APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 25 18 JUNE 2001

Femtosecond switching with semiconductor-optical-amplifier-based Symmetric Mach–Zehnder-type all-optical switch

Shigeru Nakamura,[a] Yoshiyasu Ueno, and Kazuhito Tajima
Photonic and Wireless Devices Research Laboratories, NEC Corporation, 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan

(Received 23 January 2001; accepted for publication 25 April 2001)

We investigate the effect of intraband carrier dynamics on a nonlinear phase shift induced in a semiconductor optical amplifier (SOA) in terms of its applicability to the Symmetric Mach–Zehnder (SMZ) all-optical switch. Nonlinear phase shifts in an SOA and a passive semiconductor waveguide are compared under control-pulse durations ranging from 3.2 to 0.4 ps. The results show that femtosecond switching with higher efficiency is still possible by using the SOA. We experimentally achieve femtosecond (670 fs), femtojoule (140 fJ) switching with the SOA-based SMZ all-optical switch. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1379790]

All-optical switches are expected to be key devices for various optical signal processing required in future optical-time-division-multiplexing networks. Recently, the Symmetric Mach–Zehnder (SMZ) all-optical switch family, including the original SMZ switch,[1] the Polarization-Discriminating SMZ (PD-SMZ) switch,[2] and the Delayed-Interference Signal-wavelength Converter,[3] has attracted considerable attention.[4,5] In the SMZ switch, the relaxation rate of nonlinear refraction, on which the switch relies, does not limit the switching speed. This enables us to achieve ultrafast switching by using optical nonlinearity that is highly efficient but generally shows slow relaxation. Practical optical nonlinearity is that incoherently excited in semiconductors by optical pulses resonant with the interband transition. Such optical nonlinearity is accompanied by a carrier density change and is called a band-filling effect. One method to excite a band-filling effect is to use control pulses absorbed in a semiconductor and thereby generate photocarriers. Based on the nonlinear refraction induced in such a passive semiconductor waveguide, we have demonstrated 200 fs switching,[6] showing the capability of handling over 1 Tbps signal pulses with the SMZ-type switch. In this experiment, the control-pulse energy required for a nonlinear phase shift of π was a few pJ. A more efficient method to induce a band-filling effect is to introduce a semiconductor optical amplifier (SOA) as a nonlinear waveguide. In this case, control pulses are amplified and thus deplete carriers. The gain for control pulses is useful for reducing the input control-pulse energy. We have demonstrated error-free 168 Gbit/s demultiplexing with the hybrid-integrated SMZ switch,[7] where the control-pulse energy injected into the SOA to obtain π shift was reduced to about 50 fJ. However, to handle 1 Tbps signal pulses by using the SOA-based SMZ switch, we should consider the effect of intraband carrier dynamics induced by the femtosecond control pulses in SOAs. A major effect on the SOA gain is the reduction in saturation energy, as already reported experimentally[8] and interpreted theoretically.[9,10] However, there are few quantitative evaluations concerning the effect of intraband carrier dynamics on nonlinear refraction, which is essential for interferometric all-optical switches, except the observation of qualitative characteristics.[11] In particular, whether the SOA-based nonlinear refraction still shows higher efficiency than that induced with control-pulse absorption in a passive semiconductor waveguide should be clarified in the femtosecond region. In this letter, we report on the investigation of the effect of intraband carrier dynamics on nonlinear refraction in a SOA in terms of its applicability to the SMZ switch. Nonlinear phase shifts in a SOA and a passive semiconductor waveguide are compared under control-pulse durations ranging from 3.2 to 0.4 ps. Based on these results, we conclude that femtosecond switching with femtojoule control-pulse energy is possible with the SOA-based SMZ switch. We have experimentally achieved femtosecond (670 fs), femtojoule (140 fJ) switching.

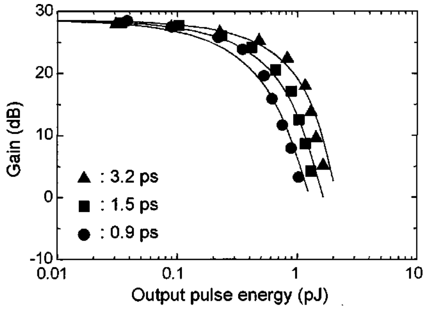

FIG. 1. Pulse duration dependence of pulse gain.

Figure 1 shows the pulse duration dependence of pulse gain, which we measured for a 1550 nm band SOA. Here, optical pulses at a wavelength of 1550 nm were amplified in a moduled SOA having a core of bulk InGaAsP with a bias current of 100 mA. The optical source of the pulses was an optical parametric amplifier (OPO), which emitted 100 fs pulses at a repetition rate of 82 MHz. The adjustment of the pulse duration was done by varying the transmission width of a filter that spectrally sliced the output of the OPO. Fitted curves shown in Fig. 1 were derived by a simple rate-equation model where a nonlinear gain coefficient of $\varepsilon = 2.4\times 10^{23}\,\mathrm{m}^3$ was included. A reduction in saturation energy with decreasing pulse duration is clearly seen. This behavior is attributed to spectral hole burning and carrier heating of electrons.[8–10] If an ultrashort optical pulse is injected into a SOA, carriers in a finite energy range interacting with

---

[a] Electronic mail: s-nakamura@dy.jp.nec.com

0003-6951/2001/78(25)/3929/3/$18.00

the optical pulse are depleted to cause spectral hole burning. Such ultrafast carrier depletion also raises the average energy of the remaining carriers, leading to carrier heating, because the removed carriers are those initially occupying energy levels well below the chemical potential of the Fermi–Dirac distribution. Besides carrier depletion, free carrier absorption also contributes to carrier heating. The typical relaxation times of spectral hole burning and carrier heating for electrons are considered to be 100 fs and 1 ps, respectively, while those time constants for holes are considered to be much shorter. Those effects prevent carriers from redistributing during the amplification process of pulses with a duration of shorter than a few ps and thus reduces the amount of carriers contributing to the pulse gain.

Although Fig. 1 implies the reduction in the nonlinear phase shift associated with carrier depletion, the nonlinear phase shift should be measured more directly. Thus, we placed the SOA used for the above pulse gain measurement in an interferometer based on the PD-SMZ switch setup detailed in Ref. 6. The temporal evolution of the phase was deduced from pump–probe traces for the interferometer output. To compare nonlinear phase shifts in a SOA and a passive semiconductor waveguide, we did the measurement for the same waveguide with and without current injection. While the wavelength of the control (pump) light which excited the nonlinear waveguide was set at 1550 nm, the wavelength of the signal (probe) light which experienced the nonlinear phase shift was set at 1700 nm, in the transparent region of the nonlinear waveguide. This wavelength assignment was kept unchanged through the measurement on the SOA and the passive semiconductor waveguide. The "signal light" and the "idler light," which were generated from an OPO without timing jitter, were used as the control and signal pulses, respectively. The control-pulse duration was varied by filtering the output of the OPO. The signal-pulse duration was set to 0.4 ps.

When the SOA was excited by 0.14 pJ control pulses having a duration of 3.2 or 0.4 ps, the temporal evolutions of the signal-light phase shown in Fig. 2(a) were obtained. The light coupling efficiency of the SOA chip was estimated to be 30% from the ratio of photocurrent to light power launched into the SOA module. The 3.2 ps control pulse modified the phase with monotonous rising accompanied by carrier depletion. In contrast, the 0.4 ps control pulse induced two components with different relaxation times. One component relaxing with a time constant of about 1 ps, as fitted to a dotted line in Fig. 2(a), is attributed to carrier heating. The other component which shows slower relaxation is due to carrier depletion. The magnitude of the slowly relaxing component (ϕ_{CD}) is smaller than the nonlinear phase shift induced by a 3.2 ps control pulse. This is attributed to the fact that a shorter control pulse induces a less amount of carrier depletion because of spectral hole burning and carrier heating. In contrast to the case of the SOA, there was no overshoot-like behavior in the phase change induced in the passive semiconductor waveguide even when the 0.4 ps control pulse was used.

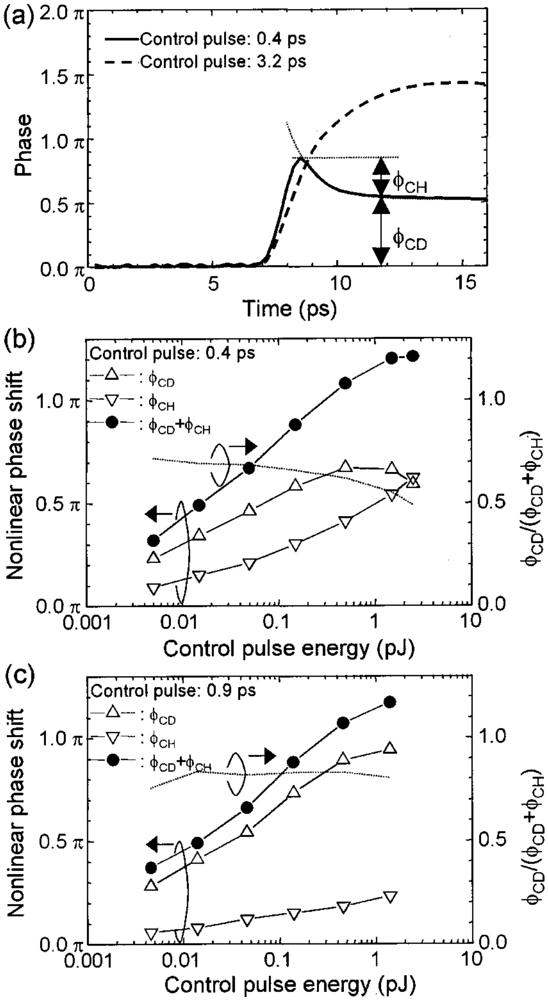

FIG. 2. (a) Temporal evolutions of the phase induced in the SOA. Solid line: nonlinear phase shift excited by a 3.2 ps control pulse. Dashed line: nonlinear phase shift excited by a 0.4 ps control pulse. Dotted line shows an exponential decay curve with a time constant of 1 ps. (b) Nonlinear phase shifts due to carrier depletion and carrier heating and their total as a function of input control pulse energy when the SOA was excited by a 0.4 ps control pulse. △: nonlinear phase shift due to carrier depletion. ▽: nonlinear phase shift due to carrier heating. ●: total nonlinear phase shift. Dotted line is the ratio of the carrier depletion component to the total. (c) Results when a 0.9 ps control pulse was used.

The influence of the component due to carrier heating on the operation of the SMZ switch is considered next. In the SMZ switch, the difference between the phase showing the above behavior and its temporally displaced replica is utilized to cancel out the relaxation tail of the nonlinear refraction associated with the carrier density change.[1,2] Inside the time region of the switching window, the component due to carrier heating contributes to enhancing the total nonlinear phase shift because the two components due to carrier heating and carrier depletion have the same sign. Outside the switching window region, however, the component due to carrier heating disturbs the complete canceling of the relaxation tail of the nonlinear phase change. This leads to degradation in the extinction ratio, although this effect can be reduced to some extent by using the sinusoidal dependence of the Mach–Zehnder interferometer output on the phase, as will be shown later. In Figs. 2(b) and 2(c), the nonlinear phase shifts (ϕ_{CH} and ϕ_{CD}) due to carrier heating and carrier depletion and their total ($\phi_{\mathrm{CH}}+\phi_{\mathrm{CD}}$) are plotted as a function of the input control-pulse energy for the case that the SOA was excited by 0.4 and 0.9 ps control pulses. Because of the contribution from carrier heating, the total nonlinear

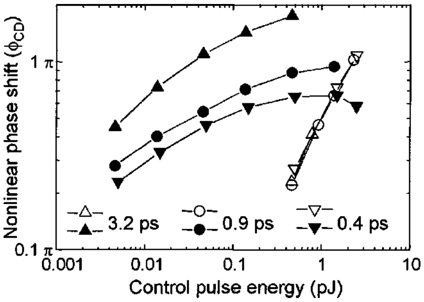

FIG. 3. Comparison of nonlinear phase shifts due to carrier density change in the SOA and the passive semiconductor waveguide. △, ○, ▽: excited in the passive semiconductor waveguide with 3.2, 0.9, and 0.4 ps control pulses, respectively. ▲, ●, ▼: excited in the SOA with 3.2, 0.9, and 0.4 ps control pulses, respectively.

phase shift reaches π at an input control-pulse energy of about 0.3 pJ for both cases. ϕ_{CH} increases with increasing the input control-pulse energy in the region where ϕ_{CD} is saturated, indicating that free carrier absorption also contributes to carrier heating. In the region where ϕ_{CD} is unsaturated, the ratio, $\phi_{CD}/(\phi_{CD}+\phi_{CH})$, is rather independent of the input control-pulse energy and seems determined only by the control-pulse duration.

Figure 3 compares the nonlinear phase shift associated with carrier depletion in the SOA for different control-pulse durations. The nonlinear phase shift induced by control-pulse absorption in the passive semiconductor waveguide is also plotted in Fig. 3. It is obvious that to obtain a small nonlinear phase shift, the scheme of control-pulse amplification induces a larger nonlinear phase shift than that with control-pulse absorption without control-pulse gain. To apply the nonlinear phase shift to all-optical switching, however, a relatively high phase shift, ideally π, is needed. For the case of control-pulse absorption, a π shift was obtained by a control-pulse energy of about 2 pJ. The nonlinear phase shift with control-pulse absorption did not depend on the control-pulse duration. In contrast, the nonlinear phase shift with carrier depletion in the SOA was highly dependent on the control-pulse duration. The 3.2 ps control pulse induced a π shift with a control-pulse energy of about 35 fJ, 2 orders of magnitude lower than that with control-pulse absorption. When the control pulse was reduced, the control-pulse energy required for a certain nonlinear phase shift increased. Even for the 0.4 ps control pulse, however, the SOA exhibited a higher efficiency up to a rather high nonlinear phase shift. Note that the performance of the SOA can be improved by further optimizing the operating conditions such as injection current while improving the performance of the passive semiconductor waveguide requires reconsideration of its materials.

The control-pulse duration of 0.4 ps is considered appropriate for opening a switching window of less than 1 ps with the SMZ all-optical switch. Thus, we constructed the SOA-based PD-SMZ switch to show femtosecond switching capability. The setup was nearly the same as that detailed in Ref. 6 except that the passive semiconductor waveguide was replaced with the SOA and the switching time determined by birefringent crystals was set to 0.67 ps. The temporal characteristic for switching was evaluated by the pump–probe technique. As shown in Fig. 4, we obtained a pump–probe trace showing a switching time of 0.67 ps with a control-pulse energy 0.14 pJ. This control-pulse energy is the same as the case shown in Fig. 2(a), thus the total nonlinear phase shift should reach about 0.9 π. The disturbance to the extinction after the switching window because of carrier heating was less pronounced because the output intensity of the Mach–Zehnder interferometer has a sinusoidal dependence on the phase.

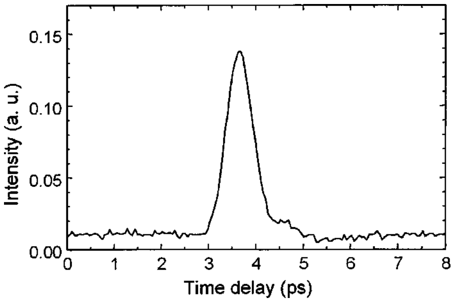

FIG. 4. Pump–probe trace showing 0.67 ps switching with SOA-based PD-SMZ switch.

In conclusion, we investigated the effect of intraband carrier dynamics on nonlinear refraction induced in a SOA in terms of its applicability to the SMZ all-optical switch. The nonlinear phase shift component due to carrier heating contributes to enhancing the output inside the switching window while hinders the complete extinction outside the switching window. The required control-pulse energy for the nonlinear phase shift due to carrier depletion increases when the control-pulse duration is reduced. However, the nonlinear phase shift in the SOA still shows higher efficiency than that in the passive nonlinear waveguide even when the 0.4 ps control pulse is used. In fact, we experimentally achieved femtosecond (670 fs), femtojoule (140 fJ) switching with the SOA-based SMZ-type switch. This is the fastest among all-optical switching induced by a control-pulse energy of less than 1 pJ.

This work was partially performed under the management of the Femtosecond Technology Research Association (FESTA) supported by the New Energy and Industrial Technology Development Organization (NEDO).

[1] K. Tajima, Jpn. J. Appl. Phys., Part 2 **32**, L1746 (1993).
[2] K. Tajima, S. Nakamura, and Y. Sugimoto, Appl. Phys. Lett. **67**, 3709 (1995).
[3] Y. Ueno, S. Nakamura, K. Tajima, and S. Kitamura, IEEE Photonics Technol. Lett. **10**, 346 (1998).
[4] R. Hess, M. Caraccia-Gross, W. Vogt, E. Gamper, P. A. Besse, M. Duelk, E. Gini, H. Melchior, B. Mikkelsen, M. Vaa, K. S. Jepsen, K. E. Stubkjaer, and S. Bouchoule, IEEE Photonics Technol. Lett. **10**, 165 (1998).
[5] S. Diez, C. Schubert, R. Ludwig, H.-J. Ehrke, U. Feiste, C. Schmidt, and H. G. Weber, Electron. Lett. **36**, 1484 (2000).
[6] S. Nakamura, Y. Ueno, and K. Tajima, IEEE Photonics Technol. Lett. **11**, 1575 (1998).
[7] S. Nakamura, Y. Ueno, K. Tajima, J. Sasaki, T. Sugimoto, T. Kato, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki, and T. Sasaki, IEEE Photonics Technol. Lett. **12**, 425 (2000).
[8] Y. Lai, K. L. Hall, E. P. Ippen, and G. Eisenstein, IEEE Photonics Technol. Lett. **2**, 711 (1990).
[9] A. Uskov, J. Mørk, and J. Mark, IEEE Photonics Technol. Lett. **4**, 443 (1992).
[10] A. Mecozzi and J. Mørk, IEEE J. Sel. Top. Quantum Electron. **3**, 1190 (1997).
[11] C. T. Hultgren and E. P. Ippen, Appl. Phys. Lett. **59**, 635 (1991).