Demonstration of optical switching by means of solitary wave collisions in a fiber ring reflector

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Received July 19, 1990; accepted November 20, 1990

We have demonstrated the use of solitary wave collisions in optical pulse switching. Our apparatus consisted of a fiber ring with 11 sections of polarization-maintaining fiber, with successive sections fusion spliced with the axes rotated 90 deg. The configuration yielded enhanced transmission (autocorrelation contrast ratio 2.82:1), in agreement with expectation for this number of sections and the unoptimized fiber coupler that was used. Design criteria for complete switching are presented.

Interferometric all-optical pulse devices have a long history of proposals and experiments. A logic gate using a Mach–Zehnder waveguide interferometer was first proposed and demonstrated by Lattes *et al.*[1] That stability could be improved by use of the interferometer in a ring configuration was realized by Otsuka,[2] who proposed the ring as an optical logic device. The virtue of the ring configuration is that the interference is insensitive to changes in the linear index of the interferometer resulting from temperature changes and other environmental effects. Doran *et al.*[3] demonstrated the imbalanced nonlinear fiber ring interferometer, operating in the positive dispersion regime, as an intensity-controlled switch. In this arrangement, the two countertraveling pulses accumulate different nonlinear phase shifts through self-phase modulation.

When the ring interferometer is operated in the positive dispersion regime, self-phase modulation leads to a nonuniform phase across the pulse, resulting in incomplete switching. In anticipation of such efforts, Doran and Wood[4] suggested operation in the negative dispersion regime. Of course, the uneven partitioning of energy between the two counterpropagating pulses does not produce perfect solitons. However, operation of the device is aided by the fact that the pulses will reshape into solitons if the propagation distance is several soliton periods. In spite of this advantage, in an imbalanced ring the interfering pulses will have different widths, and imperfect output pulse profiles result.

Experiments with imbalanced Sagnac interferometers in the negative dispersion regime were performed by Blow *et al.*[5] and Islam *et al.*[6] The degree of coupler imbalance establishes a lower bound on the switching curve but also dictates the length of fiber required for achievement of a relative phase of π.

We have sought to design balanced interferometric switches in order to avoid the aforementioned problems. Through computer studies we have found that when two orthogonally polarized solitary waves interact in a highly birefringent fiber, the pulse shapes do not change significantly if the exchange phase shift is small compared with π. Thus we can envisage devices in which a control pulse slides through half of the signal pulse several times until the latter accumulates a total phase shift of π and can be interfered with its other half.[7]

One simple configuration is shown in Fig. 1. For ideal operation, the coupler should be 50/50 for one polarization (corresponding to the signal pulse) and 100/0 for the other polarization (the control pulse). At the input to the device, the control pulse (fast axis) is delayed with respect to the signal (slow axis). In the first loop section the control pulse catches up with the clockwise propagating signal, interacts with the signal, and subsequently passes it. In the second fiber section, the signal catches, interacts with, and passes the control. The process is repeated through the remaining fiber sections. We thereby achieve 11 solitary wave collisions in one loop traversal. At the coupler, the counterpropagating signal pulses interfere to produce the output.

In the configuration depicted in Fig. 1 the control pulse will always leave the device through the transmission port, but the signal is transmitted only in the presence of the control and is reflected in the absence of the control. If a polarizer is placed at the transmission port to suppress the control pulse, the device operates as an AND gate. The signal pulse and the control pulse function as the two inputs to the device.

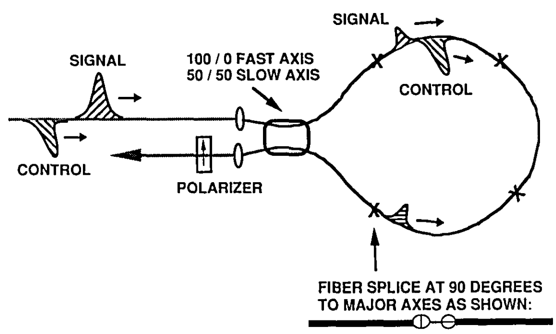

Fig. 1. Experimental apparatus.

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If the control pulse alone is present, no output is produced. The same holds for the signal pulse. An output is produced solely when both are present. Although the present configuration has no gain, it is also possible to design these devices with gain/fan-out.[7]

The fiber birefringence is selected such that, in colliding, the pulses acquire as much phase shift as possible without being significantly displaced or distorted. The collisional phase shift depends only on the effective index seen by a pulse and is independent of the parity of the relative speed of the control and signal. The collisional displacement does depend on the parity of the relative pulse speed and can be thought of as a tendency of one pulse to try to capture the other. Small collisional displacements are tolerable, particularly since the displacements of successive collisions cancel.

The lengths of the individual sections of fiber need not be identical. In fact, they could differ substantially. We require that each section be of sufficient length that the two pulses, separated by at least a pulse width, will collide and separate by at least a pulse width on reaching the end of the section. If the slip is sufficiently small, and therefore the interaction sufficiently strong, then it may be necessary to increase the length of each section in order for the pulses to equilibrate following each collision. Weaker interactions (higher birefringence) allow for shorter sections, but the number of sections required increases.

The source used in the experiment is a Tl:KCl color-center laser,[8] synchronously pumped with an acousto-optically mode-locked Nd:YAG laser (100-MHz pulse repetition rate). The color-center laser is additive pulse mode locked,[9,10] with an auxiliary cavity containing an optical fiber. Output pulses are 230-fsec, full-width at half-maximum intensity, linearly polarized, and with center wavelength $\lambda = 1.52\ \mu m$. These pulses pass through a half-wave plate, which rotates the polarization by 45 deg. Next, they enter a polarization-splitting variable-delay stage, consisting of a polarizing beam splitter, two quarter-wave plates, and two mirrors, one of which is mounted upon a translation stage. In this portion of the apparatus, each pulse is split into two orthogonally polarized pulses, the control and signal, which are then coupled into the fiber loop. A variable half-wave plate and a polarizer are placed after the transmission port of the loop. Our diagnostic is a real-time autocorrelator.

The ring consists of eleven sections of polarization-maintaining fiber with a total loop length of 10.2 m (four soliton periods). This is considerably longer than necessary; thus the device manifests significant timing insensitivity. With all other parameters fixed, complete switching would require 27 sections with a total loop length of at least 14 m. We believed that it was pointless to construct a device with the full number of sections considering the nonideal behavior of our coupler (see below). At each splice, the fast axis of one section is aligned with the slow axis of the other. The polarization-extinction ratio for the fiber itself is better than 30 dB, while at each splice it is better than 25 dB. Splice losses range from 0.05 to 0.1 dB. The anomalous dispersion of the fiber is $D = 8.8$ psec/nm^{-1} km^{-1}, the difference of index of refraction between the fast and slow axes is $\Delta n = 5.4 \times 10^{-4}$, and the core diameter is 7.5 μm.

There is a trade-off between switching energy and device length. Switching energy scales as $(A_{\mathrm{eff}}D/\tau)$, while overall device length scales with (τ/D). A_{eff} is the mode effective area. The number of sections required is proportional to $(\Delta n\ \tau/D)$, but the number cannot be reduced arbitrarily without introducing cross-phase-modulation-induced pulse distortion. We opted for a rather compact device, which as a consequence has a switching energy of 195 pJ. Note also that we chose to use equal signal and control pulses (unnecessary), each with twice the fundamental soliton energy for $\tau = 230$ fsec.

The coupler in our experiment is far from ideal. For the control, we measured a power coupling ratio of 99.3/0.7, which is adequate. However, for the signal, whose ratio is critical for clean operation, we could achieve a ratio of 61.5/38.5 at best. The counterpropagating portions of the signal therefore accumulate nonlinear phase at different rates, so that even in the absence of the control, a portion of the energy will be transmitted.[3-7] In fact, the counterpropagating pulses will reshape and radiate (of necessity, at least one of the two pulses will deviate from a fundamental soliton) differently. The unequal reshaping leads to leakage at the transmission port, while the dispersive waves from the nonsolitonlike pulse introduce a pedestal. Nevertheless, we can demonstrate the accumulation of solitary wave collisional phase shift by comparing the transmission in the presence and absence of the control pulse.

In the lower trace of Fig. 2 we see the output of the device when the signal alone is present. The polarizer is oriented parallel to the polarization of the signal. If the coupler were truly 50/50 for this polarization, we would expect no output under these conditions. The upper trace is the output signal in the presence of the control. The enhancement of the transmission is clear, and the autocorrelation contrast ratio is 2.82:1.

In order to measure and adjust the displacement of the signal and control pulses, we orient the output

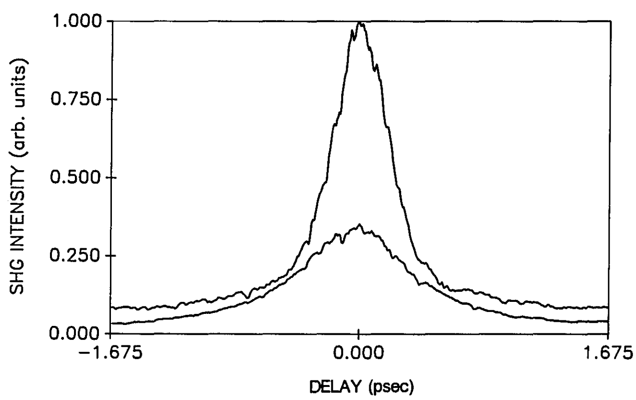

Fig. 2. Signal pulse at output: polarizer parallel to signal, orthogonal to control. Lower trace: orthogonal control pulse absent—no solitary wave collisions. Upper trace: control pulse present—enhanced transmission through solitary wave collisions. SHG, second-harmonic generation.

polarizer at 45 deg to both the signal and the control. Indeed, as we adjusted the delay in our polarization-splitting delay stage, we observed the enhanced signal transmission over a range of several pulse widths, with the transmission dropping sharply to the leakage level of the imbalanced ring outside this range.

We note that pedestals are a problem with all the proposed interferometric switches. The production of radiation background (pedestal) in collisions of orthogonally polarized pulses is unavoidable (except for special elliptic birefringence,[11] because the coupled nonlinear Schrödinger equations governing the propagation are not integrable, and the collisions are therefore nonideal. Thus all experimental schemes employing collisions of orthogonally polarized pulses will require background removal. The removal can be effected by construction of an artificial saturable absorber by using the Kerr effect and interference. Such operation was realized by nonlinear polarization[12] and is the mechanism employed in additive-pulse mode locking.[10] A nonlinear fiber interferometer incorporated into the system can accomplish this.

In our experiment the pedestals would have been significantly reduced if the coupler were balanced for the signal polarization. We could then have split the signal into fundamental solitonlike pulses, which would have undergone minimal shaping and radiate a minimum of dispersive waves, thus reducing the leakage transmission as well as the pedestal at the output.

A soliton switch using the frequency shift of stronger orthogonal soliton interactions was recently operated successfully by Islam *et al.*[13] Our structure, which utilizes phase shift alone, is more complicated but has some advantages. It is less sensitive to timing jitter in the control pulses, and it does not require clocking at the output.

In conclusion, we have demonstrated a new scheme for all-optical pulse switching in fibers in the anomalous dispersion regime. A fiber ring reflector was used, which consists of a sequence of sections of polarization-maintaining fiber, with successive sections having the polarization axes oriented 90 deg from each other. A series of solitary wave collisions provides the phase shift necessary for switching. This switching mechanism is not sensitive to the phases of the incoming pulses, nor to timing errors. Excellent switching should be achievable by using solitonlike pulses. This switching mechanism naturally allows for regenerative, synchronizing devices, in the sense that incoming bits can be replaced by locally generated pulses.

The authors thank Alcoa Fujikura, Ltd., for providing high-birefringence PM fiber. We are grateful to C. S. Draper Laboratories, Cambridge, Massachusetts, for use of their facilities and to Kevin Champagne of C. S. Draper Laboratories for his skillful fusion splicing. The Cornell National Supercomputing Facility (CNSF) provided CPU time for simulating our device. The CNSF is a resource of the Center for Theory and Simulations in Science and Engineering (Cornell Theory Center), which receives major funding from the National Science Foundation (NSF) and IBM Corporation, with additional support from New York State and members of the Corporate Research Institute. This research was supported by NSF grant EET 8703404, Joint Services Electronics Program contract DAAL03-89-C-0001, and U.S. Air Force Office of Scientific Research contract F49620-88-C-0089.

The authors are also with the Research Laboratory of Electronics, Massachusetts Institute of Technology.

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