Use of Femtosecond Square Pulses to Avoid Pulse Breakup in All-Optical Switching

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Abstract—We report measurements of ultrafast all-optical switching in dual-core fiber nonlinear couplers. By performing our measurements with square optical pulses, we minimize the pulse breakup which occurs in experiments performed by using conventional bell-shaped pulses. In this way we obtain enhanced power transfer and a sharper switching transition.

I. Introduction

All-optical switching devices, which potentially can operate at speeds much higher than those obtainable with electronic or optoelectronic devices, may play an important role in future high-speed communications systems. In the past few years, glass optical fibers have emerged as an important medium for nonlinear optical switching. Fibers have the advantage of high transparency, a guided-wave structure for long interaction lengths, and a well-developed materials technology. A number of all-optical switching devices have been demonstrated using glass optical fibers, including the birefringent fiber polarization switch [1], the optical fiber Kerr gate [2]–[4], the dual-core fiber nonlinear directional coupler [5]–[7], the modulational-instability fiber interferometer switch [8], the two-mode fiber Kerr switch [9], the birefringent fiber rocking filter switch [10], and the nonlinear fiber loop mirror [11], [12]. Recently we reported switching of 100 fs optical pulses in a glass fiber nonlinear coupler [7]; this was the fastest switching time ever measured in a guided-wave all-optical device.

One rather universal problem arises with nearly all of these all-optical switching devices. Because the switching is controlled by the instantaneous optical intensity, switching can occur within a pulse, so that low and high intensity portions of the same pulse are directed to different output ports [13], [14]. Such pulse breakup is expected to degrade the switching performance in a variety of all-optical switching geometries and on a variety of time scales. Proposals have been made to solve the pulse breakup problem by using solitons [15], [16] and recently, soliton switching was achieved with a nonlinear fiber loop mirror device [11], [12]. A more general solution, which is applicable to a broad class of all-optical switching devices, is to use square optical pulses, in which the intensity across the pulse is approximately constant. In this paper we report the first application of square pulses [17] to avoid pulse breakup in all-optical switching [18]. Measurements of switching with a dual-core fiber nonlinear coupler performed by using femtosecond square pulses demonstrate a reduced switching power, a sharper switching transition, and an improved on–off ratio compared to measurements performed by using conventional bell-shaped pulses.

This paper is structured as follows. Section II provides some theoretical background on nonlinear couplers and on the pulse breakup problem. Section III describes the dual-core fiber which we use as our nonlinear coupler, and Section IV discusses the experimental apparatus used for the switching measurements. Switching data for one-coupling-length devices, which demonstrate the improved switching performance obtained by using femtosecond square pulses, is presented in Section V. In Section VI we discuss switching data for longer (two-coupling-length) devices, in which group velocity dispersion and spectral variation of the coupling length now play an important role. In Section VII we summarize.

II. Theoretical Background

The all-optical switch investigated in our experiments is a nonlinear coupler [19], pictured schematically in Fig. 1. The device consists of two closely-spaced, parallel and identical, single-mode waveguides in a material with an intensity-dependent index of refraction. Due to evanescent field coupling, low intensity light input into core 1 transfers gradually into core 2. Complete transfer occurs at the coupling length L_c, and for longer coupler lengths power transfers periodically between the two guides. When the input power is increased above a critical power P_c, however, coupling is inhibited due to intensity dependent refractive index changes, and essentially all the light remains in the input core. The critical power is given by

$$P_c = A\lambda / n_2 L_c \quad (1)$$

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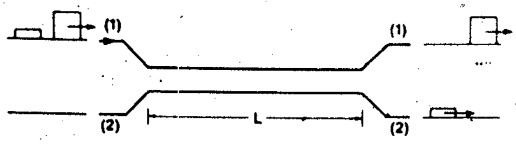

Fig. 1. Schematic of a nonlinear directional coupler.

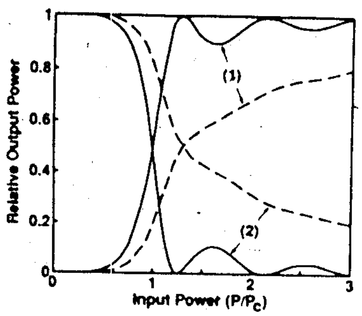

Fig. 2. Calculated fractional output power from guides 1 and 2 as a function of peak input power, for a coupler of length L_c. The input power is normalized to P_c and the input light is focused into guide 1 only. Solid curves: constant intensity input signal. Dashed curves: coupler response integrated over a $\text{sech}^2(t)$ pulse intensity profile.

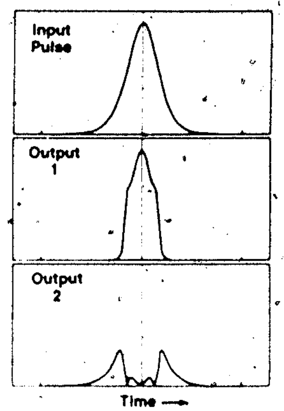

Fig. 3. Temporal profile of the output pulses from guides 1 and 2, computed for $\text{sech}^2(t)$ input pulses with peak power $2P_c$.

where A is the effective area of a single core, λ is the vacuum wavelength, and n_2 is the nonlinear index [19].

A coupler of length L_c exhibits particularly attractive switching characteristics. The calculated switching response of a length L_c nonlinear coupler is shown as the solid lines in Fig. 2, in which the fraction of the output power emerging from each of the two guides is plotted as a function of input power, for a CW or ideal square pulse input. For low input power all of the light emerges from core 2; for powers above P_c essentially all of the light remains in the input guide (core 1). Thus the nonlinear coupler is a routing device which routes pulses to either of two output ports according to their intensity.

When the input signal is a pulse (with a pulse duration much longer than the response time of the nonlinearity), the pulse breaks up according to its instantaneous intensity. Fig. 3 shows the calculated temporal profiles of the output pulses for $\text{sech}^2(t)$ input pulses with peak power $2P_c$. Group velocity dispersion is not included in this calculation, and the coupling length is assumed to be independent of wavelength. The low intensity portions of the input pulse emerge from core 2, whereas the intense central portion of the pulse remains in guide 1. Such pulse breakup has been observed experimentally both in femtosecond [7] and picosecond [20] operation of a nonlinear coupler switch as well as in picosecond operation of birefringent fiber rocking filter switch [10].

In most switching experiments one measures the average power emerging from each output port, and therefore the measured switching curves are the CW curves averaged over the pulse intensity profile. The dashed curves in Fig. 2 show the result for $\text{sech}^2(t)$ input pulses. As a result of pulse breakup, the response exhibits decreased power transfer, softening of the switching transition, and an increased switching power. Although the precise shape of the measured switching curves will depend on the actual pulse shape, similar degradation of the switching response is expected for any nonsquare input pulse.

III. The Dual-Core Fiber

In our experiments the nonlinear coupler consists of a suitable length of dual-core optical fiber. Two types of dual-core fiber, one with Ge-doped cores and pure silica cladding and the other with pure silica cores and a depressed index cladding, were tested. Both fibers yielded coupling lengths on the order of 5 mm, and both exhibited a similar switching response. We note that the coupling length was selected to minimize the effect of group velocity dispersion in our measurements performed with 100 fs, 620 nm laser pulses [21]. Furthermore, we note that the nonlinearity in glass optical fibers has a response time of only a few femtoseconds [22]. Thus, even with 100 fs input pulses, the pulse duration is much longer than the characteristic response time of the nonlinearity.

The Ge-doped fiber was also used for our prior femtosecond switching experiments [7]. Briefly, this fiber contains two 2.8 μm diameter, Ge-doped cores with 8.4 μm between core centers and with a core-cladding index difference of 0.003. The coupling length was 4.5 mm. As we reported previously, nonlinear couplers fabricated from Ge-doped fiber experience gradual degradation due to persistent, photoinduced index changes [7], [23]. Thus, in performing switching measurements with the Ge-doped fiber, we were careful to avoid excessive exposure to high intensity light during the experiments.

In order to avoid persistent photosensitivity effects, for our current experiments we fabricated the dual-core fiber with pure silica cores [24]. A photograph of the fiber end face is shown in Fig. 4. The fiber contains two adjacent, pure silica cores, each about 4.6 μm diameter and with a center-to-center separation of 7.7 μm. The cores are surrounded by a depressed index, fluorosilicate cladding, with a core-cladding index difference of 0.0033, and the fluorosilicate cladding is itself embedded in a silica outer jacket. Each fiber core is single mode for wavelengths longer than $\simeq 565$ nm. At 620 nm the V number is $\simeq 2.28$;

Fig. 4. Photograph of the dual-core fiber nonlinear coupler.

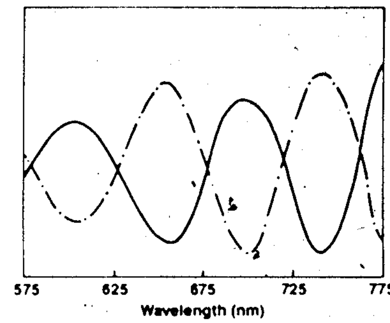

Fig. 5. Spectral response of a 15 mm dual-core fiber coupler. Input light is focused into core 1. Dashed-dotted curve: output power from core 1. Solid curve: output power from core 2.

and the coupling length is $\simeq 5.05$ mm. The fractional throughput of the device is determined by the coupling efficiency into the input guide, typically 40–50 percent. With this new fiber no photosensitivity or long term degradation were observed.

In the following we describe our fiber fabrication and characterization procedures. The dual-core fibers were drawn from a composite preform made by a modified rod-in-tube method. First a preform with fluorosilicate core and silica cladding was fabricated by the modified chemical vapor deposition (MCVD) process. The preform was then cut along its axis and polished. The polished surfaces were grooved and ground to accept two pure-silica rods with an appropriate spacing. The two polished half-preforms were mated and jacketed with a silica tube and then collapsed to draw the dual-core fiber.

We characterized the fiber coupler by measuring its spectral properties. Incoherent light from a tungsten–halogen source was spectrally filtered by a monochromator and focused into one core of a section of fiber, while the other core was carefully blocked by a razor blade. The output of each of the two cores was measured as a function of wavelength for the range 575–775 nm. One such measurement for a pure-silica-core fiber section 15 mm long is shown in Fig. 5. The variation in coupling is predominantly caused by the dependence of the mode size on wavelength. By fitting the measured traces to a theoretical formula for circular core fiber couplers [25], we could determine precise values for core size and separation and thus estimate the coupling length at the wavelength of interest. The fiber was then cleaved into pieces of approximately one coupling length, and the output of each of the two cores was measured with a low intensity laser input. Typically a power transfer in the range of 80–95 percent was achieved.

IV. Experimental Setup

Our experimental setup is shown schematically in Fig. 6. Except for the addition of the pulse shaping apparatus, the setup is similar to that used for previous investigations of femtosecond all-optical switching in dual-core optical fibers [7]. The switching experiments were performed by using pulses from a colliding-pulse-mode-locked (CPM) ring dye laser and a copper vapor laser-pumped dye amplifier system [26]. The laser produced 90 fs pulses at a wavelength of 620 nm, which were amplified at an 8.6 kHz repetition rate to an energy of $\simeq 5$ μJ. The pulse shaper could be adjusted either to reshape the amplified pulses into square pulses or to pass the amplified pulses unchanged. Amplified (and shaped) pulses were focused by a 10× microscope objective into one fiber core, which we denote core 1; the other input core was carefully blocked by the edge of a razor blade. A stepper motor-driven attenuator wheel was used to control the input intensity to the fiber, and a pair of SF-2 glass prisms (not shown in figure) were used in a double pass geometry to compensate for group velocity dispersion in the attenuator wheel and the input microscope objective. The output from each fiber core was focused by a 40× microscope objective onto a separate power meter. For purposes of data acquisition, the input laser beam was chopped, and the outputs of the power meters were connected to two separate lock-in amplifiers. Switching curves were recorded by using a laboratory computer to increment the stepper motor driven attenuator wheel and to digitize and store the lock-in amplifier outputs for each position of the attenuator wheel. Typically, a complete scan corresponding to an 80× variation in the intensity of the beam transmitted through the attenuator wheel was accomplished in $\simeq 8$ s; five such scans were averaged together on the computer.

Our femtosecond pulse shaping technique has been described in detail elsewhere [27], [28]. Briefly, pulse shaping is achieved by spatial masking within a temporally-nondispersive lens and grating apparatus, which consists of a pair of diffraction gratings placed at the focal planes of a unit magnification, confocal lens pair. Midway between the gratings, the optical frequency components comprising the incident femtosecond pulses are spatially dispersed; at this point we place spatially-patterned masks

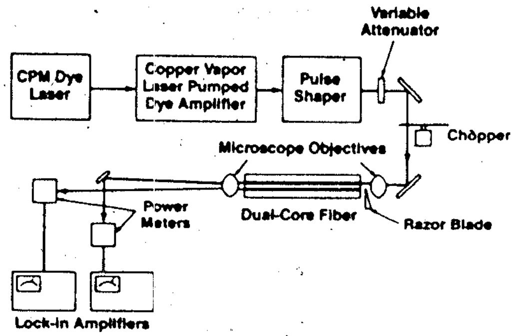

Fig. 6. Schematic of the experimental setup for femtosecond switching measurements.

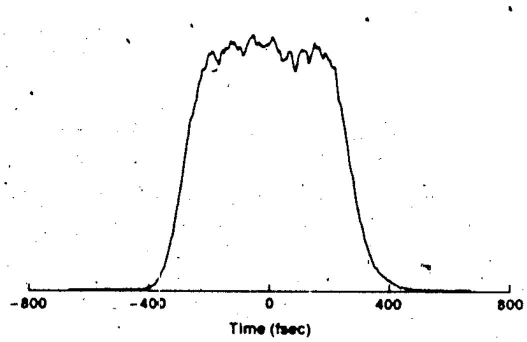

Fig. 7. Intensity cross correlation measurement of a 540 fs square pulse with a 90 fs probe pulse.

to control both the amplitude and the phase of the individual frequency components. The second lens and the second grating recombine the spatially-dispersed spectral components into a single collimated beam, resulting in a temporal pulse shape which is the Fourier transform of the pattern transferred by the masks onto the spectrum.

The pulse shaping masks consisted of fused silica substrates which were patterned by using standard microlithographic techniques. Phase and amplitude masks were fabricated on separate substrates and positioned back-to-back within the pulse shaping apparatus. The amplitude mask was prepared by evaporating a variable transmission titanium–gold film onto a substrate [28], [29], and the phase mask was prepared by reactive ion etching. We designed the masks to provide an apodization of the spectrum which would avoid ringing and overshoot on the square pulses. A measurement of the experimental square pulses, obtained by cross correlation with 90 fs pulses directly from the laser amplifier system, is shown in Fig. 7. The duration of the square pulse is 540 fs full-width at half-maximum, and the rise and fall times are below 100 fs. Note that no ringing or overshoot are visible.

In addition to the phase and amplitude patterns corresponding to the square pulse, the pulse shaping masks also included an unpatterned region, which passed the 90 fs input pulse unchanged. Thus, we could conveniently select between square and bell-shaped pulses by adjusting the positions of the masks. We do note that pulse shaping decreases pulse energy and peak power; for the 540 fs square pulse, the energy and peak power are reduced to $\simeq 15$ and 3 percent, respectively, of the corresponding values for the unshaped, 90 fs pulses. Therefore, a neutral density filter is used when the unshaped pulse is selected so that comparable peak intensities are available with either pulse shape.

V. Switching Data ($L = L_c$)

We now present the results of our switching measurements for fibers of length $L = L_c$. Fig. 8 shows the fraction of the power emerging from each output of the silica core fiber as a function of peak input power, for square pulses as well as for bell-shaped (or normal) pulses. Comparing these curves with the theoretical prediction (Fig. 2), we can clearly recognize the sharper switching transition, the lower switching power, and the enhanced power transfer associated with square pulse operation. The square pulse switching power, at which the output is split equally between the two cores, is 86 kW. This value is in good agreement with the predicted critical power $P_c = 77$ kW, which is obtained from (1) using the known nonlinear coefficient for silica ($n_2 = 3.2 \times 10^{-16}$ cm^2/W) and using 20 μm^2 as the effective area. At the highest peak power available for square pulses (154 kW), 84 percent of the energy emerges from core 1. Although higher input powers are available with bell-shaped pulses, even at 280 kW only 72 percent of the energy emerges from core 1. Thus, switching contrast is greatly improved by square pulse operation.

Similar switching curves were measured with several other samples of the pure-silica two-core fiber; and comparable results were also obtained with the Ge-doped two-core fiber, although in the latter case the switching power was somewhat reduced due to the smaller core diameter. In general, at low power $\simeq 5$–20 percent of the power emerges from core 1, compared to $\simeq 85$–90 percent at high powers (with square pulses). The switching contrast at high powers is limited primarily by the finite rise and fall times of our experimental square pulses, and this also tends to average over the oscillations predicted for the CW signal. The imperfect extinction observed at low power indicates incomplete energy transfer from core 1 to core 2. This may be the result of a small mismatch (on the order of 10^{-5}) in the effective indexes of the two fiber guides [23], [30].

The importance of the sharpened switching transition associated with square pulse operation is emphasized by Fig. 9, which shows the integrated power (pulse energy) emerging from each of the dual-core fiber output cores as a function of peak input power. For the square pulses the core 2 output power reaches a maximum at 66 kW input power and then decreases as the input power is further increased. At 154 kW input power, the core 2 output is reduced to 47 percent of its maximum value. In contrast, for the normal (bell-shaped) 90 fs input pulses, the core 2 output reaches a maximum at $\simeq 100$ kW input power and then remains approximately constant for increasing input power.

For comparison, in Fig. 10 we show a theoretical plot of the integrated power (pulse energy) emerging from

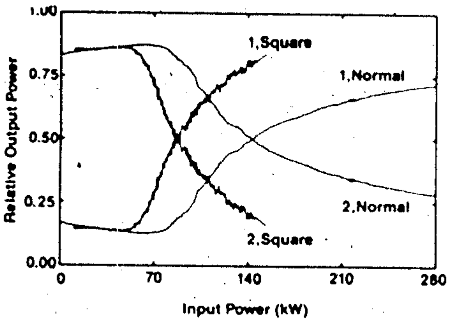

Fig. 8. Switching data for a one-coupling-length section of the pure-silica-core fiber nonlinear coupler. The fraction of the output power emerging from core 1 and core 2 is plotted as a function of peak input power, both for 540 fs square pulses and for 90 fs bell-shaped (normal) pulses.

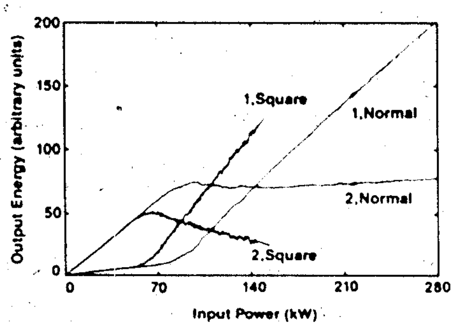

Fig. 9. Switching data for a one-coupling-length section of the pure-silica-core fiber nonlinear coupler. The integrated intensities (pulse energies) from core 1 and core 2 are plotted as a function of peak input power, both for 540 fs square pulses and for 90 fs bell-shaped (normal) pulses. The integrated intensity is normalized so that the sum of the integrated intensities from both cores (in normalized units) is equal to the peak input power (in kW).

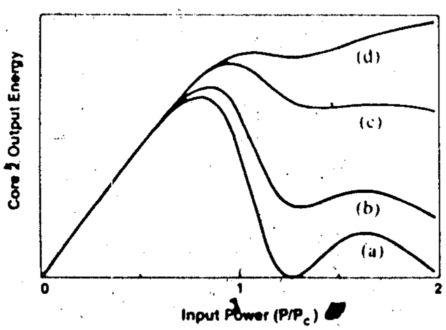

Fig. 10. Theoretical plot of the integrated intensity (pulse energy) emerging from core 2 as a function of peak input power, for various input pulse shapes. (a) CW or ideal square pulse input. (b) Experimental (finite rise time) square pulse. (c) sech$^2(t)$ pulse. (d) Lorentzian pulse.

guide 2 as a function of input power, for several different pulse shapes. At low input intensity all of the light emerges from core 2; in this limit the plot is independent of pulse shape. When the power is increased above P_c, switching occurs; and the switching contrast depends critically on the pulse shape. For ideal square pulses (curve a), complete switching can be achieved if the input power is carefully controlled. For our experimental square pulses with finite rise and fall times, complete switching is not possible, but above P_c the integrated power from core 2 (curve b) does drop to $\simeq 45$ percent of the maximum value, in good agreement with the measured results. Finally, for bell-shaped pulses, the output from core 2 remains approximately constant when the input power is raised above P_c, although the details depend on the actual pulse shape (curves are shown for sech$^2(t)$ and Lorentzian pulse shapes). Thus, our data for bell-shaped pulses are also consistent with the theoretical switching curves.

This difference between square and bell-shaped pulses, illustrated by Figs. 9 and 10, has important implications for all-optical switching. Consider a self-switching environment, in which pulses are to be routed either to core 1 or core 2, according to their peak intensity. The most severe crosstalk in such an environment would be associated with the unswitched portion of high intensity pulses remaining in core 2. In the case of our data for bell-shaped pulses, the output from core 2 remains constant above the switching power; it is not in principle possible, by examining the output of core 2 alone, to distinguish between low intensity input pulses and crosstalk from high intensity input pulses. In the case of our square pulse data, however, the output from core 2 does decrease for input powers above the switching power, and the distinction is possible. Better discrimination between low- and high-power inputs could be obtained by increasing the duration of the square pulse relative to its rise and fall times.

At this point we comment briefly on the possible effect of group velolcity dispersion (GVD) on our switching measurements. Due to the combined influence of GVD and self-phase-modulation, pulses broaden as they propagate in the fiber; a 100 fs pulse at a wavelength of 620 nm can broaden significantly ($\simeq 50$ percent) even in a 5 mm length nonlinear coupler [21]. Recently the effect of GVD on nonlinear coupler operation was investigated by numerical simulation [31]. The results of this simulation indicate that although with our experimental parameters pulse broadening should indeed occur, nevertheless GVD should have little effect on the switching characteristics of a one-coupling-length nonlinear coupler. The experimental evidence also indicates that GVD does not seriously affect the measured switching curves for length L_c devices. Not only are the data in good agreement with the theoretical curves, which do not take GVD into account, but also the data were not significantly affected when longer bell-shaped pulses were used for the measurements.

VI. Switching Data ($L = 2L_c$)

In this section we discuss switching data for nonlinear couplers approximately $2L_c$ in length. Nonlinear couplers comprising several fiber coupling lengths are theoretically predicted to exhibit extremely abrupt switching transitions which potentially can offer very-high differential gain [19]. As we shall see; the measured switching data for $2L_c$ couplers depart significantly from the theoretical switching curves. This departure, not observed for one-coupling-length devices, may be attributed to group velocity dispersion (GVD) and to a spectral variation of the coupling length.

Fig. 11 shows predicted switching curves for a length $2L_c$ nonlinear coupler. In this figure the fractional output power from core 2 is plotted as a function of peak input power for several assumed pulse shapes. GVD is not included in the calculation. At low intensity the input light transfers from core 1 to core 2 and then back to core 1, from which it emerges. For the ideal square pulse, the output from core 2 increases gradually for increasing input power, reaching 100 percent for a power just below the critical power P_c. Above P_c the output switches abruptly back to core 1 as coupling is inhibited. On the other hand, for a bell-shaped input pulse, the abrupt switching behavior will be smeared out almost entirely. For the experimental square pulse with finite rise time, nearly abrupt switching should still be observed but with reduced contrast compared to the ideal square pulse result.

An example of the experimental switching curves is plotted in Fig. 12. This particular data was taken for a 10.0 mm length ($L \simeq 2.2L_c$) of the Ge-doped fiber. Clearly the experimental curves disagree with the theoretical predictions. In the case of the 90 fs bell-shaped pulses, the output from core 2 increases to $\simeq 50$ percent at high powers and then remains constant at this value. For the square input pulses, although the data do show a vague resemblance to theory, the switching transition is gradual and the switching contrast is low (≤ 25 percent). Somewhat longer bell-shaped pulses (e.g., $\simeq 130$ fs) give switching curves which are intermediate between the two sets shown in Fig. 12.

The difference between Figs. 11 and 12 may largely be the result of group velocity dispersion. Although the switching curves are not significantly affected for the one-coupling-length device, the pulses themselves are temporally broadened after propagation through a length L_c. Since temporal broadening reduces the intensity, this can substantially alter the switching behavior in the latter portion of a $2L_c$ device. Indeed, numerical simulation results [31] predict switching curves quite similar to those plotted in Fig. 12 (for bell-shaped pulses). For the square pulses in our experiment, we expect that GVD should soften the rising and falling edges but should not produce much overall broadening. Thus, evidence of some partial switching from core 1 (at low power) to core 2 (at intermediate power) and back to core 1 (at high power) is still observed.

Another factor which may affect the switching data is the spectral variation of the coupling length (see Fig. 5). In addition to the temporal broadening, due to self-phase-modulation in the nonlinear coupler, intense short pulses will also broaden spectrally. For example, for a 100 fs input pulse at a power of $2P_c$, the output pulse from core 1 can be as large as 40 nm ($4\times$ spectral broadening) even for a one-coupling-length device [21]. In general, the spectral variation of the coupling length will depend on the coupler design; for our device we estimate that the

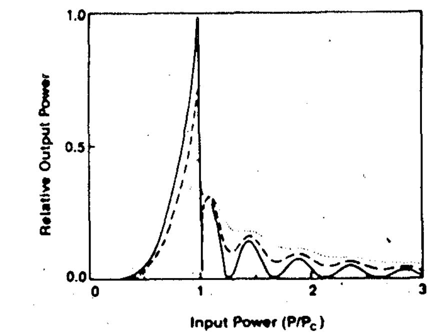

Fig. 11. Theoretical switching curves for a length $2L_c$ nonlinear coupler. The fraction of the output power emerging from core 2 is plotted versus normalized peak input power, for various pulse shapes. Solid curve: CW or ideal square pulse input. Dashed curve: experimental (finite rise time) square pulse. Dotted curve: $\text{sech}^2(t)$ pulse.

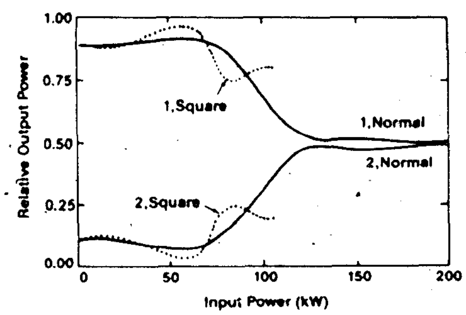

Fig. 12. Experimental switching curves for $2.2L_c$ nonlinear coupler. These data were measured by using the Ge-doped dual-core fiber. The fraction of the output power emerging from core 1 and core 2 is plotted as a function of peak input power. Dotted curves: 540 fs square pulses. Solid curves: 90 fs bell-shaped (normal) pulses.

coupling length varies by $\simeq 30$ percent over a 40 nm wavelength band centered at 620 nm. Clearly, for a two or more coupling-length device, the wavelength dependence of L_c can be expected to influence the switching performance.

VII. Summary

In summary, we report the first use of ultrafast square pulses to avoid pulse breakup in nonlinear optical switching. As a specific example, we have investigated femtosecond switching with a dual-core optical fiber nonlinear coupler. Compared to measurements performed by using conventional bell-shaped pulses, our measurements yield decreased switching power, a sharper switching transition, and improved power transfer. We anticipate that square pulse switching can be utilized to enhance the switching performance of any ultrafast all-optical switching device triggered by instantaneous intensity.

In addition to our measurements of one-coupling-length devices, which are in good agreement with the predicted nonlinear coupler switching characteristics, we have also investigated switching with longer (two-coupling-length) nonlinear couplers. These data do not agree with the theoretical switching curves, a difference which we ascribe to pulse reshaping by dispersion and to the wavelength dependence of the coupling length. These effects may be avoided by choosing a laser wavelength more closely matched to the zero dispersion point of the fiber, by working with longer (picosecond!) pulses, and by designing couplers with a decreased wavelength dependence. With these modifications and with our square pulse-switching technique, it should be possible to demonstrate abrupt switching transitions in several coupling length nonlinear couplers.

More generally, we expect that ultrafast square pulses can beneficially impact any nonlinear optical measurement for which constant pulse intensity would be advantageous. Applications could include determination of nonlinear optical susceptibilities, investigation of high-field laser-matter interactions, and ultrafast optical coherent transient spectroscopy.

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References

[1] S. Trillo, S. Wabnitz, R. H. Stolen, G. Assanto, C. T. Seaton, and G. I. Stegeman, "Experimental observation of polarization instability in a birefringent optical fiber," *Appl. Phys. Lett.*, vol. 49, pp. 1224-1226, 1986.

[2] N. J. Halas, D. Krokel, and D. Grischkowsky, "Ultrafast light-controlled optical-fiber modulator," *Appl. Phys. Lett.*, vol. 50, pp. 886-888, 1987.

[3] K. Kitayama, Y. Kimura, and S. Seikai, "Fiber-optic logic gate," *Appl. Phys. Lett.*, vol. 46, pp. 317-319, 1985.

[4] T. Morioka, M. Saruwatari, and A. Takeda, "Ultrafast optical multi/demultiplexer utilizing optical Kerr effect in polarization-maintaining single-mode fibers," *Electron. Lett.*, vol. 23, pp. 453-454, 1987.

[5] S. R. Friberg, Y. Silberberg, M. K. Oliver, M. J. Andrejco, M. A. Saifi, and P. W. Smith, "Ultrafast all-optical switching in a dual-core fiber nonlinear coupler," *Appl. Phys. Lett.*, vol. 51, pp. 1135-1137, 1987.

[6] D. D. Gusovskii, E. M. Dianov, A. A. Maier, V. B. Neustruev, V. V. Osiko, A. M. Prokhorov, K. Yu. Sitarskii, and I. A. Shcherbakov, "Experimental observation of the self-switching of radiation in tunnel-coupled optical waveguides," *Sov. J. Quantum Electron.*, vol. 17, pp. 724-727, 1987.

[7] S. R. Friberg, A. M. Weiner, Y. Silberberg, B. G. Sfez, and P. W. Smith, "Femtosecond switching in a dual-core-fiber nonlinear coupler," *Opt. Lett.*, vol. 13, pp. 904-906, 1988.

[8] M. N. Islam, S. P. Dijaili, and J. P. Gordon, "Modulation-instability-based fiber interferometer switch near 1.5 μm," *Opt. Lett.*, vol. 13, pp. 518-520, 1988.

[9] H. G. Park, C. C. Pohalski, and B. Y. Kim, "Optical Kerr switch using elliptical-core two-mode fiber," *Opt. Lett.*, vol. 13, pp. 776-778, 1988.

[10] S. Trillo, S. Wabnitz, N. Finlayson, W. C. Banyai, C. T. Seaton, G. I. Stegeman, and R. H. Stolen, "Picosecond nonlinear polarization switching with a fiber filter," *Appl. Phys. Lett.*, vol. 53, pp. 837-839, 1988.

[11] K. J. Blow, N. J. Doran, and B. K. Nayar, "Observation of optical soliton switching in an all-fiber nonlinear Sagnac interferometer," presented at the Nonlinear Guided-Wave Phenomena Conf., Houston, TX, Feb. 2-4, 1989, paper PD7.

[12] M. N. Islam, E. R. Sunderman, R. H. Stolen, W. Pleibel, and J. R. Simpson, "Soliton frequency shift in fiber nonlinear loop mirror," presented at the Nonlinear Guided-Wave Phenomena Conf., Houston, TX, Feb. 2-4, 1989, paper PD8.

[13] K. Kitayama and S. Wang, "Optical pulse compression by nonlinear coupling," *Appl. Phys. Lett.*, vol. 43, pp. 17-19, 1983.

[14] R. Hoffe and J. Chrostowski, "Optical pulse compression and breaking in nonlinear fiber couplers," *Opt. Commun.*, vol. 57, pp. 34-38, 1986.

[15] N. J. Doran and D. Wood, "Soliton processing element for all-optical switching and logic," *J. Opt. Soc. Amer. B*, vol. 4, pp. 1843-1846, 1987.

[16] S. Trillo, S. Wabnitz, E. M. Wright, and G. I. Stegeman, "Soliton switching in fiber nonlinear directional couplers," *Opt. Lett.*, vol. 13, pp. 672-674, 1988.

[17] Our experiments are performed with square-like pulses with a ratio of pulse duration to rise time of ≈6:1. For brevity we use the term "square pulse" throughout the text to refer to these square-like pulses.

[18] A preliminary version of this work was reported in A. M. Weiner, Y. Silberberg, H. Fouckhardt, D. E. Leaird, M. A. Saifi, M. J. Andrejco, and P. W. Smith, "Avoidance of pulse breakup in all-optical switching by using femtosecond square pulses," presented at the Nonlinear Guided-Wave Phenomena Conf., Houston, TX, Feb. 2-4, 1989, paper PD5.

[19] S. M. Jensen, "The nonlinear coherent coupler," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 1580-1583, 1982.

[20] A. A. Maier, Yu. N. Serdyuchenko, K. Yu. Sitarskii, M. Ya. Schelev, and I. A. Shcherbakov, "Breakup of an ultrashort pulse in the course of self-switching of light in tunnel-coupled waveguides," *Sov. J. Quantum Electron.*, vol. 17, pp. 735-736, 1987.

[21] A. M. Weiner, Y. Silberberg, S. R. Friberg, B. G. Sfez, and P. W. Smith, "Femtosecond all-optical switching in nonlinear directional couplers," in *Ultrafast Phenomena VI*, T. Yajima *et al.*, Eds. Berlin, W. Germany: Springer-Verlag, 1988, pp. 169-173.

[22] I. Thomazeau, J. Etchepare, G. Grillon, and A. Migus, "Electronic nonlinear optical susceptibilities of silicate glasses," *Opt. Lett.*, vol. 10, pp. 223-225, 1985.

[23] M. A. Saifi, Y. Silberberg, A. M. Weiner, H. Fouckhardt, and M. J. Andrejco, "Sensitivity of two core fiber coupling to light induced defects," *IEEE Photon. Technol. Lett.*, vol. 1, pp. 386-388, Nov. 1989.

[24] Pure silica core fibers are not expected to exhibit persistent photosensitivity effects—see J. Stone, "Photorefractivity in GeO_2-doped silica fibers," *J. Appl. Phys.*, vol. 62, pp. 4371-4374, 1987.

[25] A. W. Snyder and J. D. Love, *Optical Waveguide Theory.* London, England: Chapman and Hall, 1983, pp. 568-575.

[26] W. H. Knox, M. C. Downer, R. L. Fork, and C. V. Shank, "Amplified femtosecond optical pulses and continuum generation at 5-kHz repetition rate," *Opt. Lett.*, vol. 9, pp. 552-554, 1984.

[27] A. M. Weiner, J. P. Heritage, and J. A. Salehi, "Encoding and decoding of femtosecond pulses," *Opt. Lett.*, vol. 13, pp. 300-302, 1988.

[28] A. M. Weiner, J. P. Heritage, and E. M. Kirschner, "High resolution femtosecond pulse shaping," *J. Opt. Soc. Amer. B*, vol. 5, pp. 1563-1572, 1988.

[29] A. M. Weiner, J. P. Heritage, and R. N. Thurston, "Synthesis of phase-coherent, picosecond optical square pulses," *Opt. Lett.*, vol. 11, pp. 153-155, 1986.

[30] A. W. Snyder and A. Ankiewicz, "Optical fiber couplers—Optimum solution for unequal cores," *J. Lightwave Technol.*, vol. 6, pp. 463-474, 1988.

[31] S. Trillo, S. Wabnitz, and G. I. Stegeman, "Nonlinear propagation and self-switching of ultrashort optical pulses in birefringent fiber couplers: The normal dispersion regime," *IEEE J. Quantum Electron.*, vol. 25, pp. 1907-1916, 1989.

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