5-ps, 10-GHz pulse generation from an all-optical semiconductor switch embedded in a ring cavity

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We observed spontaneous generation of nearly transform-limited pulses (5 ps, 10 GHz, 1558 nm) from a semiconductor ring oscillator. This oscillator is completely different from conventional mode-locked lasers in that the pulse width is passively determined by a split delay time inside its ring cavity. This is because the ring cavity includes an all-optical semiconductor switch whose window width is determined by the split delay time.
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All-optical devices based on optical nonlinearities have recently begun to attract attention for their ability to push up the signal-processing speed limit, which has up until now been limited by transistors, optoelectronic devices, and so forth. Since the mid-1990's, the amount of research carried out on all-optical devices based on the nonlinearity of semiconductor optical amplifiers (SOAs) has increased substantially, and there are three reasons for this. The first reason is that their speeds are much faster than they had previously been believed to be: the speeds of SOA-based all-optical devices with specific interferometric structures (optical circuits) are *not* limited by the carrier's relaxation time, which ranges from 100 ps to 10 ns. Optical interference inside the devices masks the relaxation time.[1–5] In fact, the speed of all-optical logic operation now exceeds 160 GHz.[6–8] The second reason is that their nonlinearities are extremely large due to resonant enhancement and the pulse-amplification-induced recombination of current-injected electron–hole pairs: an optical input pulse with 10–100 fJ energy can generate a nonlinear phase shift that is sufficient for all-optical switching.[5–9] The third reason is that SOAs have inherent advantages in large-scale low-cost integration, which is used in commercial applications such as ultrabroadband photonic network systems. The SOA chips can be integrated both monolithically[10] and in hybrid manners on silica-based planar lightwave circuits[5,11] that are formed onto large silicon wafers.

A SOA can also be used as a nonlinear element for high-repetition mode-locked semiconductor ring lasers.[12–14] Such pulse lasers can be fabricated and integrated using technology similar to the above-mentioned all-optical devices, whereas other GHz repetition sources such as mode-locked fiber lasers and mode-locked semiconductor lasers cannot. The pulse widths of SOA-based mode-locked ring lasers are determined by the magnitude of the optical nonlinearity, just as they are for other mode-locked lasers.

We recently proposed a semiconductor ring oscillator [all-optically switched loop oscillator (ASLOS)] and predicted that it would be able to spontaneously generate short pulses.[15] This oscillator is completely different from conventional mode-locked lasers in that the pulse width is passively determined by a split delay time inside the oscillator's ring cavity. This is because the cavity includes a SOA-based all-optical switch for which the switch-window width is passively determined by the split delay time. In this study, we were able to observe pulses generated by the SOA-based ring oscillator.

Figure 1 shows a schematic view of the SOA-based ring oscillator. This oscillator consists of a ring cavity and an external continuous-wave (cw) laser source. The ring cavity consists of an all-optical semiconductor switch, an energy-distribution (ED) Mach–Zehnder interferometer (MZI), a tunable delay, a variable attenuator, a polarization controller, and an Er-doped fiber amplifier (EDFA) with a 28 dB gain. The ED MZI is an asymmetric MZI made of a customized silica planar lightwave circuit with a fixed delay time ΔT_R of approximately 100 ps (10 GHz) and a 50:50 split ratio.

The all-optical switch's structure is like that of the symmetric Mach–Zehnder-type (SMZ) delayed-interference signal-wavelength convertor (DISC).[4,6–9] The switch consists of a polarization-insensitive bulk-active-layer SOA, an isolator, a MZI, and a 2.4 nm bandpass filter. The MZI in the DISC is also an asymmetric MZI, which consists of a 10.5-mm-long birefringent calcite crystal, a Babinet–Soleil phase adjustor, and two polarizers. The delay time of the MZI, that

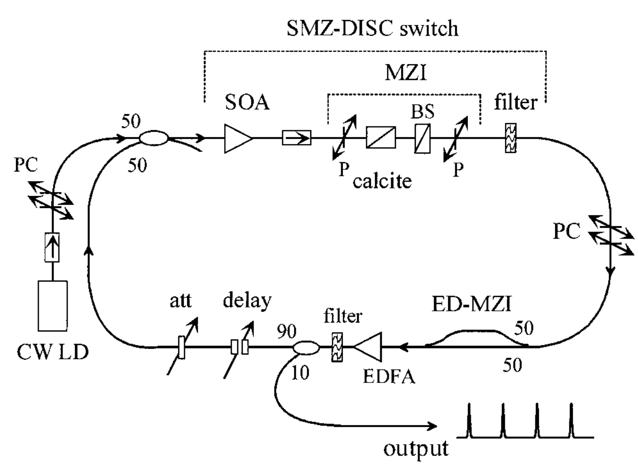

FIG. 1. Experimental setup for the semiconductor ring oscillator.

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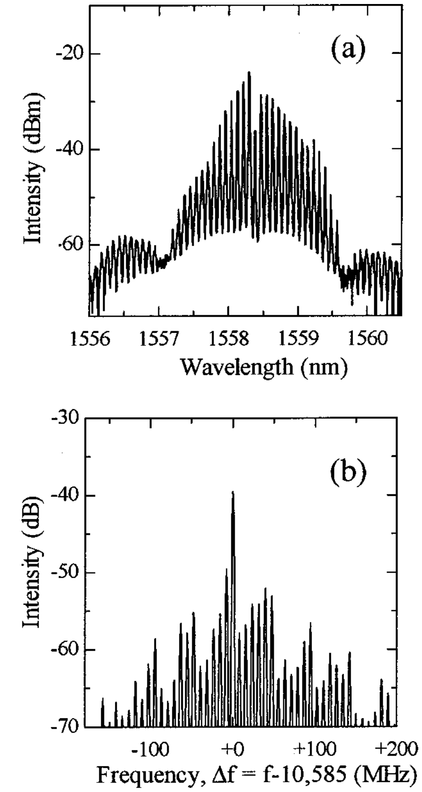

FIG. 2. Optical spectrum (a) and rf spectrum (b) observed at the oscillator output after tuning the ring cavity.

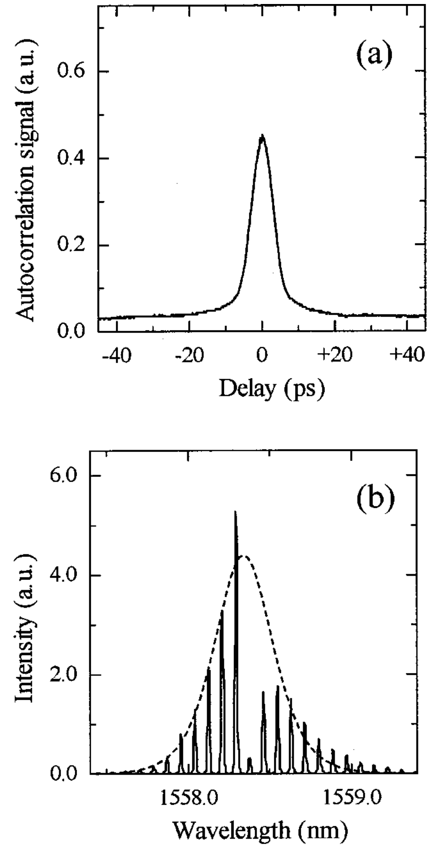

FIG. 3. Typical autocorrelation trace (a) and optical spectrum (b) of the output pulses.

is, the birefringency of the calcite crystal ($\Delta t = 6$ ps), is used to determine the width of the all-optical switch's switch window,[4] and the filter blocks some of the amplified spontaneous emissions (ASEs) from the SOA.

The ring cavity was built with fiber-pigtailed components (a SOA, a filter, an ED MZI, an attenuator, and a polarization controller) and lens-coupled components (DISC MZI). We inserted the EDFA to compensate for the large total loss of the ring cavity (26 dB) caused by the number of optical couplings. The pulse's round-trip time around the ring was 125 ns (8 MHz).

When the ring cavity is properly tuned, pulses start circulating as follows. Suppose a pulse is amplified by the SOA inside the all-optical switch. The pulse all-optically modulates the optical phase of the copropagating cw light due to the bandfilling effect. The phase of the cw light rises and relaxes, and the rise time is of the order of the pulse width, while the relaxation time is longer due to the carrier's lifetime. At the SMZ-DISC output, only a Δt-long cw component survives.[4] In the meantime, the input pulse polarization is adjusted so that the amplified pulse at the SOA output is blocked by the polarizer before the calcite. As a result, a new pulse is generated at the all-optical switch's output, which then circulates around the ring, returns to the SOA input, and then modulates the phase of the cw light again. Thus, the pulse width is passively determined by the DISC-MZI's delay time (Δt), and can be shorter than the SOA's carrier lifetime, as in the case of the SMZ DISCs discussed in previous reports.[4,6–9] On the other hand, the pulse repetition frequency is also passively determined by the ED MZI.[15] This is because the ED MZI splits each pulse into two ΔT_R-spaced pulses.

It should be noted that this pulse source is not a laser, but an oscillator. This is because each pulse is replaced with a new pulse after one round trip, as mentioned above. The new pulse is generated from a cw seed light through an incoherent nonlinear process, that is, a nonlinear refractive index change due to the pulse-amplification-induced carrier-density change in the SOA.

We experimentally adjusted the ring oscillator shown in Fig. 1 as follows. First, we observed 1558.4 nm cw lasing at the output of the 10% output coupler by injecting a 250 mA direct current into the SOA and a 0 dBm 1558.4 nm cw light into the 50:50 input coupler. We then adjusted the phase bias of the DISC MZI so that the cw component would destructively interfere with each other, and also optimized the ring's polarization controller in order to prevent cw lasing. After the MZI bias and the polarization controller were optimized, we observed strong ASE but no lasing at the cavity output. We also observed a series of 8-MHz-spaced rf components from a photodetector placed at the oscillator output.

Finally, we adjusted the round-trip time accurately with the variable time delay. Once the delay was optimized, the output optical spectrum changed into a series of 10-GHz-spaced discrete components [Fig. 2(a)]. On the other hand, one of the 8-MHz-spaced ring-cavity components rose up [Fig. 2(b)]. These two changes occurred simultaneously and dramatically. These spectra indicated that the pulses started circulating around the ring after one of the harmonics of the cavity frequency (Δ8 MHz) precisely matched the ED MZI's frequency (10.585 GHz). It should be noted that the two dips observed at 1557.0 and 1559.5 nm, as shown in Fig. 2(a), were caused by destructive interference at the DISC-MZI output. The shape of the spectral envelope was thus determined by the DISC MZI, just as the pulse width was determined.

Figure 3 shows a typical autocorrelation trace (a) and a typical optical spectrum (b) of the 10.585 GHz output pulses without dispersion compensation. The pulse width was estimated to be 5 ps, assuming a sech pulse shape. The limited extinction ratio shown in Fig. 3(a) was attributed to the limited cavity-mode suppression ratio given in Fig. 2(b). We believe that both the pulse extinction and cavity-mode suppression ratios could be improved by stabilizing or integrating the ring cavity. This is because the present cavity was built with non-polarization-maintaining fibers that had a total length of 25 m, which are easily affected by environmental vibration and temperature fluctuations.

As shown in Fig. 3(b), the width of the output spectrum envelope was 0.42 nm. The dashed curve shows the calculated spectrum of a 6 ps sech pulse. These results indicate that the output pulses are close to a transform limit, as theoretically discussed in detail for the DISC's wavelength-converted pulses given in Ref. 16.

In summary, we observed spontaneous generation of 5-ps, 10-GHz, 1558-nm pulses from a semiconductor ring oscillator [all-optically switched loop oscillator (ASLOS)] that included a SOA-based all-optical switch. The output pulse width of 5 ps was determined not by the magnitude of the SOA's nonlinearity, but by the width (6 ps) of the all-optical switch window. More specifically, the pulse width was passively determined by an asymmetric MZI split delay time inside an all-optical switch.

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