# Ultrafast light-controlled optical-fiber modulator

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We report the ultrafast operation of a light-controlled optical-fiber modulator, driven by subpicosecond, compressed, and amplified (6000 Å) dye laser pulses, controlling frequency-doubled (5320 Å) yttrium aluminum garnet laser pulses. The operation of the modulator is based on the optical Kerr effect, and its main component is 7 mm of single-mode optical fiber. Using this system as a light-controlled shutter, we produced either 0.4 ps green light pulses or 0.5 ps holes on the much longer duration second harmonic pulses.

The idea of using one beam of light to modulate a second beam of light has been implemented in many ways based on a number of different physical effects. The pioneering work of Duguay and Hansen[1,2] demonstrating the optically driven Kerr gate, has been a particularly productive approach. Here the driving beam changes the index of refraction of a material by the optical Kerr effect, and thereby changes the polarization of a second beam which is then switched out by a polarizer. This concept is the basis for a number of different modulators using different Kerr materials.[2] A recent example was the switching out of 0.5 ps pulses by optical Kerr gating a 100 ps optical pulse with powerful ultrashort pulses at 1 kHz repetition rates.[3]

One important application is the use of the optical Kerr effect in single-mode fibers for a light-driven optical modulator.[4-6] Here one has the advantage of an enormous reduction in driving power requirements together with an increase in stability due to the long single-mode interaction path. In the initial demonstration of the optical-fiber modulator, response times of microseconds were obtained.[4] Later work has obtained nanosecond response times.[5,6] The closely related nonlinear birefringence effect in fibers has also been proposed for pulse reshaping,[7] which has been demonstrated on the picosecond time scale.[8-10]

In this letter we report the ultrafast operation of a light-controlled optical-fiber modulator, driven by subpicosecond, compressed, and amplified (6000 Å) dye laser pulses controlling either frequency-doubled (5320 Å) YAG laser pulses or Ar ion (5145 Å) laser pulses. The operation of the modulator is based on the optical Kerr effect, and the main component of the modulator is a 7-mm length of low-birefringence single-mode optical fiber. Using this system as a light-controlled shutter, we produced either 0.37 ps green light pulses or 0.46 ps holes (dark pulses) on the much longer duration second harmonic pulses.

A schematic diagram of the experiment is shown in Fig. 1. The driving pulses were the compressed and amplified pulses from a synchronously pumped, mode-locked, tunable dye laser. The initially 6 ps, 6000 Å dye laser pulses were compressed to typically 0.20 ps by passage through an optical-fiber pulse compressor.[11] These compressed pulses were then amplified up to 100 times to a peak power of 400 kW. The amplifier was a 1-cm cell containing rhodamine 610 in water and was pumped by the frequency-doubled output of a mode-locked Nd:YAG laser, $Q$ switched at 700 Hz. The long duration green signal pulses were from either the mode-locked Ar ion laser which pumped the dye laser or the second harmonic pulses from the YAG laser used to pump the amplifier. In order to achieve the shortest switched out pulses, the input powers of the driving pulses and the long duration green pulses were attenuated to 40 kW and to below 1 kW, respectively. These driving and signal pulses were combined on the dichroic beam splitter, adjusted to be temporally coincident, overlapping, and collinear, and were then coupled into the short length of single-mode optical fiber (ITT 1601). The polarization angle of the linearly polarized input signal beam was adjusted by the $\lambda/2$ plate to obtain the best linear polarization of the output signal beam with typical extinction ratios of 1000:1. The input polarization angle of the driving beam was then rotated to obtain the strongest modulation effect. The two output beams from the fiber were recollimated by the output lens and were then separated by the prism. Usually, the driving beam was simply blocked as shown, but with a simple insertion of one mirror it could be measured by the same cross-correlation arrangement. The green signal beam then traversed the polarizer which is shown in the figure to be oriented to transmit the signal beam in the absence of the driving pulses. This configuration produced dark pulses when the driving pulses were applied. The corresponding light pulses were reflected from the polarizer. Alternatively, the polarizer could be set to pass the light pulses and reflect the dark pulses. The output pulses from the polarizer were measured by cross correlation with the 0.20 ps probing pulses obtained by a partial reflection from the beam of amplified pulses. All the pulse widths stated are the deconvolved values taking into account the 0.20 ps width of the probing pulse. Typically, the deconvolved pulse width is 0.1 ps less than the measured cross-correlation value.

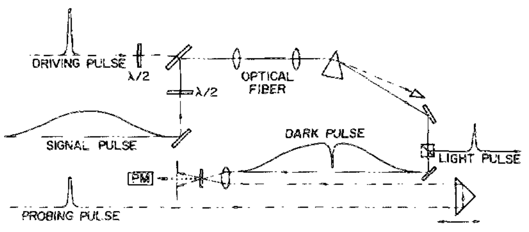

FIG. 1. Schematic diagram of the experiment.

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The actual cross-correlation signal was obtained by the noncollinear generation of second harmonic light in a 300-$\mu$m-thick potassium dihydrogen phosphate (KDP) crystal. The generated light was monitored by a photomultiplier connected directly to a boxcar integrator, which in turn was connected to a multichannel analyzer. The analyzer was synchronized with the delay setting of the correlator as determined by a computer-controlled stepping motor. In order to reduce the effect of pulse to pulse fluctuations, the light pulse was monitored by a photodiode connected to a discriminator, which triggered the boxcar only if the energy of the light pulse was within a narrow window. Although this selection procedure reduced the data rate to about 200 pulses per second, it increased the signal-to-noise ratio so that only single scans of the correlator delay were required. A typical scan was made in about 100 s.

Our measurement of the 0.46 ps dark pulse on the 103 ps output signal pulse is shown in Fig. 2(a). The modulation depth of 1/4 was partially limited by the response time of our detection system. A slower higher resolution scan is shown in Fig. 2(b), where the modulation depth and pulse width are measured to be 1/3 and 0.46 ps, respectively. When the polarizer was rotated by 90°, we obtained the 0.37 ps light pulse displayed in Fig. 2(c). The switched-out light pulse is quite sharp with not much energy in the wings. This is in accord with the wing clipping feature of the modulator[8,10] with respect to the driving pulse. The peak of the light pulse is approximately as strong as the dark pulse, i.e., 1/3 of the strength of the coupled 500 W signal pulse. This gives an energy of 70 pJ in the light pulse. The fact that these pulse widths are approximately twice that for the 0.20 ps amplified pulses calls for some explanation to be given below.

We show the autocorrelation of the probing pulse in Fig. 3(a); the basic pulse shape is quite good and the narrow wings indicate that the optical fiber pulse compressor was operating in the enhanced chirping mode.[12] These data were numerically deconvolved and a good fit was obtained with a pulse width of 0.20 ps and a pulse shape similar to a sech$^2$ in the central region, but with more extensive wings. The measured driving pulse after passage through the 7-mm-long fiber is shown in Fig. 3(b). Here we see that the initial 0.20 ps amplified pulse has broadened to 0.37 ps. Initially we thought the observed broadening was due to passage through the 7 mm fiber. However, subsequent theoretical analysis could not account for this broadening, and later experimental measurements showed that the pulses were broadened mainly by the focusing and collimating lenses used with the fiber. With the fiber removed, the initially 0.20 ps pulses broadened to approximately 0.35 ps due to passage through these lenses. Passage through the fiber did not significantly further broaden the driving pulse. The driving pulse coupled into the fiber was about 0.3 ps due to broadening by the focusing lens. The collimating lens should not broaden the switched-out dark and light pulses because of their much narrower bandwidths.

A broadening effect on the switched-out pulses is the group velocity difference between the input (5320 Å) and driving (6000 Å) pulses. For 7 mm of fused quartz the difference in transit times for the two pulses is 0.18 ps, which implies that for an infinitely narrow driving pulse, the output dark and light pulses would have pulse widths of 0.18 ps. Another effect is phase modulation of the output signal pulse. The optical Kerr effect, due to the linearly polarized driving pulse, induces onto the weak optical signal beam a different amount of intensity-dependent phase parallel and perpendicular to the polarization axis of the driving pulse. Because we are using a low-birefringence optical fiber, we are in the short-fiber limit for our 7 mm fiber length, and can assume the optical fiber to be isotropic. The intensity-dependent phase of the signal component along the axis of the driving pulse is $\Phi_1(t) = 2\pi n_2 E(t)^2 z/\lambda$, whereas the component of the weak signal beam perpendicular to the driver acquires the intensity-dependent phase $\Phi_2(t) = 4\pi n_2 E(t)^2 z/3\lambda$, where $n_2$ is the nonlinear index, $E$ is the field strength of the driving beam, $z$ is the propagation distance (fiber length), and $\lambda$ is the wavelength of the signal beam. For switching applications, this leads to a phase difference between these two components of

$$\phi(t) = \Phi_1(t) - \Phi_2(t) = 2\pi n_2 E(t)^2 z/3\lambda\ .$$

The optical phase transmitted through the polarizer can be shown to be $\Phi_T(t) = [\Phi_1(t) + \Phi_2(t)]/2$. For a maximum phase difference $\phi(t)$ of $2\pi/5$, corresponding to the observed depth of modulation of the dark pulse, we obtain a predicted bandwidth due to phase modulation of $(\partial\Phi_T)/\partial t = 48\ \text{cm}^{-1}$ or 14 Å. This value compares well to the mea-

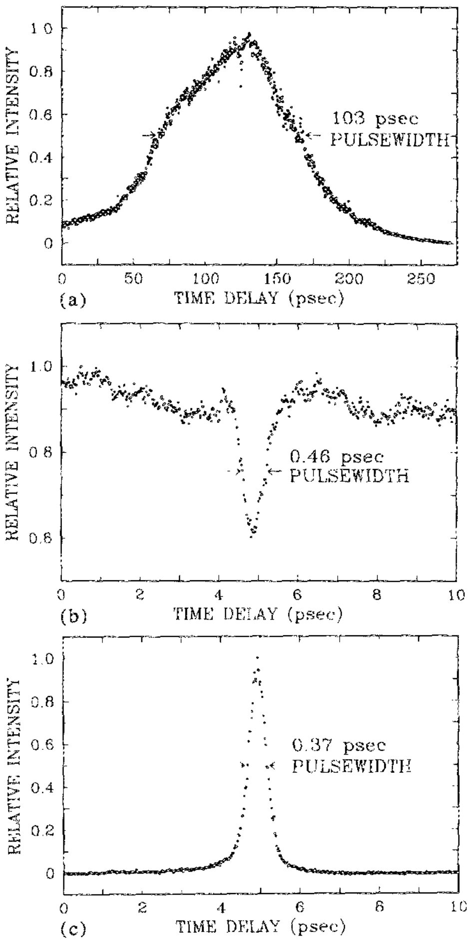

FIG. 2. (a) Cross-correlation measurement of the dark pulse on the second harmonic YAG pulse. (b) Cross-correlation measurement of the dark pulse. (c) Cross-correlation measurement of the light pulse.

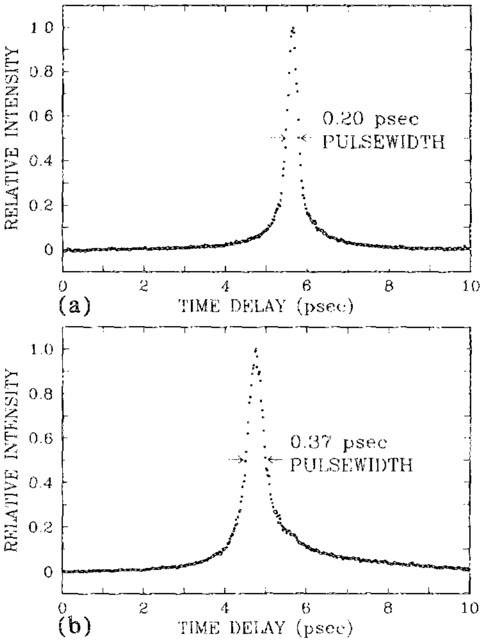

FIG. 3. (a) Autocorrelation measurement of the probing pulse. (b) Cross-correlation measurement of the output driving pulse.

sured bandwidth of 10 Å for the output light pulse. As the driving power was reduced the bandwidth of the light pulse decreased to a limiting value of 8 Å, which is equal to the transform limit of a 5300 Å, 0.4 ps, $\mathrm{sech}^2(t)$ pulse. The bandwidth of the driving pulse was 50 Å and did not change due to passage through the fiber.

These effects were treated quantitatively in a numerical calculation based on the theory of the Kerr effect in an isotropic, single-mode fiber. Our calculation included group velocity mismatch between the driver and the signal beams, group velocity dispersion at both the driver and signal wavelengths, and the third-order nonlinear polarization terms relevant for self-phase modulation, intensity-dependent polarization change, and the two-frequency interaction of the Kerr effect.[13] The calculated output dark and light pulses for our experimental conditions[14] are shown in Fig. 4, as well as the calculated output driving pulse (not to scale). The calculated output driving pulse shape does not significantly change due to passage through the fiber. Because of the group velocity difference between the driving and signal pulses, the switched-out light and dark pulses are broader than that of the driving pulse squared.[8,10] Also, the peak of the driving pulse comes before the peaks of the switched-out pulses. As can be seen, agreement with our experimentally obtained modulation depth and output pulse widths is good considering the nonlinear nature of the problem.

It is of interest to consider that this modulator can transfer information from one light beam to another at a potentially very high data rate. In the present experiment the data rate was limited to the 700 Hz repetition rate of the laser amplifier. However, if the wavelengths of the signal and driver beams are closer together and operate closer to the wavelength of minimum group velocity dispersion of the optical fiber, fiber lengths of the order 100 cm or more could be used. This situation would eliminate the need for the laser amplifier and repetition rates of 100 MHz, typical of mode-locked lasers, would be possible. A factor of ten increase in the data rate above the laser pulse rate would be reasonable using pulse splitting procedures. However, further increases are limited by the power handling capabilities of optical fibers and by the output powers of present day laser systems. One way of bypassing the power limit of a single fiber would be to use a matrix of fibers and sequentially switch from one to the other. A more fundamental approach would be to develop nonlinear materials compatible with fiber technology. A cw data rate, limited only by the response time of the modulator, requires a fiber core 1000 times more nonlinear than fused silica and pulse splitting techniques capable of generating 10 000 uniformly spaced pulses from a single powerful subpicosecond pulse.

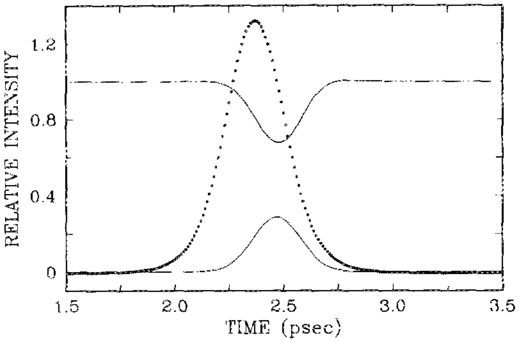

FIG. 4. Calculated dark and light pulses. The dotted line shows the calculated output driving pulse.

In summary, we have demonstrated subpicosecond operation of an ultrafast light-controlled optical-fiber modulator, which can produce either dark or light pulses. The modulator can also operate as an AND gate with subpicosecond response times. Such a modulator can transfer information from one light beam to another at potentially very high data rates. In addition, the modulator can provide a source of synchronized, subpicosecond, tunable, second-frequency pulses for ultrafast measurement applications.

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[14] 50% of the energy of the input 0.3 ps driving pulse was coupled into the 4-$\mu$m-diam fiber. The best fit was obtained with a peak power in the fiber of 25 kW, compared to the experimental value of 15 kW. The nonlinear index $n_2 = 1.1\times10^{-13}$ esu. GVD at 5300 Å was 1.3 times larger than the GVD at 6000 Å, where GVD = (0.034 ps/Å m).