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Letter

Temporal multiplexing and shaping of few-cycle pulses with microoptical retroreflector arrays

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Abstract

Temporal shaping of femtosecond pulses with microoptical retroreflector arrays was studied experimentally. It was demonstrated that pulses of variable duration and multiple pulses of variable delay can easily be generated by varying the tilt angle of the compact device. The corresponding pulse characteristics were determined by second order autocorrelation measurements.

Keywords: microoptics; optical processing; retroreflector; temporal shaping; ultrashort pulses.

OCIS codes: 320.5540 pulse shaping; 230.3990 micro-optical devices; 320.7085 ultrafast information processing.

The shaping of femtosecond (fs) laser pulses in the temporal domain is of increasing interest for pump-and-probe spectroscopy, coherent control, optical information processing and numerous further applications. A synthesis of waveforms can be obtained by direct space-to-time pulse shapers, either working in Fourier [1] or Fresnel domain [2]. Both concepts are based on a separation and modification of spectral compartments in multiple channels. In modified Fourier transform pulse shapers, an improvement of the performance was achieved with arrays of microlenses by converting continuous spectral bands into discrete spots in the mask plane of transmittive [3] or reflective 4f-setups [4]. Other approaches are based on stacked mirror structures [5] or the nonlinear-optical generation of frequency combs (e.g., for the stabilization of oscillators [6]). Arbitrary waveforms in few-ps range were obtained from 100 fs pulses by shaping with digital micromirror arrays in combination with an interferometer arrangement [7].

Most of these approaches, however, suffer from dispersive pulse distortion or require complex optoelectronic components and software. Here, we report on an alternative, efficient method to temporally reshape or multiplex femtosecond laser pulses with arrays of miniaturized retroreflectors [8, 9], which was proposed in the frame of tapped delay-line filters for optical information processing and theoretically described by the mathematical formalism for finite impulse response filters [10]. The capability of the technique to shape near infrared pulses at initial pulses durations in the range of 10 fs is demonstrated here.

Similar to the known spectral domain approaches with linearly arrayed channels, the setup is based on dividing the pulse into numerous parallel propagating subpulses by reflecting it from an array of miniaturized prismatic retroreflector elements. The geometry is schematically shown in Figure 1. In the case of a perfect 90° angle between the two extended sidewalls, assuming a plane wave illumination and neglecting any diffraction, each incoming light ray is exactly redirected by the double reflection. If the retroreflector array with the spatial period p is tilted by an angle α with respect to the normal incidence, the resulting optical pathways for pulses passing adjacent channels are significantly different thus causing a time delay Δt between the corresponding subpulses:

$$\Delta t = 2\times\frac{p}{c}\times\sin\alpha \tag{1}$$

where c denotes the speed of light. At sufficiently large tilt angles, temporally separated subpulses appear (multiplexing), whereas overlapping subpulses at small angles allow for a certain variation of the temporal distribution function (pulse shaping). Number and signal ratio of active channels are adjusted by the spatial parameters of the illuminating beam. The maximum possible number of subpulses is identical with the number of retroreflectors integrated in the component. The theoretical limit for the tilt angle is nominally 45° (here corresponding to a delay of >2.5 ps). It can, however, not be reached in practice because of approximating the case of striking incidence at the reflector facets (i.e., reduction of the effective illuminated area and enhanced diffraction). In our experiments, a metallic retroreflector array with a period of p=640 μm and a total number of 19 prismatic grooves was applied. The array was monolithically fabricated by an ultra-precision diamond cutting technique in an Al-cuboid (highly reflecting area 12.5×12.5 mm^2, thickness 9.5 mm). To precisely control the tilt angle, the array was fixed within the center of a rotatable holder. The minimum angular resolution was <0.01° corresponding to a travel time difference of 0.7 fs. According to Eq. (1), the time delay depends linearly on the period. Therefore, the theoretical maximum delay for any period p' can easily be obtained by multiplying the maximum value 2.5 ps (which was relevant in our experiments) with a factor p'/p.

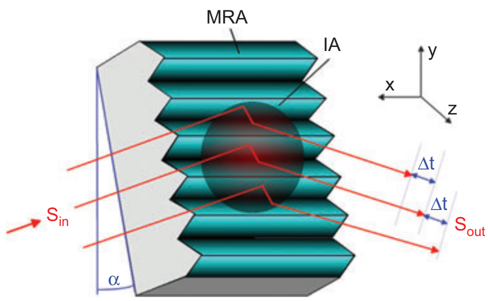

Figure 1 Setup for the temporal processing of ultra-short pulses with a compact, linear microoptical retroreflector array consisting of prismatic grooves of rectangular cross-section (schematically; S_{in}, input signal; S_{out}, output signal representing the superposition of subpulses from all contributing channels depending on the illuminated area IA; MRA, microoptical retroreflector array; α, tilt angle of MRA against the *x*-*y* plane, Δ*t*, temporal delay between the subpulses propagating in neighboring channels). To illustrate the principle, the propagation paths for three active channels are sketched symbolically by the red rays.

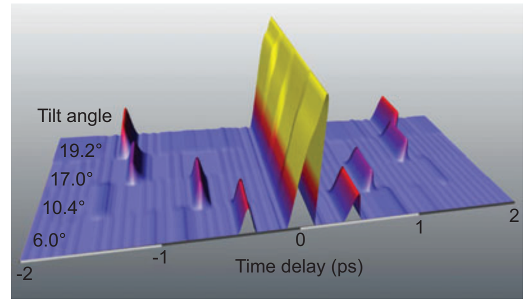

Figure 2 Generation of pulse trains of variable delay by tilting a microoptical retroreflector array (spatial period: 640 μm). The curves represent the measured second order autocorrelation functions. The time delay was found to be 445 fs at a tilt angle of 6.0°, 768 fs at 10.4°, 1.25 ps at 17.0° and 1.4 ps at 19.2°.

The array was illuminated with linearly polarized femtosecond pulses generated by a Ti:sapphire laser oscillator [FemtoSource Scientific Pro (Femtolasers, Wien, Austria), pulse duration 10–12 fs, center wavelength 790 nm, maximum spectral FWHM 120 nm, 250 mW average power, repetition rate ca. 80 MHz]. The angle of incidence was chosen to be ca. 45° and located in the plane parallel to the prism axis thus not affecting the temporal properties. To characterize the pulses in time domain, the reflected sub-beams were spatially integrated on the detector of a second order autocorrelator (Mini, APE, Berlin, Germany). The minimum distance between retroreflector and the entrance aperture of the autocorrelator was 1.5 cm. The spectral bandwidth (FWHM) of the pulses inserted in the beam shaping system was ca. 120 nm and the angular bandwidth of the laser (divergence) was in the range of 0.1°. Depending on the distance between array center and laser output coupling mirror and tilt angle, two or three neighboring elements were illuminated without additional beam expanders. Reference pulses were obtained by replacing the retroreflector array by a plane mirror.

The normalized autocorrelation signals of temporally processed pulses as a function of the tilt angle (Figures 2 and 3) illustrate the two different modes of operation: (i) generation of temporally separated pulses in adjacent channels (corresponding to large tilt angles) and (ii) generation of pulses of variable shape by coherent addition (for small tilt angles). As demonstrated in Figure 2, multiple pulses were obtained by tilting the microoptical retroreflector array by angles between 6° and ca. 20°. The normalized fits of the measured autocorrelation signals indicate the formation of double subpulses with a maximum delay of 1.4 ps corresponding to a minimum repetition frequency of 0.7 THz. The pulse number can be enhanced by magnifying the beam diameter. With a slightly enlarged spot size of the illuminating laser beam, triple subpulses were also generated (indicated by five maxima in the autocorrelation trace, not shown here). The intensity ratio of subsequent pulses can be influenced by the illumination profile (e.g., by using a flat-top illumination of the retroreflector). At extremely short pulse duration, however, such a preshaping is not trivial because of travel time effects. The amplitude of the side lobes of the autocorrelation signal was changed by shifting the retroreflector array relative to the spatial beam position (i.e., sampling the intensity envelope) without expanding the beam. The variation of the pulse shape by superimposing subpulses at slightly changed small tilt angles (<0.1°) is shown in Figure 3. The time delay is estimated to be ca. 6 fs (corresponding to a theoretical angle of 0.08°). The autocorrelation traces can be described by different distribution functions. The best fits were found to be Lorentzian and Gaussian profiles. It has to be mentioned that these measurements were performed when a passive liquid crystal device (LCoS-SLM) was also in the optical path. Because of coherently adding adjacent pulses, we observed an oscillating behavior depending on the delay time caused by interference and influencing the FWHM of the output pulses (e.g., transition from Gaussian to Lorentzian shape). For a detailed study of these effects at the very smallest angles, the angular resolution of the system has still to be improved.

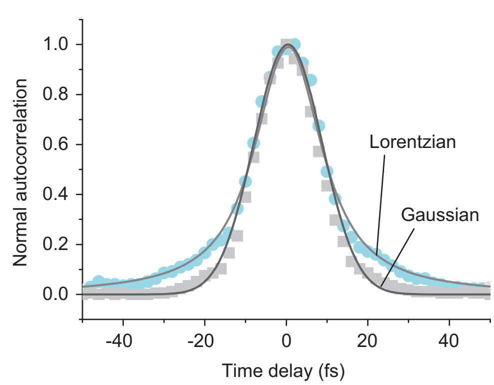

Figure 3 Variation of the pulse shape of a femtosecond pulse by superimposing subpulses generated by adjacent elements of a retroreflector array at small tilt angles (<0.1°). Two normalized autocorrelation traces of approximately equal FWHM but significantly different distribution function are compared. Best fits were Lorentzian and Gaussian profiles (dark cyan and dark gray, respectively).

To conclude, it was demonstrated that microoptical retroreflector arrays of variable tilt angle enable for an effective temporal processing of broadband ultra-short laser pulses by controlling tilt angle and illumination geometry. The most important advantages of the reflective microoptical approach are its low dispersion, minimum damage risk and compactness enabling for a stable pulse shaping regime. The initial pulses can be multiplexed into sequences of subpulses with a time delay up to the ps range. Pulses of variable shape and FWHM can be obtained by overlapping subpulses at small tilt angles. For the array structure used here, the maximum possible delay was ca. 2.5 ps. The illumination can be modified with an additional beam expander, whereas the delay range can be extended by applying a serial arrangement of multiple arrays. By reversing the principle, it should be possible to exploit the high sensitivity of the temporal response against tilt for a measurement of small angular deviations in the range well below 0.1°. Thus, the setup can serve as a tool for the high-precision alignment of ultrafast optical systems. The angular performance at small angles will be the subject of future work. Currently, the studies are continued with LIGA-fabricated structures [11] and even shorter pulse durations down to 6 fs. In the experiments reported here, the SLM was used as a passive reflector. Continuing measurements with graded and structured illumination are currently under investigation. Adaptive masking of the facets of retroreflector arrays by programming amplitude and phase functions into the spatial light modulator should enable to shape trains of individually encoded subpulses for ultrafast optical communication, pump-and-probe spectroscopy and other emerging applications. Furthermore, a smart masking can be used to overcome unwanted side effects of diffraction (energy loss in nonzero orders, crosstalk, Talbot effect, pulse lengthening). As a general improvement, we propose to illuminate the retroreflector with an array of well-adapted quasi-nondiffracting sub-beams [12]. For this case, we expect a significant reduction of diffractive distortions of the spatial and temporal pulse transfer.

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