Generation of terahertz-rate trains of femtosecond pulses by phase-only filtering

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We describe a simple linear filtering technique for transforming individual femtosecond light pulses into terahertz-repetition-rate bursts of femtosecond pulses. By using phase-only filtering, high efficiency is achieved. Pulse repetition rates approaching 6 THz are obtained.

Future high-speed optical communication and computation systems will transmit, route, and manipulate extremely high-rate streams of picosecond and femtosecond pulses. Recently, researchers have been exploring techniques for generating optical pulse trains at repetition rates beyond those obtainable by mode locking or direct modulation. One main approach uses the modulational instability based on nonlinear pulse propagation in optical fibers in the anomalous dispersion regime.[1] Modulational instability was first demonstrated experimentally by Tai *et al.*, who generated bursts of pulses at repetition rates of hundreds of gigahertz,[2] and was subsequently extended by a variety of researchers.[3–5] An alternative, linear approach for generating high-repetition-rate pulse trains involves spectral filtering. In this Letter we demonstrate a simple technique for converting individual femtosecond pulses into terahertz-rate pulse trains by spectral phase filtering. Repetition rates approaching 6 THz are achieved, and bursts of pulses with smooth envelopes as well as flat-topped envelopes are obtained. Our linear generation technique results in clean, stable pulse trains with little energy between pulses; because we utilize phase-only filtering, the efficiency is nearly unity.

Our experiments are based on an apparatus for high-resolution femtosecond pulse shaping.[6,7] A dispersion-compensated, colliding-pulse mode-locked ring dye laser[8] with a typical pulse duration of 75 fsec at a 0.62-μm wavelength is the source of fsec pulses. Pulse shaping is achieved by spatial filtering of the constituent optical frequency components that are spatially dispersed within a simple lens and grating apparatus.[6,7,9,10] The resultant pulse shape is the Fourier transform of the pattern transferred by the spatial filter onto the spectrum. The intensity profile of the shaped pulse is measured by cross correlation with a 75-fsec probe pulse directly from the laser. Using this approach we previously demonstrated encoding and decoding of femtosecond pulses[6] as well as generation of femtosecond dark pulses for studies of dark-soliton propagation in fibers.[11] In the present research we are interested in pure phase filtering. Phase masks are fabricated on fused silica substrates, which are patterned by standard microlithographic techniques and etched by reactive ion etching. This procedure yields a binary phase mask, with the phase difference given by $\Delta\phi = 2\pi(n-1)D/\lambda$, where n is the refractive index, D is the etch depth, and λ is the optical wavelength. For a phase difference of π, the required depth is $\simeq 0.68$ μm.

The use of spectral filtering to produce high-rate pulse trains is illustrated schematically in Fig. 1. We consider the case of a single ultrashort input pulse with an optical spectrum shown in Fig. 1(a). The bandwidth of the pulse is $\Delta\nu$, corresponding to an input pulse width $\Delta\tau = 0.44/\Delta\nu$ (for a Gaussian pulse). The input pulse can be spread into a burst of pulses either by spectral amplitude filtering [Fig. 1(b)] or spectral phase filtering [Fig. 1(c)]. Sizer[12] and Kobayashi and Morimoto[10] have used Fabry–Perot amplitude filters to generate pulse trains with repetition rates of 1 GHz and several tens of gigahertz, respectively, and we previously demonstrated terahertz-rate pulse trains by amplitude masking within our pulse-shaping apparatus.[7] In any of the amplitude filtering approaches, all but a periodically spaced set of fre-

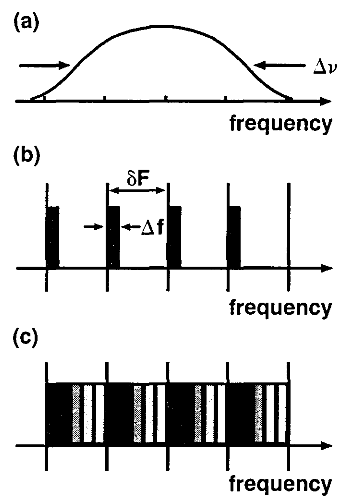

Fig. 1. Generation of high-repetition-rate pulse trains by spectral filtering: (a) input spectrum, (b) amplitude filter, (c) phase filter. For the phase filter, the various shaded rectangles denote different phases.

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quency components are blocked. The resulting pulse train consists of a series of pulses, each of duration $\Delta\tau$, with a repetition rate equal to the frequency spacing δF. The number of pulses in the train is of the order $\delta F/\Delta f$, where Δf is the spectral width of the individual passbands of the filter. Since the total filter transmission is only $(\delta F/\Delta f)^{-1}$, any amplitude filter designed to produce a large number of pulses will inherently be inefficient.

High-quality pulse trains can be generated without loss by using phase-only filtering [Fig. 1(c)]. The phase response of the filter should vary periodically with frequency, and the amplitude response should be constant. As mentioned above, the repetition rate of the resulting pulse train is equal to the frequency periodicity δF, but the envelope of the pulse train depends on the structure of the phase response within a single period. The output intensity profile $I(t)$ is related to the baseband spectrum $E(\omega)$ as

$$I(t) = (1/2\pi)^2 \int \mathrm{d}\Omega \exp(i\Omega t) \int \mathrm{d}\omega\, E^*(\omega)E(\omega + \Omega). \quad (1)$$

The intensity is the Fourier transform of the autocorrelation of the filtered spectrum. To obtain a burst of pulses under a smooth envelope by using a phase filter, one must choose a phase response with an autocorrelation that consists of a series of isolated spectral peaks. Various pseudorandom phase sequences, which have wide application in precision ranging, spread spectrum communications, and phased-array radar, satisfy this criterion.[13,14]

We have fabricated phase masks based on the so-called M (or maximal length) sequences.[13,14] In our mask design the phase response is periodic with period δF. Each period is divided into P pixels of width $\Delta f = \delta F/P$, with each pixel assigned a phase of either zero or $\Delta\phi$, as determined by a particular M sequence (a pseudorandom code of length $P = 2^L - 1$, where L is an integer). Previously we were able to obtain pulse trains at a 1.2-THz repetition rate by using this approach.[7] We now report generation of pulse trains at repetition rates approaching 6 THz. These pulse trains were generated with phase masks consisting of periodic repetitions of the M sequence {000100110101111}, with $P = 15$ and $\Delta\phi = 0.84\pi$, and with δF set to various values in the range 1.5–6 THz. The phase difference $\Delta\phi = 0.84\pi$ was chosen because the intensity of the central ($t = 0$) pulse is determined by the quantity $\int E(\omega)\mathrm{d}\omega$; for $\Delta\phi = \pi$ the central pulse would be missing from the pulse train. The phase masks are sufficiently wide to pass the entire input bandwidth; consequently, the pulses in the shaped train are as short as the input pulses, $\simeq$75 fsec FWHM.

Figures 2(A) and 2(B) show cross-correlation measurements of 4.0- and 5.85-THz pulse trains, respectively. The 4-THz train shows a series of well-defined pulses under a smooth envelope. Owing to the finite duration of the 75-fsec probe pulses used for cross correlation, the minima between the pulses do not completely reach zero, with a contrast of $\simeq$85%. For the 5.8-THz train the effect of the finite probe duration is more serious; the contrast is reduced to the 60–70% range, in line with theoretical expectations. In addition, however, the envelope of this pulse train becomes somewhat irregular, and the contrast between individual pulses varies within the envelope. We expect the pulse train to degrade further as the repetition rate is increased. This degradation occurs when the individual pulses within the train begin to overlap. For pulse trains produced by phase filtering, the phase varies from pulse to pulse in a manner determined by the particular code; therefore interferences between neighboring pulse pairs will contribute to the observed irregularity. In the limit when only one repetition of the M-sequence phase code fits within the input spectrum, a pseudonoise burst rather than a pulse train is produced.[6,7] Higher-repetition-rate pulse trains can be achieved by using shorter input pulses.

It is of interest to compare pulse trains produced by phase filtering with those produced by amplitude filtering. We previously showed such a comparison for relatively low-repetition-rate (1.2-THz) pulse trains.[7] The data revealed that the pulse trains obtained by these two approaches had nearly identical intensity profiles, except that phase masking resulted in an overall intensity $\simeq$15 times higher than that which resulted from amplitude masking. A similar high efficiency is obtained in our current research. The enhanced efficiency associated with phase filtering will be even more dramatic for filters designed to generate bursts containing larger numbers of pulses.

As a further illustration of phase-only filtering, we demonstrate generation of flat-topped pulse trains. Suitable phase filters can be borrowed from the field of coherent optics, in which they are used to convert individual input beams into equal-intensity beam arrays. Termed Dammann gratings,[15,16] these are binary, phase-only filters consisting of periodic repetitions of a single building block of width δF. Unlike M-sequence filters, the individual pixels within a primary building block are not of identical size. Prescriptions for Dammann gratings yielding beam arrays of various

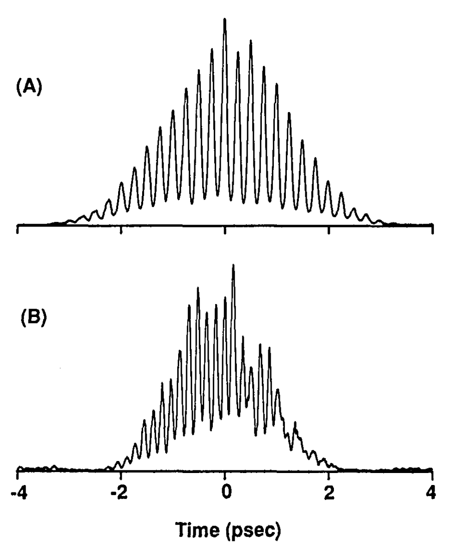

Fig. 2. Cross-correlation measurements of (A) 4.0-THz and (B) 5.85-THz pulse trains produced by phase-only filtering. For both traces the phase difference was $\delta\phi = 0.84\pi$.

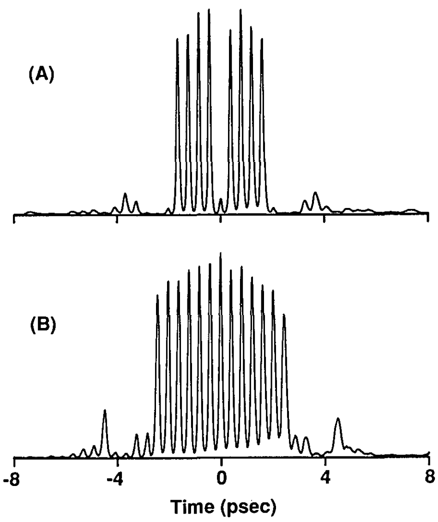

Fig. 3. Cross-correlation measurements of flat-topped, 2.5-THz pulse trains produced by phase-only filtering with (A) $\delta\phi = \pi$ and (B) $\delta\phi = 0.85\pi$.

dimensions are given in Ref. 16. We have fabricated phase masks based on these prescriptions that we use to generate flat-topped pulse trains. Figure 3 shows two examples of our data. The masks were chosen to produce 2.5-THz output trains consisting of 8 and 13 pulses, respectively. The phase differences were $\delta\phi = \pi$ [Fig. 3(A)] and $\delta\phi = 0.85\pi$ [Fig. 3(B)], respectively, resulting in a missing central pulse in Fig. 3(A) but not in Fig. 3(B). The nearly equal-intensity central pulses contain $\simeq$80–85% of the total energy, with the remaining energy distributed among various low-intensity pulses outside of the central region. The observed 80–85% efficiency is consistent with the predicted efficiency of Dammann gratings.[16]

Tailored trains of femtosecond pulses could find important applications in ultrafast time-resolved spectroscopy, an application in which the high efficiency provided by phase-only filtering is extremely helpful. We have recently demonstrated this point by applying terahertz-rate pulse trains to impulsive stimulated Raman scattering (ISRS) experiments. Previously ISRS has been used for generation and observation of coherent optic phonons in a variety of liquid and solid-state materials.[17,18] However, one difficulty often associated with this technique is an inherent lack of mode selectivity.[17] By using terahertz pulse trains for repetitive impulsive excitation in ISRS experiments and by tuning the repetition rate to match a desired phonon frequency, we have demonstrated selective amplification of individual phonon modes in α-perylene molecular crystal. Details of this research will be published elsewhere.[19]

In summary, we have utilized high-efficiency, phase-only spectral filtering techniques to produce bursts of femtosecond pulses at repetition rates approaching 6 THz. Compared with amplitude filtering approaches, our technique provides substantially higher intensities, since essentially no energy is lost in the filtering process. Our results make possible new forms of time-resolved spectroscopy, such as multiple-pulse ISRS, and could have a direct impact on future high-speed communications systems that will manipulate extremely high-rate streams of ultrashort pulses.

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