Record low-power all-optical semiconductor switch operation at ultrafast repetition rates above the carrier cutoff frequency

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The switch repetition-rate limit of all-optical semiconductor switches, for which the dynamic extinction ratio decreases with increasing repetition rate, is examined and overcome. The extinction ratio is improved by optimization of the interferometer phase bias, which has previously been set to π. The extinction-ratio increase accompanies a drastic change in the output pulse spectrum. Both the output pulse profiles and the spectra, before and after optimization, are successfully reproduced by simulation. As a result, switch repetition of 42 GHz (2.5 times higher than the semiconductor-carrier cutoff frequency) is achieved by use of 5-ps, 1548-nm pump pulses. What are believed to be record low input pump-pulse energies of 750 aJ (peak power, 140 μW) at 10 GHz and 6 fJ (1.1 mW) at 42 GHz are used. © 1998 Optical Society of America

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Ultrafast optical switches controlled by light pulses, that is, all-optical switches,[1] have been a major application target for nonlinear optics since the early 1960's and are intended for use in information processing that will be faster than that under the electronics limit. In the early 1990's two similar semiconductor switches[2–4] based on the band-filling effect near resonance energy decreased pump-light power to a practical level. The semiconductor carrier lifetime of each switch, which was believed to limit its fall time, was masked by a combination of a time delay and an interferometer incorporated into the switch structure. Consequently, the fall time as well as the rise time of the switch was determined by the pump-pulse width. In fact, switch windows as narrow as 800 fs were demonstrated,[5] which suggested that these switches could be used at bit rates of more than 1 terabit/s.

The repetition rate of these switches is an issue independent of the rise and fall times. Tajima and co-workers suggested that the carrier lifetime should not limit the repetition rate of switches incorporating absorptive semiconductor waveguides.[2] For switches with semiconductor optical amplifiers (SOA's), Manning *et al.* also suggested that the carrier lifetime should not limit the repetition rate when the carrier injection rate is increased to suppress the carrier-density saturation.[6] In fact, switch repetition of 40 to 100 GHz was demonstrated for such switches incorporating absorptive waveguides[7] and for those with SOA's.[8–10] In Ref. 7, however, four consecutive 25-ps-spaced pulses instead of 40-GHz pulses were used as the pump pulses (carrier lifetime, 600 ps). In Refs. 8–10 the carrier lifetimes in the SOA's were not described. Thus previous experimental studies are of limited usefulness with regard to the repetition-rate limit.

The pump-pulse average power required for these switches basically increases in proportion to the repetition rate. The required energy for absorption-type switches is 4–7 pJ,[2] which corresponds to a 160–280-mW average power if the switches are operated at 40 GHz. When SOA's are used in place of the absorptive semiconductor waveguides, the pump-pulse energy is reduced owing to the stimulated amplification of the pump pulse in the SOA's to 100–300 fJ.[6,8]

In this Letter it is reported that the repetition rate of all-optical semiconductor switches is limited by the ratio of the switch-window width to the repetition period. We have found that this limit can be overcome by optimization of one of the operating conditions (the phase bias). It is also reported that this optimization helps to reduce the input pump-pulse energy.

Figure 1 shows the all-optical switch studied here.[11] Input pump pulses switch a cw light on and off through the switch. The mechanism that ensures the ultrafast rise time of this switch is the same as that of the switches studied in Refs. 2–4: Each time the SOA amplifies a λ_1 pump pulse at t_0, the SOA modulates the phase of the copropagating λ_2 signal light owing to the band-filling-induced nonlinear refractive-index change. Although the rise time of the phase change is determined by the pump-pulse width (t_p), its recovery is determined by the carrier lifetime (τ_c). The SOA also modulates the signal-light amplitude. After the SOA, the signal is split into two components, A and B, in the split delay. The B component [dashed curve in Fig. 2(a)] is delayed by Δt relative to the A component (solid curve). [Details of the calculation and Fig. 2(b) are described below.] After the split

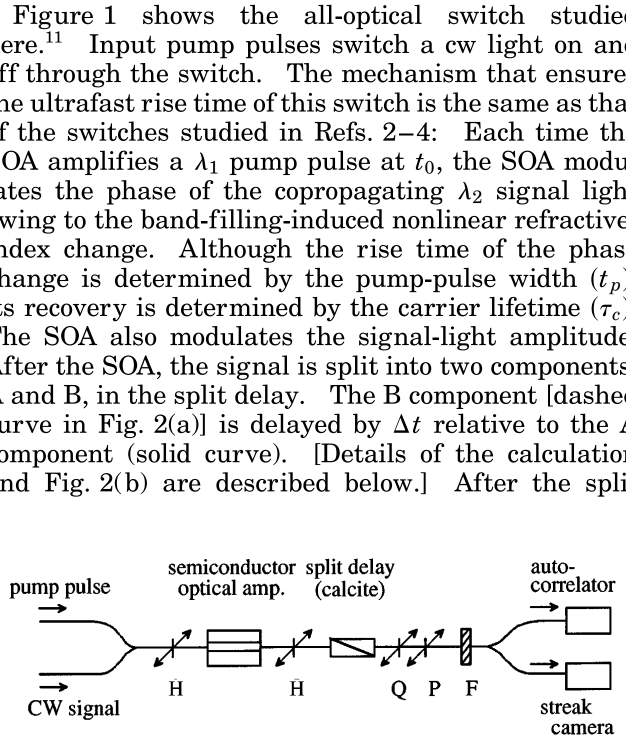

Fig. 1. Experimental setup: Each input pump pulse switches the signal light owing to the band-filling effect in the SOA. The switch-window width is determined by the delay time Δt of the split delay. Q, quarter-wave plate; P, polarizer; F, spectral filter; H's, half-wave plates.

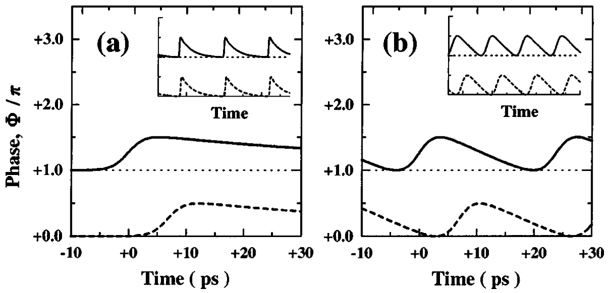

Fig. 2. Calculated phase shifts for the two split signal components. Solid curves, fast component; dashed curves, slow component. (a) f_R = 4.2 GHz, τ_c = 60 ps; (b) f_R = 42 GHz, τ_c = 60 ps.

delay, the two components reach the switch output port through a quarter-wave plate and a polarizer. The quarter-wave plate is tuned so that in the absence of pump pulses the two components interfere destructively after the polarizer. This tuning ensures that the A-component phase is biased by $+\pi$ relative to the B component. As a result the pump pulse is believed to switch on the signal light at t_0 and switch it off at $t_0 + \Delta t$, because the phase difference remains $+\pi$ before t_0 and after $t_0 + \Delta t$ [Fig. 2(a)]. The pump pulse forms a switch window from t_0 through $t_0 + \Delta t$ (the switch window is square if $t_p \ll \Delta t$; see Ref. 2). This switch is useful for experiments because of its structural simplicity and stability.

For the experiments we used a SOA with a 0.2-μm-thick, 1.2-μm-wide, 800-μm-long InGaAsP bulk active layer; a 12-mm-long calcite crystal (Δt = 6.8 ps); 5.0-ps, 1548-nm, 10.5-GHz mode-locked pulses emitted from a fiber-ring laser (Soliton Source, Pritel, Inc.); an optical multiplexer (from 10.5 to 42 GHz); and 5-μW 1560-nm cw light from a single-mode semiconductor laser. The internal unsaturated gain of the SOA at 1548 and 1560 nm was 700 for a 200-mA current injection. The pulse gain-saturation energy and carrier lifetime were measured to be 180 fJ and 60 ps, respectively, in separate experiments with 4.8-ps, 82-MHz mode-locked pulses. This carrier lifetime indicates that the SOA's cutoff frequency ($1/\tau_c$) was 16.7 GHz. The mode-locked pulses were amplified by an Er-doped fiber amplifier before pumping of the all-optical switch. The output pulses were amplified by another Er-doped fiber amplifier before being detected.

At a 10.5-GHz repetition rate, our switch generated clean 7-ps, 1560-nm output pulses. However, when the repetition rate was increased from 10.5 to 42 GHz (2.5 times higher than the cutoff frequency), the output pulse extinction ratio significantly decreased [solid curve in Fig. 3(a)]. The input pulse energy was 6.0 fJ (peak power, 1.1 mW).

We also found that optimizing the phase bias by slightly rotating the quarter-wave plate drastically improved the extinction ratio at 42 GHz from 2 to 12 [solid curve in Fig. 3(c)]. A significant change in the output spectrum was also observed [solid curves in Figs. 3(b) and 3(d)].

To clarify the mechanism behind these phenomena we performed a simulation, using a simple model. The nonlinear refractive-index change and gain coefficients were assumed to be proportional to the carrier density. We took into account the carrier saturation to account for both the pulse gain saturation and the carrier cutoff frequency. We determined the band-filling coefficients at 1548 and 1560 nm by fitting the calculated self-phase-modulated spectrum of the amplified pump pulse (Fig. 4) and the cross-phase-modulated spectrum of the signal light to those spectra measured under strong pump conditions. No other fitting parameters were used.

The calculated autocorrelation trace and the spectrum before the optimization matched the measured ones very well [Figs. 3(a) and 3(b)]. According to the simulation, the extinction-ratio decrease at 42 GHz originated from the phase difference between the A and the B components before t_0 and after $t_0 + \Delta t$, which decreased from approximately π at 10 GHz to 0.90 π at 42 GHz. This phase-difference drift from π can be approximately written as

$$\Phi_A(t) - \Phi_B(t) = \Phi_{\mathrm{bias}} - \frac{\Delta t}{t_R} \Delta\Phi_{\mathrm{NL}} , \qquad (1)$$

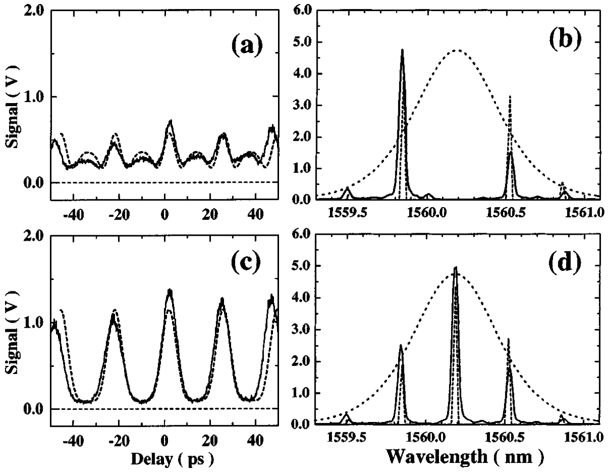

Fig. 3. Measured (solid) and calculated (dashed) autocorrelation traces and spectra for the 42-GHz output pulses (a), (b) before and (c), (d) after optimization. The dotted curves in (b) and (d) are calculated spectra for a transform-limited 4-ps pulse for comparison.

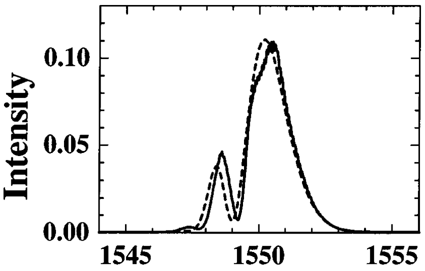

Fig. 4. Measured (solid) and calculated (dashed) spectra of the amplified pump pulses. The input pulse energy was 340 fJ. The nonlinear phase shift was estimated to be 2.0 π.

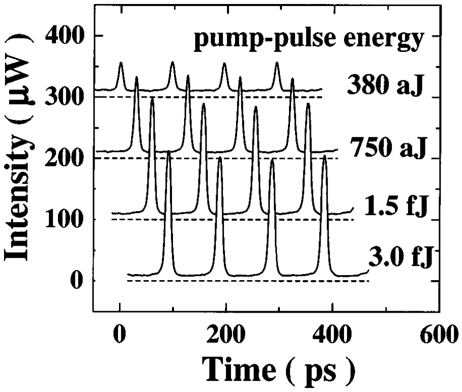

Fig. 5. Streak-camera traces of the 10-GHz output pulses. The intensity scale was carefully calibrated so that the +38-dB gain of the post-Er-doped fiber amplifier was taken into account.

because the phase recovers almost linearly in time [Fig. 2(b)] when the repetition rate ($f_R = 1/t_R$, where t_R is the repetition period) is larger than the carrier cutoff frequency ($1/\tau_c$) considered here. Equation (1) suggests that the switch repetition rate is limited by the factor $\Delta t/t_R$, under the previous condition, $\Phi_{\text{bias}} = \pi$.

Both the measured and the calculated spectra in Fig. 3(b) basically consisted of 42-GHz (0.34-nm) spaced peaks but lacked the 1560.2-nm center component. We explain this by considering the Fourier components of the output field amplitude:

$$f(\Delta\omega) = \int [E_0(t)\exp(i\Phi_{\text{bias}}) + E_0(t - \Delta t)] \times \exp(-i\Delta\omega t)\mathrm{d}t\,. \tag{2}$$

Equation (2) shows that $f(\Delta\omega = 0)$ should vanish when Φ_{bias} is set to π.

Equation (1) suggests that one can set the phase difference $\Phi_A(t) - \Phi_B(t)$ close to π by optimizing the phase bias as $\Phi_{\text{bias}} = \pi + (\Delta t/t_R)\Delta\Phi_{\text{NL}}$ ($=1.10\ \pi$ for the above experiment). In fact, the calculated autocorrelation trace and spectrum with the optimized phase bias reproduced the measured ones successfully [Figs. 3(c) and 3(d)]. The above suggestion should be valid for overcoming the repetition-rate limit of all switches similar to those in Refs. 2–4, including absorption-type switches.

In the spectrum, the center component was generated. The spectrum envelope became similar in shape to the calculated spectrum of a 4-ps transform-limited pulse [dashed curves in Figs. 3(b) and 3(d)], in a manner similar to mode-locked pulse spectra. This spectrum change should be helpful for tracking the optimum phase bias of all-optical switches for long-term operation (regardless of the repetition rate) as well as for optimizing the phase bias.

The switch transmittance for the 5-μW signal, measured with a calibrated streak camera, was 16 (owing to amplification) at 42 GHz. The calculated transmittance was 8, which matched fairly well with the measured transmittance. When the input pulse energy increased from 6 fJ, the transmittance decreased both experimentally and theoretically because the gain decreased faster than the phase shift increased. The nonlinear phase shift was estimated to be 0.20 π.

The phase-bias optimization also helped to reduce the input pump-pulse energy for switching at 10 GHz. The lowest input pulse energy at which an extinction ratio greater than 10 was obtained was 750 aJ (Fig. 5), in which the peak power was 140 μW (20 kW/cm^2). The continuous noise component originated from the SOA's amplified spontaneous emission. The nonlinear phase shift was 0.30 π. These values led to a effective nonlinear index of refraction ($n_2{}^{\text{eff}}$) of 1.3×10^{-8} cm^2/W [$\chi^{(3)}$ of 3.5×10^{-6} esu], which is several orders of magnitude larger than those of reported $\chi^{(3)}$- or $\chi^{(2)}$-cascading materials used or proposed for use in ultrafast all-optical switches.[1]

In summary, after considering the origin of the repetition-rate limit for all-optical semiconductor switches, we have shown how this limit can be overcome. As a result, ultrafast switching operation at 10–42 GHz with record low input pump-pulse energies was demonstrated.

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