All-optical timing restoration using a hybrid time-domain chirp switch

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We demonstrate a hybrid time-domain chirp switch (TDCS) in which the nonlinear chirper is an AlGaAs waveguide and the soliton dispersive delay line is a polarization-maintaining fiber. The hybrid TDCS can restore timing in a switching or transmission system, and when combined with an optical amplifier, it can act as an ultrafast, all-optical regenerator for soliton pulses. The timing restoration concept is applicable to other nonlinear materials with negligible walk-off, and the acceptable time window can be tailored by adjusting the width and intensity of a reference pulse.

In optical switching and transmission systems, it is important to restore logic level and timing periodically, with current networks performing the restoration at regenerators. However, with the trend toward light-pipe systems in which the regenerators are replaced by erbium-doped fiber amplifiers, the system becomes limited by timing jitter and fluctuations. Here we show that a hybrid time-domain chirp switch (TDCS) that consists of a semiconductor waveguide followed by a polarization-maintaining fiber can act as an ultrafast, all-optical timing restorer.

Recently, TDCS logic gates that are based on soliton dragging in optical fibers have been demonstrated with switching energies approaching 1 pJ.[1] The TDCS consists of a nonlinear chirper followed by a soliton dispersive delay line and has two orthogonally polarized inputs (signal and control pulses). The digital logic is based on time-shift keying in which a logical one corresponds to a control pulse that arrives within a clock window and a logical zero corresponds to a control pulse outside the clock window. In the soliton-dragging experiments, a moderately birefringent fiber corresponds to the nonlinear chirper, and a polarization-maintaining fiber corresponds to the soliton dispersive delay line. We now confirm the mechanisms in the TDCS by replacing the moderately birefringent fiber with an AlGaAs semiconductor waveguide as the nonlinear chirper.

The hybrid TDCS, which is shown schematically in Fig. 1, is tested in the same experimental apparatus as described in Ref. 1. A passively mode-locked color-center laser supplies $\tau \sim 415$ fs pulses near 1.69 μm. The soliton delay line is 600 m of polarization-maintaining, dispersion-shifted fiber with a zero dispersion wavelength of 1.585 μm. The inset of Fig. 1 shows the details of the 2.1-mm-long AlGaAs waveguide, which has a cross-sectional area of approximately 2.5 μm $\times$ 5 μm. The ridge waveguide is formed in a 2.55-μm-thick layer of $Al_{0.2}Ga_{0.8}As$, and the guiding is assured by a 2.55-μm buffer layer of $Al_{0.5}Ga_{0.5}As$ that has a refractive index 0.15 less than the active layer. The material composition is chosen so that the laser spectrum lies more than 100 meV below the half-gap energy, thus avoiding two-photon absorption. In this wavelength range we find that $n_2 \sim 3 \times 10^{-14}$ cm^2/W and that the material is isotropic (e.g., cross-phase modulation is two thirds of self-phase modulation).[2] We obtain a π-phase shift from self-phase modulation with an absorption of less than 10% and find that the nonlinear absorption originates primarily from three-photon absorption. Furthermore, time-resolved pump-probe measurements confirm that the nonlinearity is instantaneous on the 500-fs time scale of the pulses.

Figure 2(a) illustrates the time-shift-keyed data for the hybrid TDCS, where the signal energy in the waveguide is 9.8 pJ and the control energy is 96.5 pJ. The rectangle outlines the clock window, and we see that the addition of the signal shifts the control pulse out of this window. Because of mode mismatch and poor coupling into the fiber, the control energy exiting the fiber is 30.2 pJ, yielding a device fan-out or gain of approximately 3. Based on earlier nonlinear spectroscopy in longer lengths of the same waveguide,[2] we can estimate the nonlinear phase shifts. The peak self-phase-modulation phase shift for the control pulse in the waveguide is about $\pi/3$, while the peak cross-phase-modulation phase shift imposed by the signal on the control is approximately $\pi/24$. The measured shift of the control pulse as a function of signal energy also is shown in Fig. 2(b), and to lowest order we expect the shift to be linearly proportional to the switching energy.

In soliton dragging the control pulse chirps because of the combined action of cross-phase modula-

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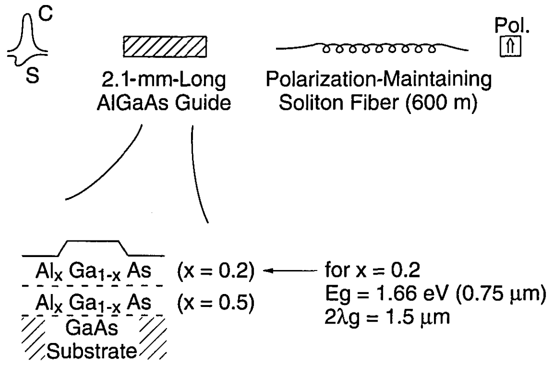

Fig. 1. Schematic of the hybrid TDCS and details of the semiconductor waveguide.

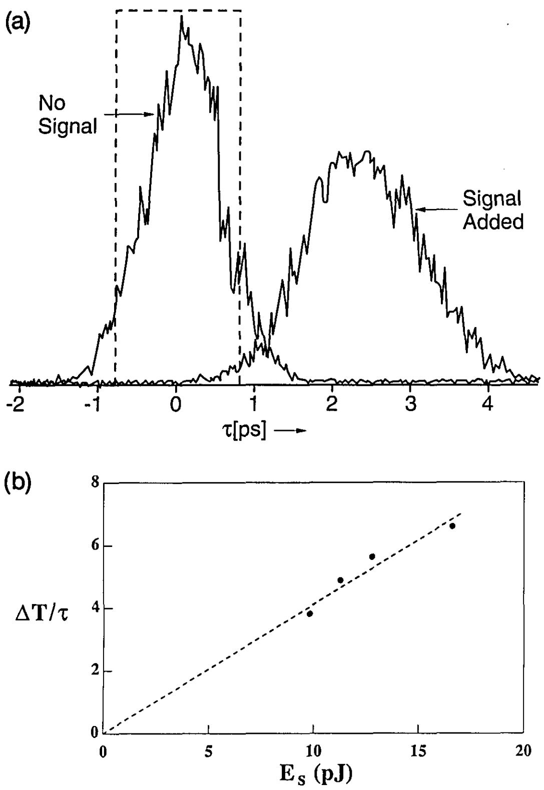

Fig. 2. (a) Time-shift-keyed data for the hybrid TDCS with a switching energy of 9.8 pJ and a fan-out of three. (b) Shift of the control pulse versus the signal energy for a control energy of 96.5 pJ in the waveguide.

tion and walk-off[3]: the walk-off asymmetrizes the frequency modulation, thereby leading to a shift in the center frequency of the pulse. However, time-resolved measurements in waveguides as long as 7.7 mm indicate negligible walk-off for our 415-fs pulses. To understand the origin of the time shift without walk-off, we experimentally studied the shift of the control pulse ΔT as a function of the separation between the control and signal pulses δt (Fig. 3). Indeed, no time shift occurs when the two pulses are perfectly overlapped. On the other hand, when the pulses are partially separated and one pulse travels on the wing or side of the other pulse, a net chirp or shift of the center frequency can result.

The data in Fig. 3 also show that the hybrid TDCS can provide timing restoration. For example, suppose that the control pulse is the input pulse and that the signal pulse is a reference pulse with the proper temporal position. We define the separation between the pulses $\delta t = t_{\text{input}} - t_{\text{ref}}$ and the shift of the input pulse ΔT. Therefore, if the input pulse is earlier than the reference pulse ($\delta t < 0$), then the nonlinear interaction pulls the input pulse to later times ($\Delta T > 0$), and vice versa.

We can understand the timing correction intuitively by considering the effects of frequency shift and anomalous group-velocity dispersion. The instantaneous frequency change $\delta\omega$ of the input pulse that is caused by cross-phase modulation is given by[4]

$$\delta\omega(t) = -\frac{\partial \Delta\Phi}{\partial t} = -\frac{2\pi}{\lambda}\frac{2}{3} n_2 L \frac{\partial I_{\text{ref}}}{\partial t} \tag{1}$$

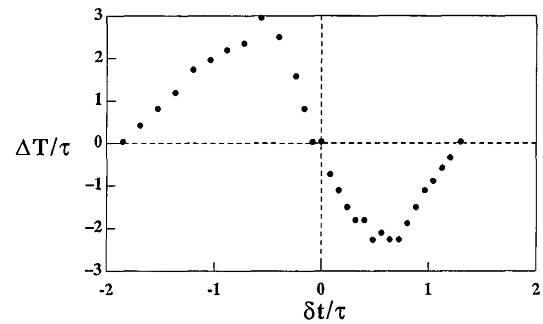

Fig. 3. Shift of the control pulse versus the initial separation between the control and signal pulses.

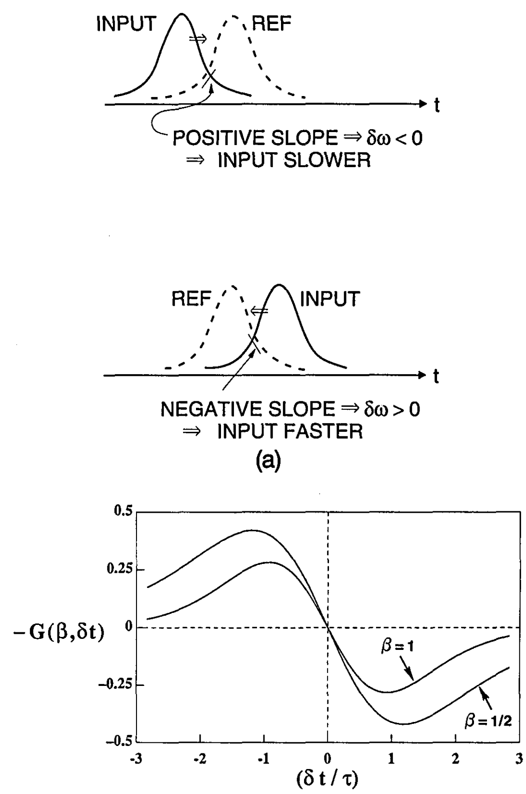

Fig. 4. (a) Intuitive picture of the temporal correcting nature of the nonlinear interaction for $n_2 > 0$ and anomalous group-velocity dispersion in the fiber. (b) Calculated frequency shift of an input pulse due to cross-phase modulation ($\beta = \tau_{\text{input}}/\tau_{\text{ref}}$).

and is proportional to the negative slope of the reference pulse for $n_2 > 0$. Because lower frequencies travel slower in anomalous dispersive material, a pulse with downshifted frequency arrives later and travels toward the right on a time axis. Figure 4(a) illustrates the correcting nature of the interaction. When the input pulse arrives earlier than the reference pulse (top), the input pulse sees a positive index slope, which lowers its instantaneous frequency. This in turn slows the input pulse and moves it to later times. Note that proper operation requires $n_2 > 0$ ($n_2 < 0$) and anomalous (normal) dispersion in the fiber, and this simple picture holds as long as there is negligible walk-off between the two pulses.

We can derive simple formulas to describe the shift of the input-pulse center frequency $\Delta\omega_c$ due to cross-phase modulation in the limit of negligible walk-off and dispersion. Standard soliton normalizations are used in the following equations, where t is local time on the pulse and z is distance along the waveguide. Let us assume that the input u and reference ν pulses are given by

$$u(z = 0, t) = \mathrm{sech}(t),$$

$$|\nu(z, t)|^2 = A_s^2 \,\mathrm{sech}^2[\beta(t + \delta t)], \qquad (2)$$

where $\delta t = t_{\mathrm{input}} - t_{\mathrm{ref}}$ and $\beta = \tau_{\mathrm{input}}/\tau_{\mathrm{ref}}$. The input pulse accumulates a nonlinear phase shift as a result of cross-phase modulation and is proportional to

$$u(z = L, t) \propto \mathrm{sech}(t)\exp[i\Delta\Phi(t)],$$

$$\Delta\Phi(t) = \frac{2}{3}A_s^2 L \,\mathrm{sech}^2[\beta(t + \delta t)]. \qquad (3)$$

A phase shift also arises from self-phase modulation,[4] but for a symmetric pulse this only leads to a symmetric broadening of the spectrum without a shift in the center frequency.

The shift in the frequency centroid is given by[3]

$$\Delta\omega_c = i \int_{-\infty}^{\infty} \mathrm{d}t u^* \frac{\partial u}{\partial t} \Big/ \int_{-\infty}^{\infty} \mathrm{d}t |u|^2, \qquad (4)$$

and note from symmetry arguments that $\Delta\omega_c = 0$ when $A_s = 0$. Introducing relation (3) into Eq. (4), we obtain

$$\Delta\omega_c = \frac{2}{3}A_s^2 LG(\beta, \delta t), \qquad (5a)$$

where

$$G(\beta, \delta t) = \beta \int_{-\infty}^{\infty} \mathrm{d}t \,\mathrm{sech}^2(t) \times \mathrm{sech}^2[\beta(t + \delta t)]\tanh[\beta(t + \delta t)]. \qquad (5b)$$

In Fig. 4(b) we plot the negative of $G(\beta, \delta t)$, which is proportional for anomalous dispersion to $\Delta T/\tau$ of the input pulse, and we find qualitative agreement with the experimental data of Fig. 3. The more abrupt drop-off of the experimental data may result from laser pulses that are Gaussian rather than hyperbolic secant, whereas the asymmetry in the experimental data may be caused, in part, by asymmetric laser pulses.

The timing restoration provided by the hybrid TDCS can be tailored by adjusting the characteristics of the reference pulse. The width of the timing window can be adjusted by changing the width of the reference pulse, and the slope of the correction can be adjusted by changing the intensity of the reference pulse. For example, in the calculations of Fig. 4(b), we increase the timing correction window from 1.8τ ($\beta = 1$) to 2.4τ ($\beta = 0.5$) by doubling the pulse width of the reference. Although our experiments are carried out with 415-fs pulses, the concept is generalizable to different pulse widths and other nonlinear materials with negligible walk-off.

We can design an all-optical regenerator for solitons by cascading a hybrid TDCS with an optical amplifier such as an erbium-doped fiber. The erbium-doped fiber amplifier can restore the amplitude of the pulses. Because fundamental solitons try to maintain a constant π-area pulse, amplification results in both intensity and pulse-shape restoration for solitons. The remaining time restoration function of a regenerator can be accomplished by the hybrid TDCS.

In summary, we demonstrate a hybrid TDCS in an AlGaAs waveguide followed by a polarization-maintaining fiber with a switching energy of ~9.8 pJ, a gain of 3, and a nonlinear phase shift of only $\sim\pi/2$ in the waveguide. The switching energy can be lowered to ~1 pJ by reducing the cross-sectional area of the waveguide to ~1 μm^2. Furthermore, we show that timing restoration can be achieved in a hybrid TDCS, or more generally, in a nonlinear material with negligible walk-off followed by a fiber ($n_2 > 0$ requires anomalous group-velocity dispersion, or vice versa). We also provide simple formulas for the shift of the frequency centroid in the nonlinear material that results from cross-phase modulation.

References

1. M. N. Islam, C. J. Chen, and C. E. Soccolich, Opt. Lett. **16,** 484 (1991).
2. S. T. Ho, C. E. Soccolich, W. S. Hobson, A. F. J. Levi, M. N. Islam, and R. E. Slusher, "Large nonlinear phase shifts in low-loss AlGaAs waveguides near half-gap," submitted to Appl. Phys. Lett.
3. M. N. Islam, C. R. Menyuk, C. J. Chen, and C. E. Soccolich, Opt. Lett. **16,** 214 (1991).
4. R. H. Stolen and C. Lin, Phys. Rev. A **17,** 1448 (1978).