Each switch window gates the λ_2 light and consequently forms a λ_2 pulse at the DISC output. The band-pass filter allows these λ_2 pulses to pass but blocks the amplified λ_1 control pulses.

The part of the SOA that induced the ultrafast nonlinear phase shift was composed of two cascaded bulk-InGaAsP active-layer SOAs. We used two SOAs in order to increase the nonlinear phase shift at 168 GHz. Each SOA had an unsaturated gain of 700 and a carrier lifetime of 60 ps. The MZ interferometer was composed of bulky optics (a bi-refringent calcite crystal, a Babinet-Soleil phase retarder, a quarter-wave plate, and polarizers). The two ends of the MZ interferometer were lens-coupled to pigtails of the second SOA module and the band pass filter module, respectively (note: the entire DISC structure can be integrated on a silica-based planar-lightwave circuit[5,7] and consequently be made polarization insensitive, for practical application). The length of the calcite crystal determined the MZ delay time, which was measured to be 1.2 ps by observing the interferometer fringe spacing ($\Delta 6.8$ nm). The phase retarder was calibrated and then used to optimize the interferometer's phase bias.[14]

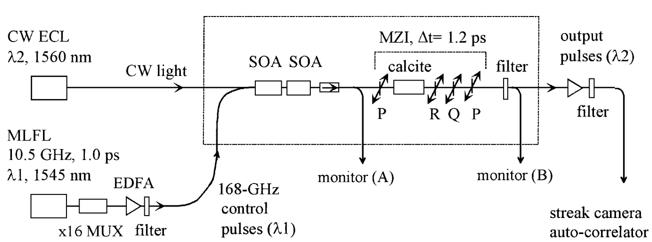

Fig. 1. Experimental Setup: 168 GHz 1.0 ps 1545 nm control pulses modulate 1560 nm CW light through all-optical SMZ switch (DISC configuration). SOA (nonlinear element) consists of two cascaded SOA modules.

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The 168 GHz, 1545 nm, 1.0 ps input pulses were generated by the 16-times multiplexing of the 10.5 GHz pulses from an actively-mode-locked fiber ring laser and preamplified by an Er-doped fiber amplifier (EDFA). The 1560 nm CW light was generated by an external-cavity laser diode. The switch output was detected by a streak camera and an autocorrelator after being amplified by another EDFA. We confirmed that neither EDFA broadened the 1.0 ps pulses.

Figure 2(a) shows the 168 GHz 1545 nm control pulses that were input to the switch, as detected by the streak camera. The nonuniformity of the peak heights originated from the 16-times multiplexing. Figure 2(b) shows the 1560 nm component at the SOA output, where the input pulse energy (coupled to the SOA) was 10 fJ and the input CW power was 80 μW. The 1560 nm component indicated cross-gain modulation (XGM) induced by the control pulses through the carrier density oscillation. The extinction ratio of the XGM was small, as expected, because the carrier lifetime was 10 times the control-pulse spacing so that the carrier density recovered only partially between the control pulse arrivals. The solid curve in Fig. 2(c) shows the optical spectrum at the SOA output. This spectrum shows the amplified 1545 nm pulses, the cross-phase-modulated (XPM) 1560 nm components, the broadly spread amplified spontaneous emission (ASE) of the SOAs, and the EDFA's ASE peak at 1536 nm. The dashed curve in Fig. 2(c) shows the SOA output spectrum with the 10 fJ input pulses but without the input CW. The dotted curve shows the SOA output spectrum without any input light. Comparisons between these spectra indicate that only the input control pulses strongly depleted the carrier density (CW light passed through the SOA as a probe). The measured average gain (G_t) with respect to the 1560 nm CW was saturated to 75 by the 10 fJ control pulses. The G_t recovered partially to 280 when the control-pulse energy was reduced to 1 fJ.

The shape of the XPM spectrum with 168-GHz-spaced components at around 1560 nm suggests the magnitude of the nonlinear phase shift given to the 1560 nm CW component. By accurately reproducing the XPM spectrum shape using our numerical simulation[14] in which the 168 GHz carrier oscillation was taken into account, we estimated the nonlinear phase shift induced by the 1 fJ control pulses to be 0.31π. When the pulse energy was increased to 10 fJ, the nonlinear phase increased only slightly to 0.42π because of the above mentioned carrier density depletion.

Figure 3(a) shows the 168 GHz 1560 nm switch output pulses controlled by the 10 fJ pulses. The CW input power was 80 μW. An extinction ratio of 10 dB was obtained after optimizing the MZ interferometer phase bias to 1.14π (with monitoring the 1560 nm XPM spectrum shape[14]). No 1545 nm component leakage was detected, as indicated by the switch output without the CW input (dashed curve). The background noise (dashed curve) originated from the ASE of the EDFAs and the SOAs. The switch output peak intensity at the band-pass filter output was measured to be 40 μW.

When the control-pulse energy was decreased to 1 fJ and the phase bias was optimized to be 1.09π, the switch output peak intensity increased to 55 μW, as shown in Fig. 3(b). The reason for this peak-intensity increase is that the increase in the gain contributed more than the decrease in the nonlinear phase shift. If the coupling losses between optical components are neglected, the intrinsic switch transmittance is 48. This transmittance coincides approximately with interference factor $\sin^2(\Delta\Phi_{NL}/2)$ ($\Delta\Phi_{NL}$: nonlinear phase shift) multiplied by gain G_t, as expected. An extinction ratio of 10 dB was obtained again. The width of the switch output pulses observed using an autocorrrelator was 1.5 ps.

It should be noted that the switch repetition time (6.0 ps) in Figs. 3(a) and 3(b) was ten times shorter than the carrier lifetime (determined by carrier population relaxation) of 60 ps. In addition, the switch width was close to the carrier cooling time of approximately 2 ps.[4] Our results revealed that neither the population relaxation nor the carrier cooling deteriorates aspects of the SMZ switch performance such as the switch window shape or its extinction ratio.

The switch in this work was controlled by continuous pulses only (Fig. 3). This type of operation is sufficient for soliton-preserving modulators. In contrast, the switch for wavelength conversion and regeneration is controlled by digitally encoded signal pulses. This type of operation could cause a pattern induced effect. It is well known that the pattern induced effect can be suppressed by increasing the CW input power (holding-beam technique[8,15]) because the CW light effectively accelerates the carrier recovery.

Finally, Fig. 4 shows the dramatic change in the optical spectral quality of the pulses we observed in our experiments. The spectrum of the 168 GHz 1.0 ps input pulses shown in Fig. 4(a) did not indicate any 168 GHz structures. Because

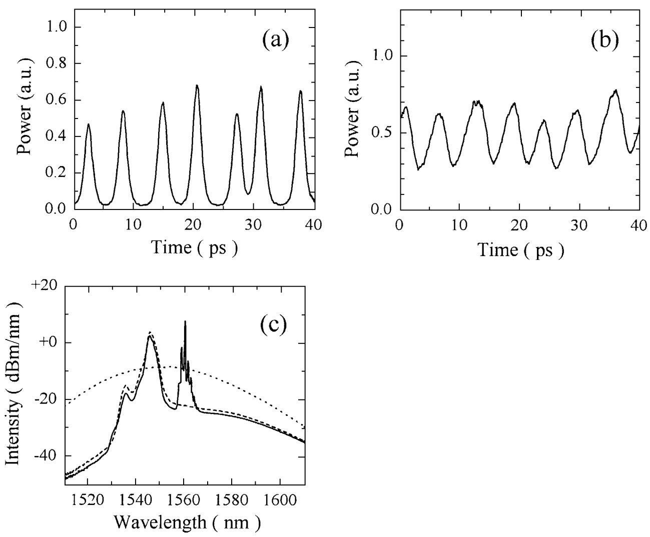

Fig. 2. Optical components before and after cascaded SOAs (a) 168 GHz 1545 nm control pulses, (b) 1560 nm component at SOA output, (c) optical spectra at SOA output.

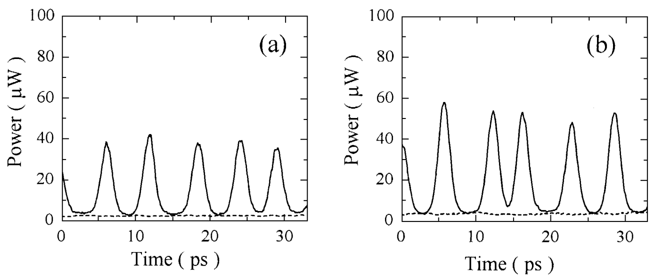

Fig. 3. All-optically switched 1560 nm component at switch output 168 GHz control pulse energies were (a) 10 fJ (average power = 1.7 mW) and (b) 1 fJ (170 μW).

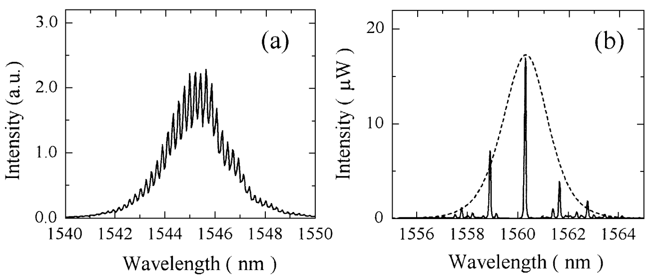

Fig. 4. Comparison of optical spectrum qualities of 168 GHz pulses (a) 1545 nm control pulses, and (b) 1560 nm output pulses (dashed curve shows calculated spectrum of transform-limited 1.2 ps pulses).

there was already spectral instability of the input pulses at the 10.5 GHz mode-locked laser output, we attributed the continuum-like spectrum to the fluctuations of the lasing optical frequency (to an order of $\Delta 10\,\mathrm{GHz} = \Delta 0.08\,\mathrm{nm}$). In contrast, the spectrum in Fig. 4(b) of the 168 GHz 1.5 ps switch output pulses in Fig. 3(b) was composed of clearly isolated 168-GHz-spaced components. We observed similar dramatic changes in the spectral quality at switch repetitions of 10.5 GHz and 42 GHz. These results indicate that the spectral quality of the input pulses was 'regenerated' by the SMZ switch. We attribute this regenerative property to the incoherent nature of the switch mechanism (in contrast to four-wave mixing), as the optical spectrum quality of the switch output was determined by that of the CW input light. Although the control pulse determines the switch window through the carrier-density change, only the pulse's intensity profile affects the carrier-density change. Because the carrier-density change occurs due to the incoherent band-filling effect and since both the nonlinear refractive-index change and the gain are relatively insensitive to the wavelength (in the range of one order of 168 GHz), the spectral quality of the control pulses does not affect that of the switch output pulses.

In summary, the repetition rate limit of an SMZ-type all-optical semiconductor switch was pushed up to 168 GHz. The switch window width was 1.5 ps and the control pulse energy was 1 fJ. These results, combined with the well-established holding-beam technique for suppressing the signal-pattern-induced effects, support the realistic potential of these types of switches for use in a variety of ultrafast signal-processing applications (wavelength converters, regenerаters, logic gates, and soliton-preserving modulators) at over 160 Gbps. Furthermore, this switch regenerates the optical spectral quality of pulses, a useful feature for all-optical cross-connects and transmission of ultrahigh-speed optical signals.

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