Simple technique for generating trains of ultrashort pulses

T. Robinson,[1,*] K. O'Keeffe,[1] M. Landreman,[1] S. M. Hooker,[1] M. Zepf,[2] and B. Dromey[2]

[1]*Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
[2]*Department of Physics and Astronomy, Queens University Belfast, Belfast BT7 1NN, UK*
**Corresponding author: t.robinson1@physics.ox.ac.uk*

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A simple method for generating trains of high-contrast femtosecond pulses is proposed and demonstrated: a linearly polarized, frequency-chirped laser pulse is passed through a multiple-order wave plate and a linear polarizer. It is shown theoretically that this arrangement forms a train of laser pulses, and in experiments the production of a train of approximately 100 pulses, each of 200 fs duration, is demonstrated. In combination with an acousto-optic programmable dispersive filter this technique could be used to generate and control pulse trains with chirped spacing. Pulse trains of this type have widespread applications in ultrafast optics.

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Numerous applications arising from the coherent control of atomic and molecular processes require the efficient generation of high-contrast ultrafast pulse trains. Examples include the use of counterpropagating pulses in all-optical quasi-phase-matching of high harmonic generation [1]; multipulse excitation of atoms, molecules, and solids [2,3]; multiple-laser-pulse excitation schemes for high-gradient plasma accelerators [4]; and high-fluence terahertz wave-train generation for radar and microwave communications [5].

Several approaches for generating trains of optical pulses have been investigated. Low-energy pulse trains have been generated by placing spectral masks in the focal plane of a temporally nondispersive grating stretcher [6]. However, this method cannot be extended to high-energy pulse trains due to damage to the mask. Sequential Michelson interferometers have also been used to produce high-energy trains with adjustable pulse separations [7], although this method may be impractical for applications where large numbers of pulses are required. An array of birefringent crystals has also been shown to produce pulse trains with adjustable spacing and high contrast [8]. In this paper a simple method for producing trains of pulses is described and shown to produce high-contrast trains of up to approximately 100 pulses, where each pulse has a duration as short as 200 fs.

The method employed is straightforward. A frequency chirp is introduced to a linearly polarized laser pulse by a pulse stretcher composed of two parallel diffraction gratings. A linear polarizer is placed after the stretcher and oriented so as to transmit the radiation. Prior to the polarizer is placed a multiple-order wave plate oriented with its fast axis at 45° to the transmission axis of the polarizer. For radiation to pass through the combination of the wave plate and the linear polarizer it is necessary for the wave plate to introduce a phase shift of $2m\pi$, where m is an integer, between the field components polarized parallel and perpendicular to the fast axis of the wave plate. This condition can only be met for certain frequencies and, since the pulse passing through the wave plate is chirped, the transmitted laser pulse is modulated to form a series of pulses. We note that the center frequency of the pulses will vary by approximately the bandwidth of the original pulse, but in many applications this is unimportant.

To provide more quantitative information it is insightful to consider the case in which the chirped pulse has a Gaussian temporal profile, so that the electric field in the plane $z=0$ may be written as $E(0,t)=A\exp(-\Gamma t^2)\exp(-i\omega_0 t)$, where A is the amplitude of the electric field and ω_0 is the central angular frequency. The complex parameter $\Gamma \equiv a+ib$, where $a\tau_p^2=2\ln 2$, in which τ_p is the full width at half-maximum (FWHM) of the temporal profile of the *intensity* of the laser pulse [9]. The instantaneous frequency within the pulse is given by $\omega=\omega_0+2bt$, and hence the parameter b describes the magnitude of the frequency chirp.

It may be shown [9] that after passing through a quadratically dispersive medium located between the planes $z=0$ and $z=l$, the amplitude of the pulse may be written as

$$E(l,t)=f(l,t)\exp(-i\omega_0 t)\exp[i\phi(l,t)], \tag{1}$$

where

$$f(l,t)=A\exp\{-\Re[\Gamma(l)](t-\beta_0' l)^2\}, \tag{2}$$

$$\phi(l,t)=\beta_0 l-\gamma(t-\beta_0' l)^2, \tag{3}$$

$$\gamma=\frac{b+2\beta_0'' l(a^2+b^2)}{(1+2\beta_0'' lb)^2+(2\beta_0'' la)^2}. \tag{4}$$

In the above $\Gamma(l)^{-1}=\Gamma(0)^{-1}-2i\beta_0'' l$, and the wave vector, group velocity, and group velocity dispersion (GVD) of the medium at an angular frequency of ω_0 are given by β_0, $1/\beta_0'$, and β_0'', respectively.

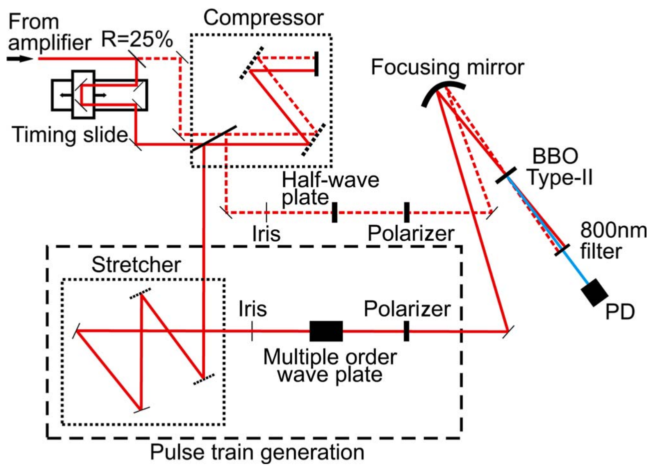

Fig. 1. (Color online) Experimental arrangement used to generate and measure trains of femtosecond pulses. PD, photodiode.

The amplitude of the radiation passing through the polarizer is given by $\sqrt{2}E_{\mathrm{pol}}(l,t)=E_{\mathrm{e}}(l,t)+E_{\mathrm{o}}(l,t)$, where the amplitudes E_{e} and E_{o} are given by expressions of the form of Eq. (1), and the subscripts o and e denote the ordinary and extraordinary polarizations, respectively. Provided the *difference* of the second- and higher-order dispersion terms for the two polarizations in the wave plate are not too large, the pulse envelopes $f_{\mathrm{o}}(l,t)$ and $f_{\mathrm{e}}(l,t)$ will be approximately equal, and consequently

$$E_{\mathrm{pol}} \approx \sqrt{2}\bar{f}(l,t)\exp[\mathrm{i}\bar{\phi}(l,t)]\cos\left[\frac{\phi_{\mathrm{o}}(l,t)-\phi_{\mathrm{e}}(l,t)}{2}\right], \tag{5}$$

where $\bar{f}(l,t)$ and $\bar{\phi}(l,t)$ are the average pulse envelope and phases for the two polarizations. It is seen that a train of pulses is formed, with a cosine-squared temporal profile.

Peaks of intensity occur when the argument of the cosine is equal to $m\pi$, where m is an integer. It is straightforward to show that the interval between adjacent pulses is

$$\Delta\tau = \frac{\pi}{(\beta'_{0\mathrm{e}}\gamma_{\mathrm{e}}-\beta'_{0\mathrm{o}}\gamma_{\mathrm{o}})l+(\gamma_{\mathrm{o}}-\gamma_{\mathrm{e}})t}, \tag{6}$$

$$\approx \frac{\pi}{bl}\frac{1}{\beta'_{0\mathrm{e}}-\beta'_{0\mathrm{o}}}, \tag{7}$$

where the approximation holds if for both polarizations $2\beta''_0 l(a^2+b^2) \ll 1$, whereupon $\gamma_{\mathrm{o}} \approx \gamma_{\mathrm{e}} \approx b$.

It may be seen that if the initial stretched pulse has a constant frequency chirp, and GVD in the wave plate can be neglected, the pulses in the train have a constant separation. If these conditions are not met, the spacing of pulses in the train will vary during the train.

These concepts were tested using the arrangement shown in Fig. 1. The laser radiation was provided by a 10 Hz Ti:sapphire chirped-pulse amplification laser system, delivering linearly polarized pulses with energy up to 125 mJ at a center wavelength of 808.8 nm. The beam was split prior to the compressor of the laser system using a beam splitter of 25% reflectivity. The reflected beam was used to form the pulse trains, while the transmitted beam was used as a probe beam. The relative delay between the probe and pulse train beams could be changed by adjusting a computer-controlled timing slide. The pulse train and probe beams were compressed in the same compressor to give pulses of 70 and 80 fs FWHM, respectively.

The probe beam passed through a combination of a half-wave plate and a linear polarizer to allow energy control. The pulse train beam was restretched by a pair of gratings with 1200 lines/mm to give pulses with FWHM durations between 5 and 33 ps. The stretched pulse train beam then passed through a multiple-order calcite wave plate oriented with its fast axis at 45° to the plane of polarization, followed by a linear polarizer oriented parallel to the polarization of the beam prior to the wave plate. Cross-correlation of the generated pulse trains and probe pulses was performed by overlapping the two beams in a 1 mm thick type II BBO crystal and observing the second-harmonic light generated as the timing slide was adjusted.

Figure 2 shows the results obtained for a stretched pulse of 33 ps duration. The first plot shows the

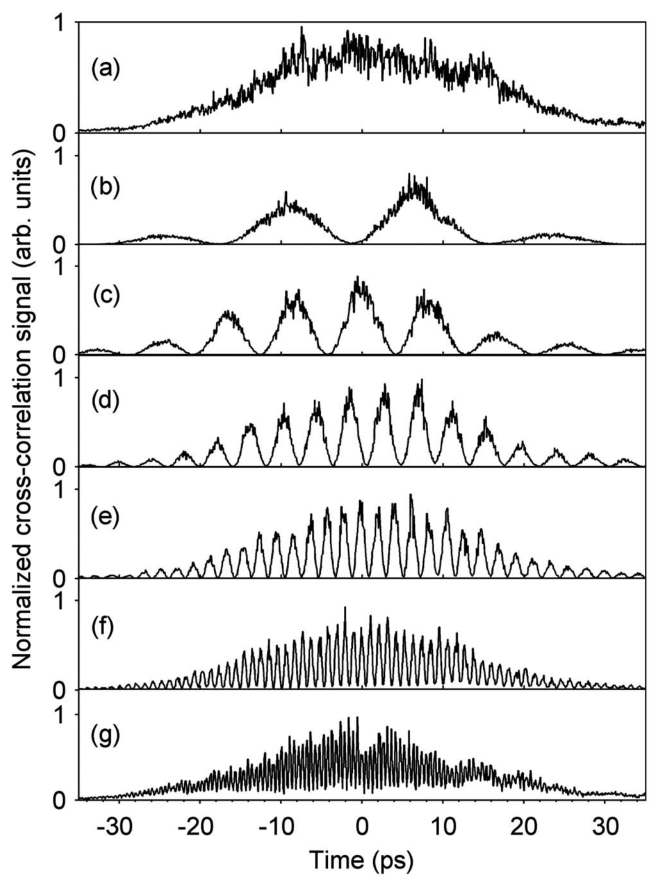

Fig. 2. Cross-correlation traces obtained with a stretched pulse of 33 ps FWHM duration and multiple-order calcite wave plates of thickness: (a) 0 mm (no crystal), (b) 0.83 mm, (c) 1.65 mm, (d) 3.30 mm, (e) 6.61 mm, (f) 13.22 mm, (g) 26.43 mm.

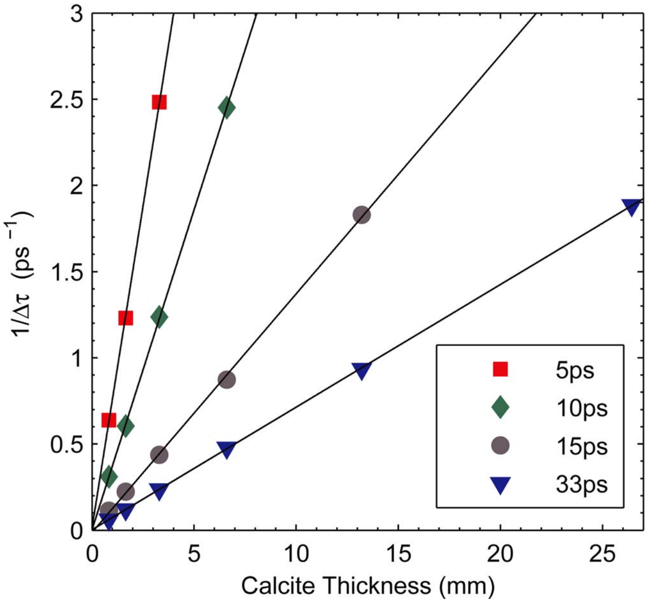

Fig. 3. (Color online) Plot of $1/\Delta\tau$ as a function of the thickness of the multiple-order calcite wave plate for stretched pulses of duration 5, 10, 15, and 33 ps.

cross-correlation of the unmodulated stretched pulse, i.e., that obtained without the multiple-order wave plate in the pulse train beam. The other plots show the cross-correlations measured with multiple-order wave plates of various thicknesses inserted into the stretched beam.

It is seen that as the thickness of the wave plate was increased the number of pulses in the train increased and the separation between pulses decreased, as expected from Eq. (6). The reduction of contrast of the cross-correlations shown in Figs. 2(f) and 2(g) arises largely from the finite duration of the probe pulse. For thick wave plates, differences in GVD for the two polarizations can reduce the intensity contrast r of the pulse train. However, modeling shows that even for the thickest wave plate employed, $r > 9:1$ within the FWHM of the train.

Since the temporal intensity profile of the pulse train corresponds to a cosine-squared modulation of that of the stretched laser pulse, the FWHM duration of pulses in the train is half the pulse separation. The shortest pulse separation and FWHM pulse duration measured in this work were 400 and 200 fs, respectively.

The measurements of Fig. 2 were repeated for stretched pulses of FWHM duration 5, 10, and 15 ps. Figure 3 plots $1/\Delta\tau$ as a function of the thickness of the wave plate, l. It is seen that $1/\Delta\tau$ varies linearly with l in agreement with Eq. (7).

Equation (6) shows that the separation of pulses in the train will be approximately constant if $2\beta_0'' l(a^2 + b^2) \ll 1$, that is if the second-order dispersion of the wave plate is sufficiently small. For the parameters used in our experiment the variation of $\Delta\tau$ over the FWHM of the stretched pulse is calculated to be approximately 1% or less. In practice $\Delta\tau$ was found to vary by up to 6%. This behavior is likely to arise from third- and higher-order dispersion in the pulse stretcher.

In conclusion, a simple method for generating trains of high-contrast femtosecond pulses was proposed and demonstrated. The number of pulses in the train, or their spacing, may be varied by adjusting the separation of the gratings in the stretcher and the retardance of the wave plate employed. We note that in principle high-order dispersion effects in the stretcher or in the wave plate can cause the spacing of the pulses in the train to vary, although in this work these effects were small. The effect of such high-order dispersion could be compensated by employing an acousto-optic programmable dispersive filter [10] to tailor the phase of the stretched pulse; indeed this approach could be used to generate and control pulse trains with a pulse spacing that varies within the train. Chirped pulse trains of this type could find widespread applications in ultrafast optics.

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