Picosecond pulse shaping by spectral phase and amplitude manipulation

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The temporal profile of ultrashort optical pulses may be tailored by physically manipulating the phase and the amplitude of frequency components that are spatially dispersed within a grating pulse compressor. Arbitrary pulse shapes may be synthesized subject only to the usual restrictions imposed by finite bandwidth and spatial resolution. We demonstrate this technique by generating a burst of evenly spaced picosecond pulses, a pulse doublet with odd field symmetry, and a burst of evenly spaced pulse doublets with odd field symmetry.

We present a technique that permits arbitrary reshaping of a compressed optical pulse into a nearly endless variety of temporal profiles with picosecond or subpicosecond features. The range of pulse profiles that may be achieved is limited only by the spectral bandwidth available and by the spatial resolution imposed by finite beam diameter. The pulse shaping is accomplished by amplitude and phase manipulation of the spatially dispersed frequency components within a grating-pair pulse compressor. The resulting temporal field amplitude is described by the inverse Fourier transform of the spatially masked spectral field that emerges from the compressor.[1] We anticipate that the ability to synthesize arbitrarily shaped, Fourier-transform-limited picosecond and subpicosecond pulses will have important applications for guided-wave optical communications systems and devices and for optical radar systems as well as for studies of transient optical properties of materials and devices.

In this Letter we describe a sequence of experiments in which simple spatial masks were used to synthesize a variety of unusual pulse shapes. These include a burst of evenly spaced picosecond pulses, a pulse doublet with odd field symmetry, and an evenly spaced burst of such pulse doublets.

The experimental arrangement, Fig. 1, is identical with the configuration used previously for spectral windowing[2] in a grating pulse compressor, but with the addition of pulse-shaping spatial filters. Seventy-five-picosecond, 1.06-μm wavelength pulses from a cw mode-locked Nd:YAG laser, with a repetition rate of 100 MHz, are coupled into a 400-m length of single-mode, polarization-preserving optical fiber. Because of self-phase modulation, the spectrum is broadened from approximately 0.02 to more than 4 nm. The chirped pulse that emerges from the fiber is compressed to a duration as short as 0.9 psec by using a double-pass grating pair.[3,4] After a single pass through the grating pair (grating period 1200 lines/mm; separation 1.3 m), the various frequency components are spatially dispersed over a range of approximately 7 mm, forming a fan-shaped beam. A spectral window[2] placed in the beam at this point eliminates undesirable energy in the wings of the compressed pulses without introducing pulse-width broadening.

The pulse-shaping spatial-amplitude and -phase filter is inserted adjacent to the spectral window. The second pass through the grating pair reassembles the dispersed beam into a collimated beam with nearly circular cross section. In order to minimize the spot size (for a given frequency component) and thus obtain maximum resolution, the fiber output spot is imaged by a lens assembly onto the filter plane. The measured spot diameter was 300 μm for these experiments.

We present in Figs. 2(a) and 2(b) the power spectra (measured at the output of the compressor) that result when a spectral amplitude mask is placed at the filter plane. The physical mask consisted of a periodic array of opaque stripes, formed by placing wire segments on a frame. The width of each opaque region was 0.8 mm, and the open apertures between the stripes were 0.3 mm wide. A variable-width spectral window pro-

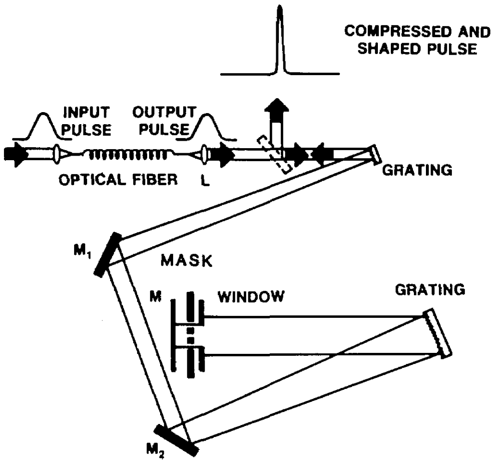

Fig. 1. Experimental arrangement. The spectral amplitude and phase filters are inserted adjacent to the return mirror M and the spectral window.

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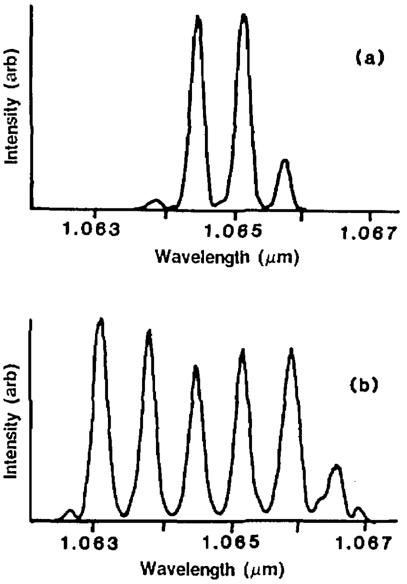

Fig. 2. Power spectra produced by evenly spaced opaque stripes. (a) Spectral window adjusted to pass two principal spectral features. (b) Spectral window opened to pass four principal features.

vided an adjustable total spectral width. Thus in Fig. 2(a) there are two principal spectral peaks, whereas in Fig. 2(b) there are four. This window also removed undesirable, not linearly chirped frequency components at each maximum frequency excursion.[2]

Measured autocorrelation traces, corresponding to the spectra in Figs. 2(a) and 2(b), are shown in Figs. 3(a) and 3(b), respectively. A burst of three pulses (five peaks in the autocorrelation) is observed with the same period in each case, as expected. The measured period of 6.0 psec is in agreement with the inverse of the measured frequency spacing f = 167 GHz ($\Delta\lambda$ = 0.63 nm) between the spectral features. The Fourier-transform relations predict that the width of the individual pulses should be inversely proportional to the total spectral width. Thus the narrower spectral width evident in Fig. 2(a) compared with that in Fig. 2(b) yields a pulse width in Fig. 3(a) that is substantially broader than that of Fig. 3(b). The breadth of the temporal envelope is determined by the inverse width of the individual spectral features. Narrower spectral widths produce a broader envelope. This relationship turns out to be a sensitive test of how accurately one can calculate the effect of spatial masking, including the influence of diffraction at the edges of elements that make up a mask. We have developed a procedure for calculating the temporal shape of the pulses synthesized by an arbitrary physical mask, using realistic spectra while including the influence of finite spot size.[5] The temporal autocorrelation shapes, calculated using no adjustable parameters, are plotted as dashed lines in Figs. 3(a) and 3(b). The excellent agreement between calculation and experiment shows that the calculation may be used to predict the effect of arbitrary spectral filters placed in the grating pulse compressor.[5]

We have extended our pulse-shaping measurements to masks that control the phase of the spectral field components. We present an example in which the phase of the higher-frequency half of the spectrum was shifted from that of the lower half by $(2n + 1)\pi$ rad (n is an integer) by placing a thin, optically transparent film in one half of the spectrum at the filter plane. A thin pellicle (~5 μm thick), a cover-glass slide, a sheet of transparency plastic, and a thermally evaporated film of SiO covering half of a microscope slide all produced the same results when suitably adjusted for $(2n + 1)\,\pi$ phase shift. The autocorrelations obtained with a cover-glass slide are presented in Fig. 4. As the cover-glass slide was rotated about an axis parallel to the direction of the spectral spreading, the relative phase change could be varied. The autocorrelation

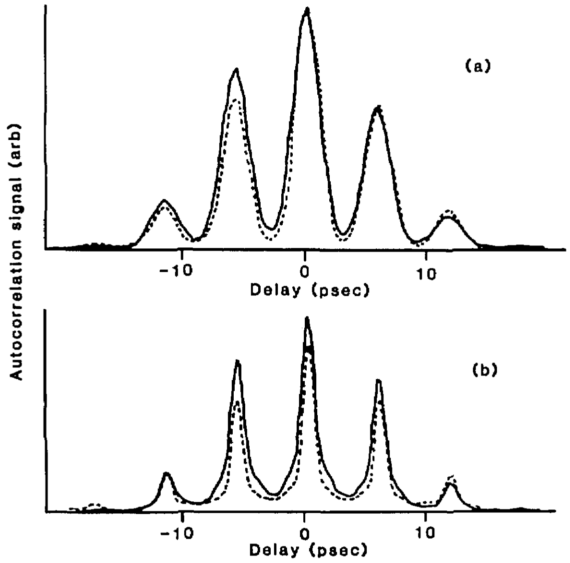

Fig. 3. Autocorrelation traces produced by the simple amplitude mask used in Fig. 2: (a) corresponding to spectrum in Fig. 2(a), (b) corresponding to the spectrum shown in Fig. 2(b). Dashed lines are calculated.

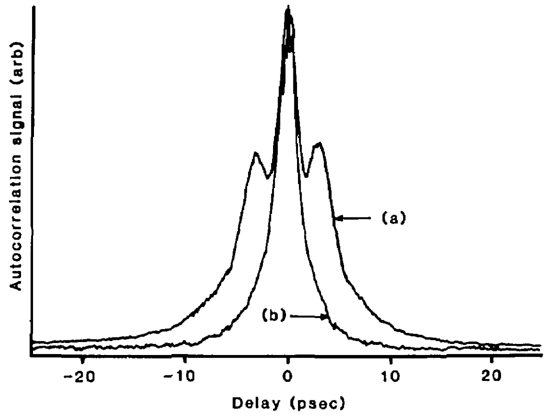

Fig. 4. Autocorrelation traces for phase retardation of higher-frequency half of spectrum. (a) phase shift of $(2n + 1)\pi$, n an integer, resulting in odd temporal symmetry of optical field: (b) phase shift $(2n)\pi$ resulting in even field symmetry.

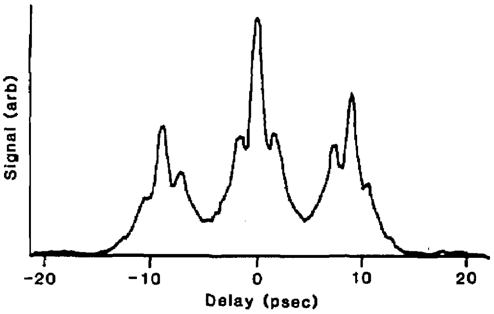

Fig. 5. Autocorrelation traces obtained for combined amplitude and phase mask resulting in a sequence of odd pulses.

evolved periodically between a triply peaked structure [trace *a*, phase shift $(2n + 1)\pi$] and a single peak (trace *a*, phase shift $2n\pi$). The single peak is indistinguishable from the trace obtained with the cover slip absent. A triply peaked autocorrelation, with a ratio of 2:1 between the central and the side peaks, is the signature of a pulse doublet. Because of the abrupt phase change of π at the center of the spectrum, the electric field amplitude of the resulting pulse is an odd function of time, with a null of $t = 0$ (provided that the input spectrum is even). The reshaped pulse-intensity profile is thus a doublet. We label this reshaped pulse an "odd" pulse, to emphasize that the doublet results from the odd temporal behavior of the electric field and is not merely two closely spaced conventional pulses. This odd pulse is closely related to the zero-area pulse produced by propagation through atomic vapors.[1]

In general, independent and simultaneous control of both amplitude and phase is required in synthesizing an arbitrary pulse shape. As a demonstration of simultaneous amplitude and phase manipulation, we simply combine the phase mask that produces the odd pulse with an amplitude mask similar to the one described above but with thinner (0.43-mm-wide) opaque stripes. The two masks are placed adjacent to each other, each centered within the spatially dispersed spectrum. The autocorrelation that results is displayed in Fig. 5. It is evident that this mask generates a sequence of regularly spaced odd pulses. This is the expected result since the total effective mask is the product of the amplitude- and phase-mask transmission functions. The Fourier transform is the convolution of the individual Fourier transforms, namely, a regularly spaced burst of pulses from the amplitude mask convolved with the odd pulse from the phase mask.

In summary, we have demonstrated a technique for synthesizing arbitrarily shaped optical pulses in the picosecond domain, limited only by total bandwidth available and by finite resolution imposed by diffraction. The technique uses a chirped input pulse to compensate for the time dispersion that various frequency components inevitably suffer whenever they are spatially dispersed by the action of a grating. Once compensated, the output-pulse field amplitude is described by the inverse Fourier transform of the input field spectrum modified by the mask transmission function. It is clear that quite complicated pulse shapes may be produced with this technique. We are continuing further work in the direction of producing shapes that are of interest for time-resolved studies of transient phenomena in matter and in developing modulation and coding techniques that are of possible future interest in communications devices and systems.

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