Synthesis of phase-coherent, picosecond optical square pulses

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We report the generation of Fourier-transform-limited, picosecond optical square pulses (with a duration of ~6 psec full width at half-maximum and a rise time of ~1 psec). Control of the pulse temporal profile is achieved by masking the amplitude and the phase of the optical frequency components, which are spatially dispersed within a grating pulse compressor.

We recently demonstrated that the temporal profile of compressed picosecond and subpicosecond optical pulses may be manipulated by apodizing the amplitude and phase of the spatially dispersed spectral components within a grating pulse compressor.[1,2] Arbitrary pulse shapes may be produced, subject to the usual limits of finite bandwith and finite spectral resolution. Previously we generated a variety of complicated pulse types, such as a train of pulse doublets with odd field symmetry, using a rather simple set of spatial masks to control the spectrum. We report in this Letter the synthesis of a phase-coherent, picosecond square pulse—a simple pulse shape that, however, corresponds to a rather complicated spectrum. Synthesis of the square pulse demonstrates the ability to manipulate the complicated spectral features generally required to produce pulse shapes that will be useful for applications. The square pulse has a potential application to nonlinear optical metrology and to future optical digital communication and signal-processing systems.

The experimental apparatus, shown in Fig. 1, is similar to that described previously.[1] Pulses from a cw mode-locked Nd:YAG laser, at a wavelength of 1.06 μm and with a duration of 75 psec, are spectrally broadened in a 400-m length of single-mode, polarization-preserving optical fiber. The chirped pulses that emerge from the fiber are compressed by using a double-pass grating pair.[3] After a single pass through the gratings, the optical spectral components are spatially dispersed. In this region a spectral window is used to eliminate the wings of the compressed pulse,[4] and spatial amplitude and phase filters are used to control the pulse's Fourier spectrum and hence the temporal pulse shape. For maximum resolution the fiber output spot is imaged onto the filter plane; the measured beam radius at the $1/e$ point of the field is 300 μm (for a given frequency component).

In order to obtain a more accurate measurement of the shaped pulse, we have employed a cross-correlation rather than an autocorrelation measurement technique. A beam splitter is placed in the compression apparatus after the first pass through the grating pair. The transmitted beam is directed through a window and pulse-shaping spatial filters; the reflected beam passes through a window only. Both beams are then directed back through the grating pair. In this way we obtain a short, subpicosecond reference pulse, without wings, which is used to sample the longer and more complicated shaped pulse. The origin of the time axis is established by measuring the autocorrelation of an unshaped, compressed pulse (obtained by sliding the patterned portion of the pulse-shaping spatial mask out of the beam, leaving a contiguous unpatterned portion of the substrate in the beam). Our reference pulse can be as short as 0.8 psec FWHM unwindowed (assuming a secant hyperbolic squared intensity profile) or 0.9 psec windowed, as shown in Fig. 2. Note that spectral windowing has been employed here to eliminate pulse tails without introducing an appreciable increase in pulse width.

We now discuss the pulse-shaping spatial masks. In order to generate a square pulse of duration T, it is necessary to produce a spectrum $E(\omega)$ shaped like a sinc function, defined as follows:

$$E(\omega) = E_0 T \sin\left(\frac{\omega T}{2}\right) \Big/ \left(\frac{\omega T}{2}\right).$$

We have obtained a truncated sinc function by using

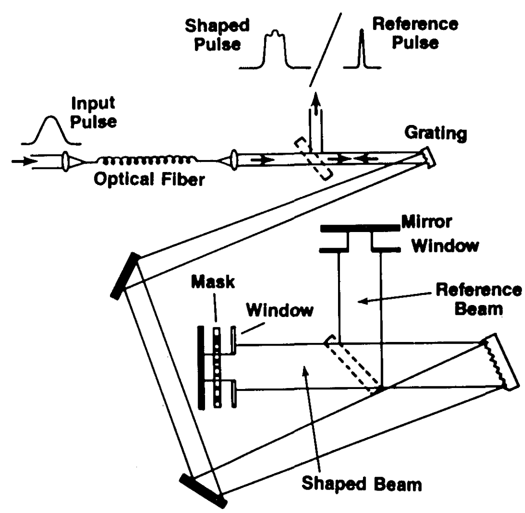

Fig. 1. Experimental apparatus.

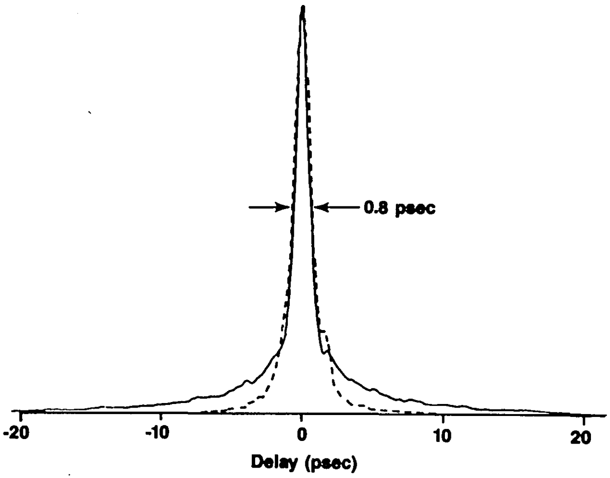

Fig. 2. Autocorrelation traces of an unwindowed, 0.8-psec pulse (solid line) and a windowed, 0.9-psec pulse (dashed line).

two separate masks, one to adjust the spectral amplitudes and the second to control the phase, together with a spectral window to set the total bandwidth. The effective frequency filter, plotted as a solid line in Fig. 3, is the convolution of the physical mask (dashed rectangles) with the spatial intensity profile of the individual spectral components.[5] The phase mask, used to impart the appropriate alternating sign to the filter, is implemented by etching tracks approximately 0.59 μm deep into a fused-silica substrate; this corresponds to a double-pass phase shift of π. In contrast to the simpler masks used in previous work,[1] in which the amplitude mask included only completely transparent and completely opaque regions, the amplitude mask required for a square pulse must be partially transmitting, with the transmission a function of position. We designed a discrete approximation for such a continuously variable mask: the mask is divided into 24 regions, each 240 μm wide, with the double-pass transmission of each region adjusted so that the ensemble approximates the sinc function. The effective frequency filter is smooth because of convolution with the beam profile.

In order to adjust the transmission of the various regions independently, we devised the following scheme. The amplitude mask consists of a series of opaque metallic lines, with a spacing of 40 μm, on a glass substrate. Each region consists of six such lines. The width W_{opaque} of the opaque lines, and hence the width W_{trans} of the transparent regions between lines, is uniform within a single region but varies from one region to another. Because the 40-μm line spacing is much smaller than the 300-μm spot size, the pattern of lines acts as a diffraction grating; light is diffracted out of the main beam into a number of diffracted orders. The amplitude of the field that is transmitted and that remains undiffracted, however, depends only on the fraction of the spot incident on the transparent regions. It can be shown analytically, and has been verified experimentally, that after the beam makes a single pass through the mask, the electric-field amplitude of the main undiffracted beam is given by

$$E_{\text{out}}/E_{\text{in}} = W_{\text{trans}}/(W_{\text{opaque}} + W_{\text{trans}}).$$

The double-pass transmission through the mask is the square of this formula.

Figure 4(A) shows a cross-correlation measurement of the shaped pulse obtained using the phase and amplitude masks described above. Compared with the reference pulses shown in Fig. 2, the square pulse of Fig. 4(A) is noticeably broadened and flattopped. The theoretical cross-correlation trace, calculated as described in Ref. 5 and plotted in Fig. 4(B), is in reasonable agreement with the experimental results. The truncation of the spectrum owing to the finite available bandwidth (3.3 nm, 875 GHz) causes a ripple on the square pulse and limits the 10–90% rise time of the calculated intensity profile (not shown) to 0.9 psec. The rise and fall times of the cross-correlation curves, calculated and experimental, are somewhat longer because of the finite width of the correlating pulse (~1 psec). Note, however, that the duration and the rise time of the experimental trace are quite comparable with those of the calculated cross correlation. The calculated results shown here, which take into account the details of the masks described above as well as the shape of the power spectrum and the nonlinear chirp of the pulse from the fiber, are essentially indistinguishable from calculations that assume that the spectrum is exactly equal to a truncated sinc function with no phase variations. From the similarity of the mea-

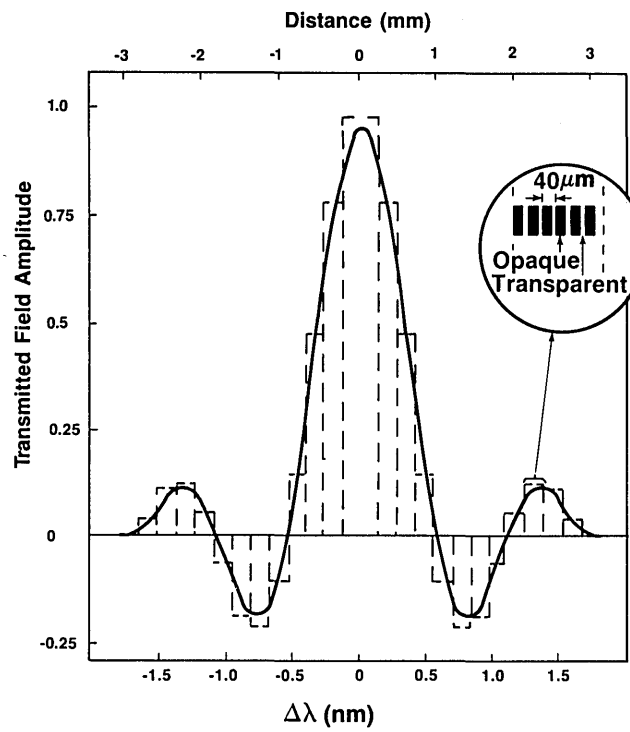

Fig. 3. Double-pass transmission of the physical mask (dashed lines, upper scale: distance) and the corresponding effective frequency filter (solid line, lower scale: wavelength).

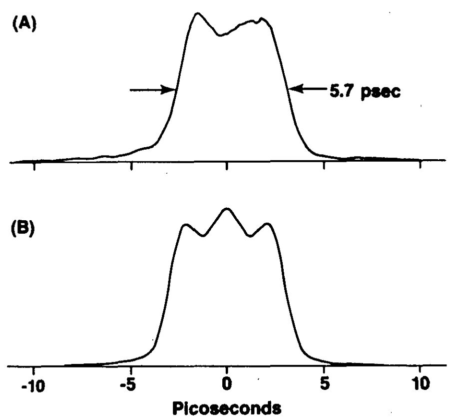

Fig. 4. (A) Experimental cross correlation of the square pulse. (B) Calculated cross correlation.

sured and calculated pulse shapes, we may therefore conclude that the square pulse shown in Fig. 4(A) is nearly transform limited and phase coherent. We also note the possibility of synthesizing square pulses of substantially longer duration than in the present example, but with a comparable rise time, by using an appropriate mask in conjunction with an experimental setup optimized for the best spectral resolution.[5]

There are of course minor discrepancies between the actual synthesized square pulse and the calculations. The experimental trace has only two well-resolved peaks rather than three, has a bit of a tail on its leading edge, and is slightly asymmetric. These differences may be attributed to a number of factors that are not included in the calculations. First, the phase plate, which was fabricated by etching, does exhibit some undercutting; thus the transitions from zero to π phase are not so abrupt as desired. Second, because of the presence of stimulated Raman scattering, the power spectrum of the self-phase-modulated light is broadened asymmetrically, sloping off toward longer wavelengths. Finally, fluctuations in the chirp of the pulses emerging from the optical fiber, caused by fluctuations in the mode-locked Nd:YAG laser pulses, may also influence the experimental results.

In conclusion, we have synthesized a phase-coherent, picosecond optical square pulse. This achievement demonstrates that our technique for picosecond pulse shaping, by masking the amplitude and the phase of the spatially dispersed spectral components within a grating pulse compressor, is applicable even when complicated spectral features are required. We anticipate that this technique may be extended to other wavelengths and to even shorter time scales and that other interesting optical waveforms, such as coded bursts of picosecond pulses, may be generated. The ability to produce complex ultrashort pulse shapes in a fully controllable manner should have important implications for future optical communication and signal-processing systems and for the field of coherent time-resolved spectroscopy.

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