# Low-energy ultrafast fiber soliton logic gates

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We have reduced the switching energy for an all-optical soliton dragging NOR gate to 5.8 pJ by using a two-fiber configuration and optimizing the fiber and laser parameters. The cascadable NOR gate has a fanout of six, restores both the logic level and timing, and can operate at bit rates of up to 0.2 THz. In addition, we show that soliton dragging can be represented as a generalized exclusive-or module with high functionality. Two such modules can be interconnected as NOR and AND gates or broadcast and routing switches.

We demonstrate a 5.8-pJ switching energy all-optical NOR gate that is based on timing shifts from soliton dragging.[1,2] The ultrafast NOR gate has a fanout of six and is implemented in two fibers joined by a polarizing beam splitter and followed by a polarizer. We previously reported a 30-pJ NOR gate achieved in a single 75-m fiber using $\tau < 300$ fsec pulses.[1] That design suffered from self- and cross-Raman amplification effects[1,3] and from partial phase interference between the two signal pulses. We have reduced the switching energy by more than a factor of 5 by optimizing the gate design, the laser pulse width, and the fiber length. Reduction of the intensity and pulse spectral width also reduces the self-Raman amplification effects by approximately sixfold in the logic gate. Furthermore, we describe here an equivalent circuit for soliton dragging in terms of a generalized exclusive-or (GEO) module. By changing the interconnections between two GEO modules, we can implement NOR and AND gates or broadcast and routing switches.

The inset in Fig. 1 shows a schematic of the NOR gate that consists of two lengths of birefringent fiber (e.g., the first fiber could be $\sim 5Z_0$ and the second between $25Z_0$ and $35Z_0$, where $Z_0$ is the soliton period[2]). The two fibers are connected through a polarizing beam splitter (PBS), and the output is filtered by a polarizer (POL) or another polarizing beam splitter. The power supply or control pulse $C$ provides gain and logic level restoration, propagates along one principal axis in both fibers, and corresponds to $A$ NOR $B$ at the output. For a cascadable gate, $C$ should be approximately a fundamental soliton and should experience insignificant frequency shift from self-Raman amplification effects.[3] The two signal pulses $A$ and $B$ are polarized orthogonal to $C$ and are blocked by the polarizer at the output. The signals are timed so that $A$ and $C$ coincide at the input to the first fiber and $B$ and $C$ coincide (in the absence of $A$) at the input to the second fiber.

The logic gate is designed for digital optical applications and operates based on time shifts from soliton dragging. We assume that a signal corresponds to a pulse with guard bands surrounding its time slot. Then a one corresponds to a pulse that arrives within the clock window and a zero corresponds to either no pulse or an improperly timed pulse. For the NOR gate the fiber length is trimmed so that in the absence of any signal the control $C$ arrives within the clock window and corresponds to a one. When either or both signals are incident, they interact with the control pulse through soliton dragging and pull $C$ out of the clock time window. In soliton dragging, two pulses interact through cross-phase modulation[1,2] and consequently chirp in frequency and time shift by propagating in a dispersive delay line. The pulse along the slow axis speeds up, while the pulse along the fast axis slows down.

Figure 1 shows the experimental apparatus for testing a single NOR gate. We obtain $\tau \sim 500$ fsec pulses near 1.685 $\mu$m from a passively mode-locked NaCl color-center laser in which a 2-mm-thick quartz birefringent plate limits the bandwidth and, thus, broadens the pulses.[4] The input stage separates the control $C$, signals $A$ and $B$, and the clock beams, and stepper-motor delay stages are used to time properly signal $B$ and the clock. The two fibers are 75 and 350 m long, have a polarization dispersion of ~80 psec/km, and exhibit a polarization extinction ratio of better than 14:1.[5] The control pulse output and the clock are directed to a correlator to measure the time shifts.

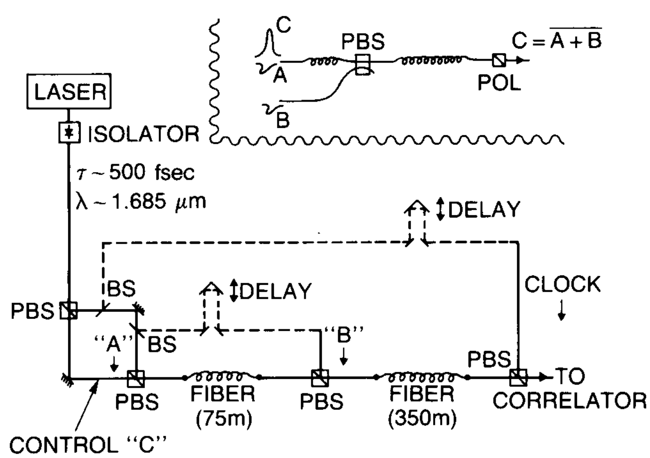


Fig. 1. Experimental configuration for testing an all-optical NOR gate. The inset shows a simplified schematic of the NOR gate with control or power supply $C$ along one axis and signals $A$ and $B$ polarized orthogonally. BS's, beam splitters.

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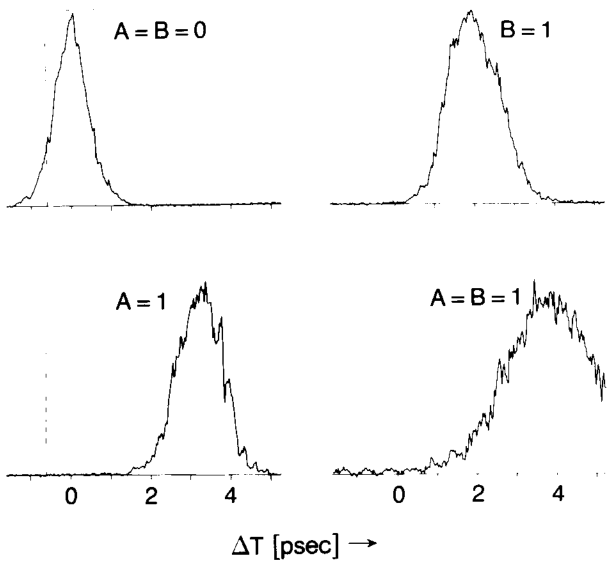


Fig. 2. Correlation of the clock with the NOR gate output. The signal energy is 5.8 pJ, and the gain (control out/signal in) is six.

The correlation of the clock with the NOR gate output is illustrated in Fig. 2. The dotted boxes correspond to the clock window, and we see that $C$ arrives within this window when no signal is present. When $A = 1$ or $B = 1$, $C$ shifts by 2–3 psec out of the clock window; the shift from $A$ is larger since $C$ can time shift in both fibers. When $A = B = 1$, $C$ shifts by ~4 psec. The additional noise and broadening for $A = B = 1$ occurs because $A$ and $B$ interfere at the polarizing beam splitter and can be avoided by using two separate beam splitters to remove $A$ and introduce $B$. In this example, the fanout or gain (which equals control out/signal in) is six and the signal energies are 5.8 pJ each, which is to our knowledge the lowest switching of any all-optical device. The control pulse energy in the first fiber is 54 pJ and is reduced to 35 pJ in the second fiber because of coupling losses.

To prove the cascadability and fanout of the logic gate, we connected the NOR gate as an inverter and fed the output back to the input ($A = 0$, $B$ equals the previous output from the gate). We placed a 50:50 beam splitter at the output and sent half the output through a delay line to the $B$ input. The correlator was set to the center of the clock time window. As Fig. 3 shows, with the feedback blocked the output is a string of ones. When the feedback is added, the output becomes an alternating train of ones and zeros whose period is twice the fiber latency (1.75 $\mu$sec). Therefore the configuration acts as a ring oscillator or a monostable multivibrator.

Having demonstrated the NOR gate operation, we now examine the design criteria for the parameters chosen in our experiment. The fiber birefringence should be such that the walk-off length for orthogonally polarized pulses is greater than the soliton period $Z_0$ (Ref. 2); otherwise, the interaction length is too short, resulting in insufficient soliton dragging. The length of the second fiber must yield at least a $\pi$ phase shift from cross-phase modulation [i.e., $(2\pi/\lambda)(2/3)n_2 I_{\text{signal}} L \sim \pi$]. The maximum control $C$ power is limited by soliton self-frequency shift or Raman amplification[3] if we want the switch to be cascadable. We adjust $C$ so that in the given fiber length the shift of the pulse center frequency is less than one sixth of the pulse spectral width. Furthermore, we verify that $C$ is approximately a fundamental soliton by checking that the output pulse width is comparable to the input.

For a given control amplitude and fiber length, we study the signal amplitude range that satisfies the system constraints. For instance, in Fig. 4 we plot the shift of the control pulse as a function of signal energy for a control energy of 48 pJ. As long as Raman amplification effects are minimized, the control pulse can propagate along either the slow or fast axis of the fiber. A positive delay means that $C$ arrives later, while a negative delay means that $C$ arrives earlier. The desired width of the clock window sets the minimum signal energy and maximum gain. In addition, the time guard band between pulses sets an upper limit on the signal energy. For example, we assume a

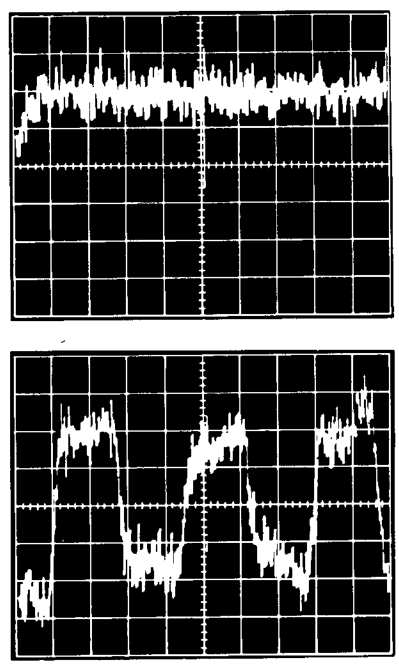

Fig. 3. Output from a NOR gate configured as an inverter whose output is fed back to the input. (Top) Feedback blocked, (bottom) feedback added.

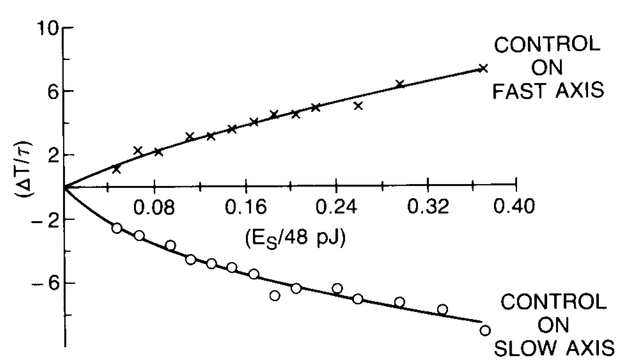


Fig. 4. Time shift of the control pulse from soliton dragging as a function of the signal energy. The control pulse energy is 48 pJ, and the fiber length is 350 m.

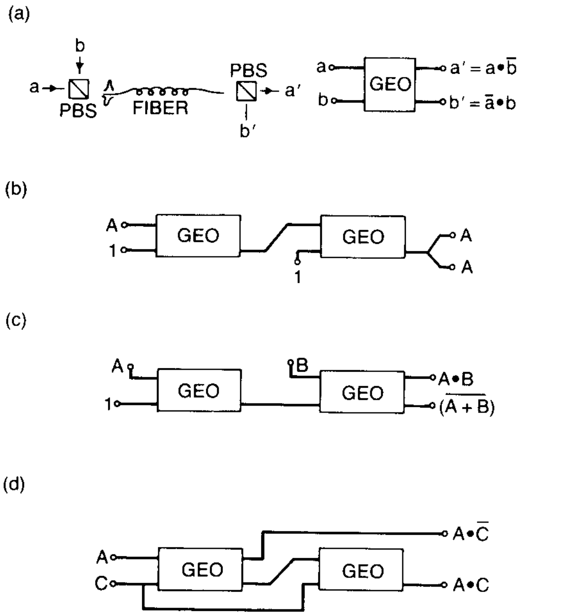


Fig. 5. (a) Basic building block consisting of a birefringent fiber surrounded by two polarizing beam splitters represented by a four-port GEO module. Two GEO modules can be configured as (b) broadcast or buffer switches, (c) NOR and AND gates, and (d) routing switches.

separation between adjacent signals of 10 pulse widths, which means a maximum bit rate of 0.2 THz for 500-fsec pulses.

We now change our focus from the physical configuration to an idealized logical construct that can be used for design purposes. Consider the basic building block consisting of a birefringent fiber surrounded by two polarizing beam splitters [Fig. 5(a)]. We treat the general case of two equal-amplitude inputs $a$ and $b$ (which may be signal or control) and outputs $a'$ and $b'$. From a logic viewpoint, this building block can be replaced by a four-port GEO module, in which $a' = a\bar{b}$ and $b' = \bar{a}b$. The rule is that the output at a given port is equal to the input on that axis AND the NOT of the other input. Note that gain occurs only when one of the inputs is a clock or power supply pulse of larger amplitude than the other signal.

Two such GEO modules can be interconnected to provide high functionality. Figure 5(b) shows that by using each GEO module as an inverter, we can implement a broadcast or buffer switch (assuming that the power supply is larger than the signal) to provide multiple copies of the input. The NOR gate described above is shown in Fig. 5(c), where the control pulse is replaced by a power supply 1. Along the control axis we find $A$ NOR $B$, and along the orthogonal axis we find $A$ AND $B$. Furthermore, for the same hardware used in the NOR gate, we can also implement a routing switch [Fig. 5(d)]. Depending on the value of the control $C$, signal $A$ will appear at one of two separate ports. Note that this is a logic switch (the logic value of $A$ is routed) rather than a physical switch (i.e., in a physical switch the photons corresponding to signal $A$ would be routed).

In summary, we have presented an all-optical cascadable NOR gate appropriate for a digital optical processor. This three-terminal gate has a switching energy of 5.8 pJ, a fanout of six, and restores the logic level and timing at the output. We also show a generalized representation of soliton dragging in terms of a GEO module. Two GEO modules can be configured as broadcast or buffer switches, NOR and AND gates, or routing switches.

## References

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2. M. N. Islam, Opt. Lett. **14,** 1257 (1989); M. N. Islam, C. D. Poole, and J. P. Gordon, Opt. Lett. **14,** 1011 (1989).
3. J. P. Gordon, Opt. Lett. **11,** 662 (1986).
4. M. N. Islam, E. R. Sunderman, C. E. Soccolich, I. Bar-Joseph, N. Sauer, T. Y. Chang, and B. I. Miller, IEEE J. Quantum Electron. **25,** 2454 (1989).
5. Other fiber parameters are dispersion $D = 7.25$ psec/(nm-km) and effective core area $A_{\mathrm{eff}} \sim 4 \times 10^{-7}$ cm$^2$.