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Measurements of the nonlinear phase shift induced by ultrafast collinear soliton collisions

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Abstract

We have directly measured the nonlinear phase shift imposed by control pulses with a range of energies, including higher-order solitons, onto an orthogonally polarized first-order signal soliton via collision in a highly birefringent optical fiber. We find that the signal pulse acquires a collisional phase shift greater than 0.3π when the pump is a third-order soliton. The experimental results agree closely with analytic and numerical predictions, and lead to the design of a low-latency nonlinear fiber loop demultiplexer. © 1997 Elsevier Science B.V.

As bitrates in communications and computing systems continue to increase, a high demand has been created for ultrafast demultiplexing components. Much research, both experimental and theoretical in nature has recently concentrated on interferometric fiber optic switching [1–3]. Many such devices have been demonstrated as demultiplexers of ultrafast optical pulses with high switching contrasts [4,5]. These devices predominantly consist of fiber loop mirrors, which rely on a nonlinear phase shift to induce the switching. However, the $\chi^{(3)}$ nonlinearity of fibers is extremely weak, and although the low propagation loss permits long interaction lengths, these long lengths have been a source of severe latency, which is unacceptable for many systems implementations.

In order to reduce this latency, it is desirable to induce a much stronger nonlinear phase shift in a shorter fiber. Here we propose a switching scheme based on a collision between two orthogonally polarized soliton pulses in a highly birefringent polarization-maintaining (PM) optical fiber. One pulse is a first order soliton, designated the signal, and the other is a higher energy pulse, designated the control. If the two pulses are delayed with respect to each other such that the pulse polarized along the fast fiber axis overtakes the pulse polarized along the slow fiber axis, the phase shift in the signal pulse due to cross-phase modulation (XPM) can be on the order of $\pi/3$ per collision in only 2 m of fiber without significantly affecting the pulse shape. By splicing together several such PM fiber sections with their birefringence axes rotated by 90 degrees, multiple collisions can be achieved to obtain a total nonlinear phase shift of π necessary for complete switching [6].

The interaction between two orthogonally polarized pulses is described by the coupled nonlinear Schrödinger equations [7] (CNLS)

$$i\frac{\partial u}{\partial z}-\frac{\beta''}{2}\frac{\partial^2 u}{\partial t^2}+\gamma\left(|u|^2+\tfrac{2}{3}|v|^2\right)u+\mathrm{i}\alpha u-\mathrm{i}\frac{\beta'''}{6}\frac{\partial^3 u}{\partial t^3}$$
$$-\gamma T_{\mathrm{R}}u\frac{\partial}{\partial t}\left(|u|^2\right)=0, \qquad (1a)$$

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$$\mathrm{i}\left[\frac{\partial v}{\partial z}-\left(\frac{1}{\nu_g^u}-\frac{1}{\nu_g^v}\right)\frac{\partial v}{\partial t}\right]-\frac{\beta''}{2}\frac{\partial^2 v}{\partial t^2}+\gamma\left(|u|^2+\tfrac{2}{3}|v|^2\right)v$$
$$+\mathrm{i}\alpha v-\mathrm{i}\frac{\beta'''}{6}\frac{\partial^3 v}{\partial t^3}-\gamma T_R v\frac{\partial}{\partial t}\left(|v|^2\right)=0, \qquad (1b)$$

where u is the amplitude of the signal pulse, v is the amplitude of the control pulse, β'' is the group velocity dispersion, which is related to the dispersion parameter, D, by

$$D\equiv-\frac{2\pi c}{\lambda^2}\beta'', \qquad (2)$$

α is the loss in the fiber, β''' is the third order dispersion (TOD), and T_R is the nonlinear response time associated with the soliton Raman self-frequency shift. The constant c is the speed of light in vacuum, and λ is the free space wavelength. The coefficient γ in Eqs. (1) is the Kerr nonlinearity parameter defined as

$$\gamma\equiv\frac{2\pi n_2}{\lambda A_{\mathrm{eff}}}, \qquad (3)$$

where A_{eff} is the modal cross section in the fiber and n_2 is the nonlinear change in refractive index per unit intensity. Here, ν_g^u and ν_g^v are the group velocities of the signal and control pulses, respectively.

Since the CNLS are not integrable through the inverse-scattering transform, we have solved them with a full numerical model. Additionally, we obtained an analytic solution based on a variational formalism [8] by employing a Gaussian approximation of the soliton pulseshape and by neglecting the TOD, loss, and Raman terms in Eqs. (1). We have reported the results of these models, which show good agreement with our experimental parameters for pulses with energy less than the equivalent third-order, elsewhere [9]. The numerical model remains valid and compares well with experiments despite the fact that the high energy control pulse may undergo significant pulse shape changes because the collisional XPM phase shift of the signal pulse depends almost exclusively on the integrated energy of the control pulse. We will see later that neglecting the Raman, loss, and TOD terms is valid because they are at least two orders of magnitude smaller than the dispersion and nonlinearity terms within the range of fiber lengths and pulse amplitudes considered here.

From our analytic approximation, the collisional phase shift, $\Delta\phi_{\mathrm{coll}}$, experienced by the signal is expressed as [9]

$$\Delta\phi_{\mathrm{coll}}=\frac{2\lambda^2|D|A^2}{3\pi\Delta n(\tau/1.76)}, \qquad (4)$$

where Δn is the fiber birefringence, τ is the pulse width (FWHM), and A is a coefficient of the control pulse peak electric field normalized to a first-order soliton. We use A rather than N to emphasize that this quantity need not be an integer. In our experiments, we use Fujikura polarization-maintaining PANDA fiber, with $D\approx 15$ ps/nm/km, $\Delta n\approx 5\times10^{-4}$, $\beta'''\approx 0.105$ ps^3/km, $\alpha=0.023$ km^{-1} (0.20 dB/km), and $T_R\approx 1$ fs. For a pulsewidth of $\tau=200$ fs, the interaction length of the collision is approximately 20 cm. The analytic solution is derived under the condition that the collision interaction length is much smaller than the soliton period, although it is insentitive to what portion of the soliton period the control pulse is in during the collision.

Fig. 1 shows the experimental setup used to measure the collisional phase shift in the signal pulse as a function of control pulse power. We performed this experiment with a low repetition rate, high pulse energy source to attain higher-order control solitons. We then repeated these measurements with a high repetition rate, low pulse energy source for measurements with low peak control powers. The first source was an optical parametric amplifier (OPA) pumped by a regeneratively amplified mode-locked Ti:sapphire laser (Coherent OPA 900, Mira, and RegA 9000), producing $\lambda=1.55$ μm pulses in its idler beam of pulsewidth $\tau=200$ fs at a repetition rate of 200 kHz. The second source was an optical parametric oscillator (OPO)

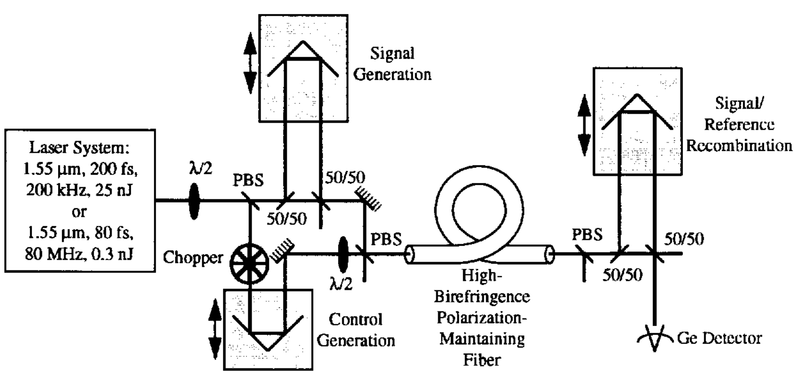

Fig. 1. Experimental setup for soliton collision in a birefringent fiber and measurement of the resulting phase shift of the signal pulse. PBS indicates a polarizing (100%) beamsplitter, 50/50 indicates a non-polarizing 50% beamsplitter, λ/2 indicates a half-wave plate.

pumped by a mode-locked Ti:sapphire laser (Spectra-Physics Opal and Tsunami), producing $\lambda = 1.55$ μm pulses in its signal beam of pulsewidth $\tau = 80$ fs at a repetition rate of 80 MHz.

The beam is split into reference, signal, and control beams as follows. A half-wave plate selects the polarization state of the original beam as it enters a polarizing beam splitter and one polarization vector becomes the control beam while the other polarization vector becomes the signal and reference beams. After this, the intensity of the control beam is independently varied during the experiment by rotating another half-wave plate before the control beam is recombined with the signal and reference beams by a polarizing beam splitter/combiner. The signal and reference pulses are held constant, with the signal pulse always corresponding to a first-order soliton and the reference pulse at a slightly lower intensity. The signal and control pulses are delayed with respect to the reference pulse by approximately 1 ns, and the signal is also slightly delayed with respect to the control. Finally, the control pulse is chopped at 400 Hz.

All three beams are launched into a 2 m length of Fujikura PANDA fiber, with the signal and reference beams along the fast fiber axis and the control pulse along the slow fiber axis. Thus, the control pulse passes through the signal pulse within the fiber, causing a collisional phase shift in the signal pulse. The reference pulse is so far ahead that it is never overtaken by the control pulse.

After the fiber, the control pulse is removed by a polarizing beam splitter, and then the signal and reference pulses are interfered on the surface of a Ge photodiode detector. The surface area of the detector is small with respect to fringes in the interference pattern, so that a phase shift in the signal causes a change in the detected intensity [10]. Since the reference and signal pulses follow the same path, the effects of self-phase modulation and linear phase accumulation are automatically canceled, and only the collisional phase shift caused by the control pulse is measured. The relative phase between the signal and reference beams is biased at each reading such that the collisional phase shift, $\Delta\phi_{coll}$, is centered about the steepest part in the interference sinusoid. This is done by setting the recombination delay stage at each reading such that the effects of the XPM, modulated by the chopper and observed on an oscilloscope, is maximized.

Assuming $\Delta\phi_{coll} \leq \pi$, the collisional phase shift can be inferred from the measured intensity change, ΔI, by the relation

$$\Delta\phi_{coll} = 2\sin^{-1}(\Delta I / I_{p\text{-}p}), \tag{5}$$

where $I_{p\text{-}p}$ is the difference between the maximum and minimum intensities measured when biasing the signal-to-reference delay for complete constructive and destructive interference, respectively.

The collisional phase shift on the signal was measured first with the OPA (high peak power, low average power) pulse source and then again with the OPO (low peak power, high average power) pulse source. The results, shown in Fig. 2, exhibit a fairly linear growth of the phase shift as a function of the control pulse intensity, as expected from Eq. (4). The falloff of the numerical simulations above $A \approx 3$ is primarily due to the increasing influence of the Raman term, which was neglected in the analytic solution.

A phase shift greater than 0.3π is achieved by a third-order $\tau = 200$ fs control soliton, and a first-order $\tau = 80$ fs control soliton achieves a 0.1π phase shift from the collision. Since the OPA and OPO pulses had signifi-

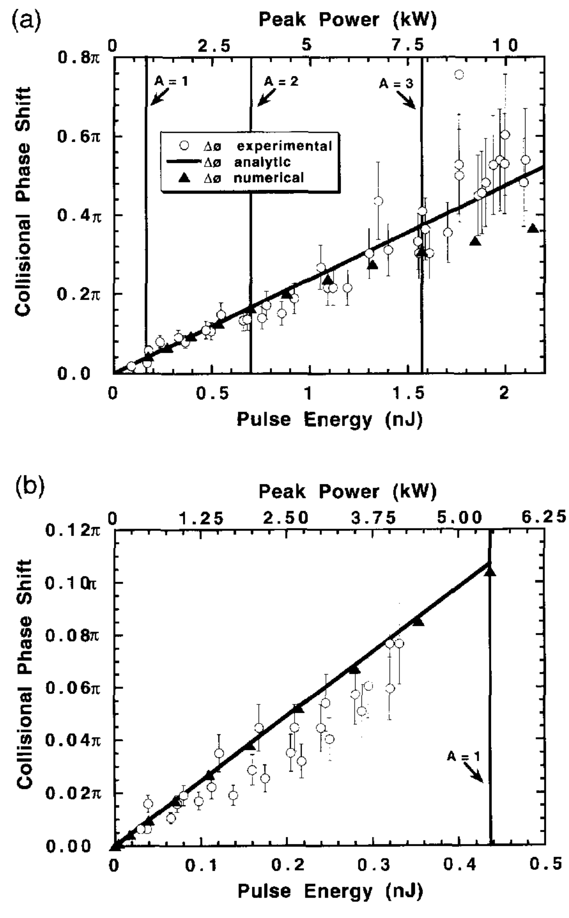

Fig. 2. Collisional phase shift on a first order signal soliton caused by colinear collision with a control pulse as a function of control pulse power (average and peak), using (a) an OPA and (b) an OPO as a light source. The circles indicate experimental data, and the line indicates the analytic solution of Eq. (4). The triangles correspond to predictions from the full numerical modeling, which includes loss, third order dispersion, and the soliton Raman self-frequency shift. The vertical lines indicate integral soliton orders in the control pulse. The experimental error bars were derived by estimating a standard deviation of 20% in the raw data.

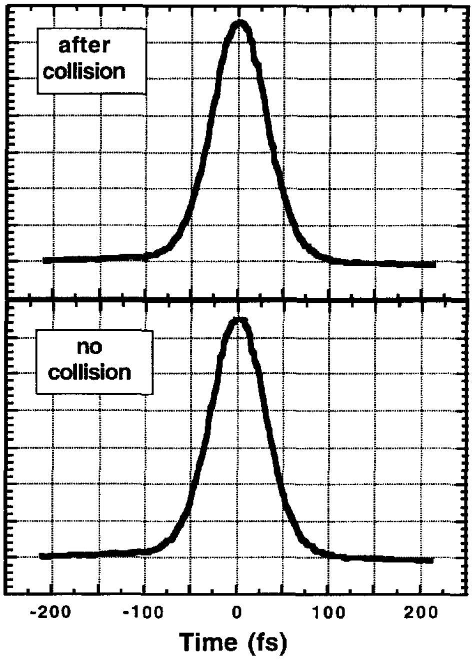

Fig. 3. Autocorrelation of signal pulse emerging from the fiber (a) with and (b) without a control pulse collision. Both the control and signal pulses are first order solitons. The signal's pulse shape is unaffected by the collision, implying good switching in a fiber loop mirror. We show the two traces separately because they are almost indistinguishable when plotted together.

cantly different pulsewidths, different pulse energies are required to form solitons. Thus, to meaningfully compare the results of Fig. 2a to those of Fig. 2b, data for identical values of A should be compared, rather than for similar pulse energies or peak powers, and the phase shifts should be scaled by a factor of 2.5 (the ratio of the pulsewidths). These two experimental regimes overlap in the region of control pulses just below $A = 1$, and we find excellent agreement.

Fig. 2 also shows the results of numerical calculations and the analytical approximation of Eq. (4). These theoretical results depend on the values of D, Δn, and γ assumed for the fiber. For this type of fiber $\gamma \approx 1.7\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$. In Fig. 2 no free parameters were used to fit the theoretical data, and very good agreement is shown with the experimental data.

Finally, we point out that the control pulse has virtually no effect on the signal pulse other than the collisional phase shift, as is expected from our theoretical and numerical models [9]. To verify that the shape of the signal pulse remains undisturbed, we autocorrelated the signal pulse emerging from the fiber (using the OPO pulse source), both with and without an $A = 1$ control signal present. The autocorrelation traces are shown in Fig. 3, and indeed, the traces look virtually identical.

In conclusion, we have demonstrated that 0.3π phase shift occurs in a first-order soliton when collided with a third-order control soliton in a highly birefringent PM optical fiber. Using shorter pulsewidths, we have also demonstrated that a 0.1π phase shift can be achieved when the control is a first-order soliton. We note that a scheme to accumulate a large phase shift by continually re-colliding first-order control and signal solitons by periodically alternating the birefringence of the fiber was first demonstrated by Moores et al. [6]. Several lengths of PM fiber were cross-fusion-spliced in a loop mirror such that their fast and slow axes were reversed at every splice. Thus, the collisional phase shift in the signal can be incremented in each fiber segment.

Since cross-splices cause significant optical losses, it is desirable to minimize the number of splices used. The measurements presented here have demonstrated the viability of a short (< 5 m), low-latency, optical loop mirror using a high order control soliton and less than ~ 3 cross-splices to achieve complete all-optical switching.

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