Femtosecond optical packet generation by a direct space-to-time pulse shaper

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We demonstrate femtosecond operation of a direct space-to-time pulse shaper in which there is direct mapping (no Fourier transform) between the spatial position of the masking function and the temporal position in the output waveform. We use this apparatus to generate trains of 20 pulses as an ultrafast optical data packet over an ~40-ps temporal window. © 1999 Optical Society of America

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The Fourier-transform (FT) optical pulse shaper is widely used for synthesis of complex femtosecond waveforms. In this geometry the temporal profile of the output waveform is given by the FT of the mask pattern that is transferred onto the optical spectrum of the pulse. FT pulse shaping was demonstrated by Froehly et al.1 for simple pulses of tens of picoseconds in duration. Weiner et al. subsequently extended pulse shaping to the sub-100-fs time scale and demonstrated highly structured waveforms, using microlithographically patterned pulse-shaping masks.2 The introduction of liquid-crystal modulator arrays3,4 and acousto-optic modulators5 into FT pulse shapers led to computer-programmable pulse shaping with millisecond and microsecond reprogramming times, respectively, and to widespread adoption of this technique.

In this Letter we report what we believe to be the first femtosecond operation of a direct space-to-time (DST) pulse shaper in which the output waveform is a directly scaled (no FT) version of the pulse-shaping mask and apply the DST shaper to generate ultrafast optical data packets. By replacing the fixed masks used in the current experiments with an optoelectronic modulator array, such as a hybrid GaAs–Si complementary metal-oxide semiconductor (CMOS) smart pixel array6 or an array of asymmetric Fabry–Perot modulators,7 in the future it should be possible to achieve packet generation with subnanosecond update rates for time-division multiplexed packet communications. Compared with the FT pulse shaper, the DST pulse shaper has two important advantages for this application: (1) It avoids the need to perform a FT to determine the masking function for each new packet, which would be very difficult at high update rates. (2) Data-packet generation with FT shaping typically requires that both spectral amplitude and phase be precisely controlled. Pulse-sequence generation with a DST shaper requires only intensity modulation, which is compatible with existing optoelectronic modulator array technologies.

We note that the concept of a DST pulse shaper was previously demonstrated for simple waveforms on a picosecond time scale by Emplit and co-workers.8,9 Here we demonstrate generation of optical data packets on a femtosecond time scale, in a geometry that is compatible with direct insertion of a high-speed optoelectronic modulator array.

Figure 1 shows a schematic representation of the DST pulse shaper. Although this system has many similarities to the conventional FT pulse shaper, there are two distinct differences: (1) the Fourier plane of the lens contains a thin slit, and (2) the spatially patterned mask, \( m(x) \), is placed at the diffraction grating (how this is physically carried out is discussed below). The field of the input pulse just before it is dispersed by the diffraction grating (at plane P1 in Fig. 1) is simply the field of the laser input transmitted through the spatially patterned mask:

\[
e_1(x, t) \propto \int \omega E_{in}(\omega)s(x)\exp(j\omega t),
\]

where \( s(x) = m(x) p(x) \) is the spatial profile at P1, given by the input beam spatial profile, \( p(x) \), multiplied by the transmission through the spatially patterned mask, \( m(x) \). \( E_{in}(\omega) \) is the FT of the input field, \( e_{in}(t) \). For simplicity we assume that all the optical frequency components have identical spatial profiles, \( s(x) \).

The diffraction grating disperses this spatially patterned input field, and the lens performs a spatial FT on the dispersed frequency components. At the Fourier plane of the lens (P2) the spatial profile of any particular frequency component is the FT of the input
Here \( S(k) \) is the FT of the spatial profile at the grating, \( \alpha = \lambda^2 f / 2 \pi c d \cos \theta_d \) is the spatial dispersion, \( \beta = (2 \pi / \lambda f) \cos \theta_i / \cos \theta_d \) is the FT scaling factor, in which the \( \cos \theta_d / \cos \theta_i \) term arises from the beam-size change when the beam is diffracted from the grating, \( f \) denotes the focal length of the pulse-shaping lens, \( d \) is the period of the diffraction grating, \( c \) is the speed of light, \( \lambda \) is the center wavelength, and \( \theta_d \) and \( \theta_i \) are the diffraction and the incident angles, respectively.

The thin slit samples the spectrally dispersed frequency components (near \( x = 0 \)) giving a spatially uniform output spectrum that is the FT of the input spatial profile. The result is

\[
e_{\beta}(t) \propto \int d\omega E_{\text{in}}(\omega) S(-\alpha \beta \omega) \exp(j \omega t) = \int d\omega e_{\text{in}}(\omega) l(-\alpha \beta) \exp(j \omega t).
\]

The temporal profile is simply determined by the input pulse convolved with a scaled representation of the input spatial profile, with the space-to-time scaling constant (in picoseconds per millimeter) given by

\[
\alpha \beta = \lambda / (cd \cos \theta_i).
\]

In our apparatus the nominally 150-fs pulses from a titanium:sapphire laser centered at 850 nm are dispersed by an 1800-line/mm diffraction grating with \( \theta_d = 53^\circ \) and \( \theta_i = 47^\circ \). This gives a space-to-time conversion constant \( \alpha \beta = 8.45 \text{ ps/mm} \) that is referenced to the masked spatial pattern just before the diffraction grating.

In planning experiments that employ an optoelectronic modulator array containing pixelated active areas separated by dead space, it is necessary to pattern the input beam into separate spots, one per modulator pixel. We accomplish this by placing a spatially patterned mask in the input beam to pattern the input beam into a periodic array of spots. The pixelated input beam is imaged with near-unity magnification by lens L1, a 100-mm focal-length two-element achromatic doublet (condenser lens) through a polarizing beam-splitter–quarter-wave plate (\( \lambda / 4 \)) combination onto the modulator plane. In current experiments a simple mirror is placed at the modulator plane. To place the spatially patterned beam (mask) onto the grating we perform a second imaging operation with lens L2, a 75-mm focal-length condenser lens set for a magnification of 3.66 from the modulator plane to the diffraction grating. We take special care in the selection and alignment of the imaging optics to generate a high-quality image of the spatially patterned mask on the diffraction grating. The effect of all the components to the left of the dashed curve in Fig. 1 has been to place a spatially patterned mask, in the form of a one-dimensional array of spots, onto the diffraction grating. Therefore the temporal output profile of the system should be a sequence of pulses. The individual pulse widths are set by the width of the spots in the one-dimensional array, and the temporal positions of the individual pulses are set by the spatial positions of the individual spots.

Before discussing experiments demonstrating pulse-sequence generation, we first discuss measurement of the space-to-time conversion constant, which we measure by replacing the input pixelated mask with a slit of known width. Intensity cross-correlation traces, obtained by second-harmonic generation with an unpatterned femtosecond reference directly from the laser, are recorded for several different transverse locations of the slit at plane P1. Figure 2 shows the results of cross-correlation measurements in which a 10-\( \mu \text{m} \) slit has been translated to three different positions separated by 80 \( \mu \text{m} \). The pulse delay from one position to the next gives a direct measure of the space-to-time conversion constant. The measured conversion constant, 31.2 ps/mm, is in excellent agreement with the calculated value of 30.98 ps/mm obtained by multiplication of the space-to-time conversion constant, \( \alpha \beta = 8.45 \text{ ps/mm} \), by the overall imaging-system magnification of 3.66.

The imaging arrangement used in our experiments leads to a quadratic phase front at the grating in addition to the desired intensity modulation. The space-to-time conversion turns the quadratic phase front into a chirp. The measured chirp at the apparatus output is in reasonable agreement with calculations indicating that the apparatus can map spatial phase as well as intensity patterns into the ultrafast time domain. Note, however, that if a chirp-free output is desired, a telescopic imaging configuration could be used in which the flat phase front at the input pixelation plane would be preserved in relaying the spatial profile onto the diffraction grating.

To demonstrate the utility of the DST pulse-shaping apparatus for generating trains of optical pulses we have fabricated a fixed-amplitude mask using standard lithographic techniques to pattern a gold layer that was deposited onto a glass substrate. The patterned mask is positioned in the pixelation plane of the pulse-shaping apparatus. The transmission mask consists of various linear arrays of 20-\( \mu \text{m} \) transparent rectangles with 62.5-\( \mu \text{m} \) center-to-center spacing. The space between the transparent rectangles is opaque owing to the presence of the gold film. Figure 3 shows a cross-correlation measurement of the optical pulse sequence generated with a pixelated mask pattern consisting of a periodic array of 20 transparent rectangles spaced as specified above.

![Fig. 2. Measurement of the space-to-time conversion constant. A 10-\( \mu \text{m} \) slit at the pixelation plane is translated by 80 \( \mu \text{m} \) for each trace.](image-url)
The separation between pulses (1.88 ps) and the pulse width (~535 fs) are in excellent agreement with the values that are expected based on a 30.98-ps/mm space-to-time conversion constant (1.89 ps and 606 fs for the pulse separation and width, respectively). The roll-off in the temporal profile toward the edges of the train is due to the finite size of the beam at the pixelation mask. The number of pulses in the output temporal train simply depends on the time window and the desired pulse spacing. If a longer pulse sequence is desired, we can enlarge the temporal window by expanding the beam on the diffraction grating while simultaneously reducing the size of the slit.

Generation of optical packets can be demonstrated by selection of different masking patterns at the pixelation plane. Instead of transmitting all 20 elements, as illustrated in Fig. 3, we can leave some of them opaque to simulate a modulator element’s being set to the off state for that bit. Figure 4 shows two examples of optical packets generated in this fashion. The sequence of transparent and opaque elements in each masking pattern is also indicated in the figure (1 equals transparent, 0 equals opaque). Clearly the ultrafast time-domain data packet is in excellent correspondence with the spatial data. One could easily generate a flatter-topped intensity profile in the output temporal train by either expanding the beam before the pixelation mask to more closely approximate a uniform spatial profile or using a diffractive optical element as the spot generator. The use of a diffractive optical element would also significantly increase the efficiency of the image-formation optics.

We briefly discuss the fundamental limitations to the throughput of the DST shaper used for pulse-sequence generation. We assume that a diffractive optical element is used to generate the desired spatial pattern on the grating without loss, and we neglect any loss from the grating or lenses. The throughput is then fundamentally determined by the amount of power that is passed by the slit. With these assumptions we can show that the optimum throughput scales as \( t_p/T \), where \( t_p \) and \( T \) are the input pulse duration and the temporal window of the generated sequence, respectively. To obtain this optimum throughput one should match \( t_p \) to the desired duration of an individual pulse in the generated pulse sequence and adjust the slit width to provide a temporal window that is matched to that defined by the aperture of the input beam on the grating. For comparison, we note that the FT shaper would have a throughput of \( \sim t_p/T \) in the case of an input pulse of duration \( t_p \) broadened to a single output pulse of duration \( T \) by use of spectral amplitude filtering.\(^2\)

In summary, we have demonstrated femtosecond operation of a direct space-to-time pulse shaper and used this apparatus to generate sequences of 20 pulses as an ultrafast optical packet over a ~40-ps temporal window. The apparatus has been designed to be directly compatible with high-speed optoelectronic modulator arrays, which should allow packet generation of pulse sequences with subnanosecond update rates for ultrahigh-speed time-domain multiplexed packet communications in future experiments.

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