Line-by-line pulse shaping control for optical arbitrary waveform generation

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Abstract: We demonstrate a fundamental operation for generating complex waveforms in the optical domain – line-by-line pulse shaping control for optical arbitrary waveform generation (O-AWG). Independent manipulation of the spectral amplitude and phase of individual lines from a mode-locked frequency comb, or spectral line-by-line pulse shaping, leads to synthesis of user-specified ultrafast optical waveforms with unprecedented control. Coupled with recent advances in frequency stabilized mode-locked lasers, line-by-line pulse shaping control should have significant impact to fields drawing upon developments in the field of ultrafast science.

OCIS codes: (200.4560) Optical data processing; (320.5540) Pulse shaping

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Mode-locked lasers generate periodic trains of ultrashort pulses which are characterized in the frequency domain by an evenly spaced series of discrete spectral lines, with the frequency spacing equal to the pulse repetition rate. Waveforms in the time domain are related to spectra in the frequency domain by a Fourier-Transform. From a time domain perspective, ultrashort pulse generation has seen significant progress for many years, with direct laser generation of pulses as short as a few optical cycles [1], with demonstration of attosecond pulses [2], and with applications ranging from time-resolved spectroscopy of ultrafast physical phenomena to generation of coherent X-rays [3]. From a frequency domain perspective, stabilization of the absolute frequency offset positions of the spectral lines of mode-locked lasers has recently been achieved [4]. The resultant optical frequency combs have led to enormous progress in precision optical frequency synthesis and metrology [5], with uncertainties reported at the 10^{-19} level [6]. Recently, a new nonlinear spectroscopy method was reported in which the time- and frequency-domain attributes of mode-locked optical frequency combs are combined to observe the time evolution of population transfer in atoms, while simultaneously affording high precision determination of the global energy structure with direct connection between frequencies spanning radio-frequency to optical [7].

In parallel with such advances in pulse generation and stabilization, pulse shaping techniques, in which phase and amplitude manipulation of optical spectral components allow synthesis of user-specified ultrashort pulse fields according to a Fourier transform relationship, have been developed and widely adopted [8]. Applications are diverse, including coherent control of chemical reactions, molecular motions, and quantum mechanical wave

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packets [9-14], single cycle pulse generation [15], frequency selective nonlinear microscopy and imaging [16,17], lightwave communications schemes based on phase-coded ultrashort pulse waveforms [18,19], and radio-frequency waveform generation [20]. However, the past pulse shapers have generally manipulated groups of spectral lines rather than individual lines, which results in waveform bursts that are separated in time with low duty factor and insensitive to the absolute frequency positions of the mode-locked comb. This is primarily due to the practical difficulty of building a pulse shaper capable of resolving each spectral line for mode-locked lasers at typical repetition rates. However, to approach true optical arbitrary waveform generation (O-AWG), the phases and amplitudes of individual spectral lines should be controlled, which would lead to waveforms spanning the full time period between mode-locked pulses (100% duty factor). Waveform contributions arising from adjacent mode-locked pulses would overlap and interfere coherently in a manner sensitive to the offset of the frequency comb [21]. Thus, manipulation of individual spectral lines leads to a new regime in which the advantages of pulse shaping and of stabilized frequency combs can be simultaneously realized. Line-by-line pulse shaping control for O-AWG promises broad impact both in optical science, allowing for example coherent control generalizations of the time-frequency spectroscopy of ref. 6 to introduce selectivity, and in technology, where truly coherent optical processing will enable new possibilities in lightwave communications and laser radar.

In previous work in the direction of line-by-line pulse shaping control for O-AWG, a hyperfine filter was used to simply select a single pair of 12.4-GHz spaced spectral lines to produce a radio frequency (RF) beat [22], but without amplitude or phase control of the spectral lines. A similar device was used for phase-only manipulation of spectral lines spaced by 5 GHz in optical coded-pulse communication experiments [23]. However, the periodic spectral response of the hyperfine filter means that independent manipulation of the spectrum is possible only within one free spectral range, which was only 75 ~80 GHz in the experiments of [22,23]. Since ultrashort pulses can have a huge bandwidth, even exceeding 100 THz, such hyperfine filter devices are not able to support true broadband O-AWG. Grating-based pulse shapers however can in principle work up to a full octave of bandwidth. We reported a first step towards grating-based line-by-line pulse shaping in ref. 20. Here we report a grating-based pulse shaper with record high resolution that for the first time allows accurate and highly independent control of amplitude and phase of individual spectral lines over a broad optical band from a mode-locked laser and demonstrate line-by-line pulse shaping control. The technique of line-by-line control demonstrated here is an important new step towards true O-AWG.

Figure 1 shows the experimental setup, in which a fiber coupled Fourier-Transform pulse shaper is constructed in a reflective geometry. A fiber-pigtailed collimator and subsequent telescope take the light out of fiber and magnify the beam size to ~18 mm diameter on the 1200 grooves/mm grating in order to enhance the pulse shaper resolution. Discrete spectral lines making up the input short pulse are diffracted by the grating and focused by the lens with 1000 mm focal length. A fiberized polarization controller (PC) is used to adjust for horizontal polarization on the grating. A 2×128 pixel liquid crystal modulator (LCM) array with a calcite polarizer (> 100,000:1 extinction ratio) on the input face is placed just before the lens focal plane to independently control both amplitude and phase of individual spectral lines. The LCM (Cambridge Research & Instrumentation, Inc.) in our experiment is fully integrated with control electronics and software. The update speed of LCM is on the order of tens of ms to ~100 ms, limited by the liquid crystal relaxation time. The individual pixels of the LCM, arranged on 100 μm centers, can be electronically controlled independently to give amplitude and phase control with 12-bit resolution. A retro-reflecting mirror leads to a double-pass geometry, with all the spectral lines recombined into a single fiber and separated from the input via an optical circulator. The fiber-to-fiber insertion loss is 11.6 dB (including circulator loss), which includes all optical component losses as well as loss incurred in focusing back into the 9 μm fiber mode after the pulse shaper. The passband width, measured by scanning a tunable, narrow-linewidth, continuous-wave laser with the LCM replaced by a

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narrow slit, is 2.6 GHz at the 3 dB points, as shown in the inset. To the best of our knowledge, this is the highest resolution ever reported for a grating-based pulse shaper. The unprecedented high resolution makes accurate and independent control of individual spectral lines possible and enables true line-by-line pulse shaping control, potentially over a broad optical band.

We note that in addition to LCMs, other spatial light modulators are also well known in pulse shaping [8]. Line-by-line pulse shaping experiments analogous to what is reported here should also be possible using other spatial light modulator technologies, provided that the key requirement of very high spectral resolution for clear separation of adjacent spectral lines is met.

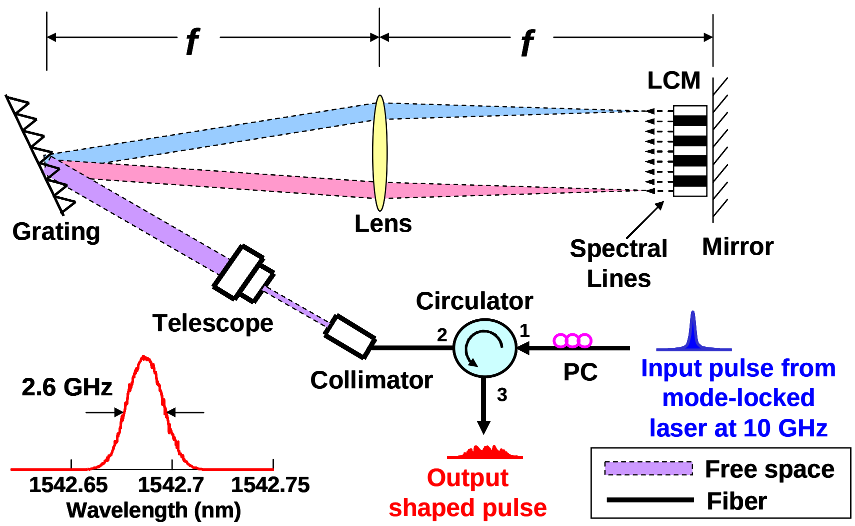

Fig. 1. Experimental apparatus for arbitrary waveform generation using line-by-line pulse shaper. The inset figure shows a measured 3 dB passband of 2.6 GHz. LCM: liquid crystal modulator. PC: polarization controller.

Our experiments are performed using a home-built harmonically mode-locked fiber laser producing 3 ps (full width at half maximum) pulses at 10 GHz repetition rate with center wavelength of 1542.5 nm. The repetition rate, selected to ensure that the spectral line spacing exceeds the pulse shaper resolution, is especially appropriate for eventual applications in optical communications. Each spectral line is spaced by 200 μm, corresponding to 2 LCM pixels. The frequency offset of the mode-locked comb is not actively stabilized; instead we exploit the passive frequency stability of the mode-locked comb, ~1 GHz over the time scale of our experiments (ten times below the comb spacing). This suffices for these first proof-of-concept experiments on line-by-line pulse shaping control for O-AWG under typical laboratory environmental conditions without additional controls (e.g., temperature stabilization). To achieve a larger number of spectral lines, the 3 ps pulses are compressed to 400 fs by a dispersion-decreasing fiber soliton compressor. Either 3 ps or 400 fs pulses at 10 GHz repetition rate are used as input to the pulse shaper according to the required bandwidth for the specific demonstration. Figure 2 shows power spectra (log plots) and resultant time-domain intensity waveforms when the pulse shaper is used to select just two spectral lines out of the mode-locked frequency comb. Data are shown for spectral line separations of 10, 20, and 100 GHz (Figs. 2(a-c), 3 ps input pulses) and 400 and 500 GHz (Figs. 2(e-f), 400 fs input pulses). The measured optical linewidths are limited by the 0.01 nm resolution of the optical spectrum analyzer. The power spectra in Figs. 2(a-c) are also plotted on a linear scale (insets) in order to clearly show the ability to control the relative amplitudes of the two selected lines (in general they don't have equal amplitudes before pulse shaping) and very strongly suppress

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deselected spectral lines (deselected lines are not visible in the linear plots). The log plots reveal that deselected spectral lines are suppressed by greater than 31.5 dB for 10 GHz, 29 dB for 20 and 100 GHz, 28 dB for 400 GHz, and 26 dB for 500 GHz.

The intensity waveform resulting from selection of two spectral lines is ideally a cosine function with DC offset. Data shown in the figure reveal cosines with periods of 100, 50, 10, 2.5, and 2 ps, respectively, as expected. These data were measured after an optical amplifier, using either a 50 GHz bandwidth photodiode and sampling oscilloscope (10 and 20 GHz) or standard short optical pulse intensity cross-correlation techniques (100-500 GHz). The pulse shaper itself is able to afford much higher frequency cosine waveforms, but here is limited by the available optical bandwidth from the laser and by the measurement process (shorter reference pulses are required to measure higher frequency cosine waveforms with shorter period). This limitation can be relaxed or eliminated by utilizing short pulse compression techniques to achieve large bandwidth at high repetition rate [24]. The increased fluctuations and distortions in the cosine waveforms at higher frequencies (especially 400 and 500 GHz) arise due to decreased optical power as the selected lines approach the edge of the input spectrum (10 μW optical power for the two lines with 500 GHz separation), which increases susceptibility to imperfect suppression of deselected lines and optical amplifier noise. Nevertheless, these data clearly demonstrate the potential to synthesize modulations over a very broad frequency range.

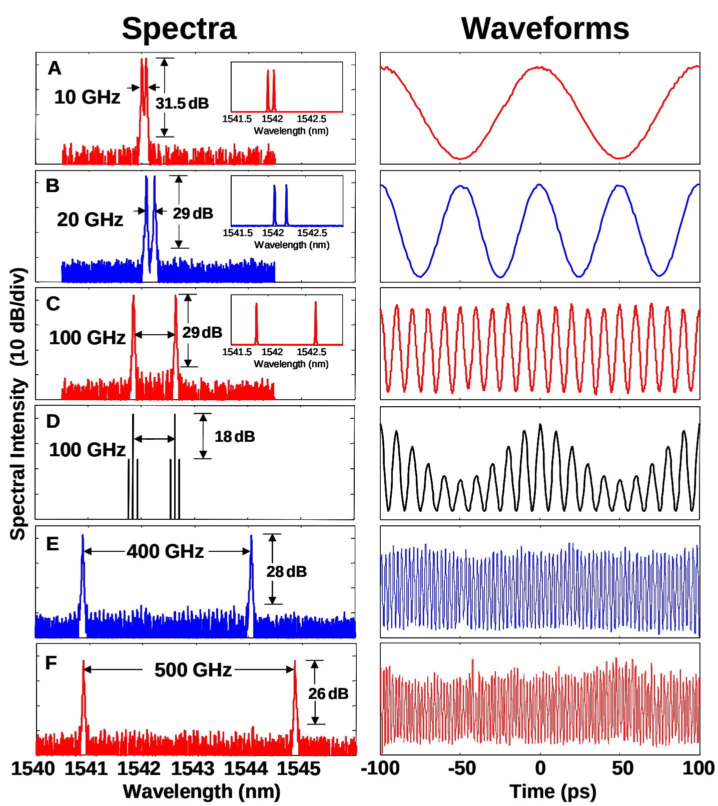

Fig. 2. Selecting two spectral lines (separated by A: 10 GHz, B: 20 GHz, C: 100 GHz, E: 400 GHz and F: 500 GHz) and corresponding cosine waveforms (with periods of 100 ps, 50 ps, 10 ps, 2.5 ps and 2 ps). The inset spectra figures in Fig. (A-C) are in linear scale to show the well-controlled relative amplitudes of the two selected lines and the strong suppression of the deselected lines. Fig. (D) shows the simulation results for a distorted cosine waveform with 18 dB suppression ratio of adjacent lines due to limited pulse shaper resolution.

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It is essential to note that strong suppression of deselected spectral lines is critical for accurate waveform generation. To validate this point, simulations are performed in which suppression is degraded for the nearest neighbors to the selected spectral lines. Figure 2(d) shows the case of a spectral line pair separated by 100 GHz, with suppression of adjacent lines limited to 18 dB (consistent with the nearest neighbor suppression ratio for our previous, lower resolution pulse shaper of Ref. [20]). Even at 18 dB suppression, coherent crosstalk from the weak undesired lines leads to huge intensity variation in the time-domain waveform (the ratio between distorted cosine waveform envelope peak to valley is ~2.8)! Furthermore, in experiments one might expect even worse waveform degradation for the same limited suppression ratio, since not only imperfectly suppressed adjacent lines, but also undesired nonadjacent lines, are likely to play a role. The dramatic effect in the time domain caused by small unsuppressed lines can be understood in the following way. Considering the example in which suppression is degraded for the nearest neighbors to the selected spectral lines as in Fig. 2(d), if the four equal nearest neighbors have normalized intensity of a, then the field amplitude is $\sqrt{a}$. The waveform envelope peak intensity is reached when all the four neighbors are in phase with the two selected lines, which gives a relative intensity of $(2+4\sqrt{a})^2$. Similarly, the waveform intensity envelope valley is reached when all the four neighbors are out of phase with the two selected lines, which yields a relative intensity of $(2-4\sqrt{a})^2$. Using a suppression value of 18 dB, the calculated ratio between peak and valley is ~2.8, which is consistent with the simulation in Fig. 2(d). In our experiments, the adjacent lines have unequal powers and nonadjacent lines also show up. But if we assume only one adjacent line is dominant (which is likely in the experiments), a similar simple calculation applies. In such case, the intensity envelope peak is $(2+\sqrt{a})^2$ and the valley is $(2-\sqrt{a})^2$. Considering the experimental example of Fig. 2(c) with 29 dB suppression, the calculated ratio between peak and valley using this model is ~1.074, which agrees well with the calculated value based on the experimental data (~1.069). It is clear that the high pulse shaper resolution in our current experiments, allowing much stronger suppression of deselected spectral lines, is key for high quality line-by-line pulse shaping control for O-AWG. Besides the pulse shaper resolution, the suppression ratio of deselected spectral lines is also affected by the amplitude control capability of the LCM.

In principle, any periodic waveform can be constructed from a complete set of harmonic (cosine and sine) waveforms. Fig. 3 shows an example of line-by-line pulse shaping control for such O-AWG by manipulating multiple spectral lines over a broad optical band. Two pairs of spectral lines are simultaneously selected and controlled, with 10 GHz frequency separation within each pair and 410 GHz center-to-center frequency separation between pairs (Fig. 3(a)). There is a clear relationship between the spectral lines in the frequency domain and the waveform generated in the time domain: the 100 ps macro period of the waveform envelope is determined by the 10 GHz spacing between lines within a single pair, while the ~2.44 ps micro period of waveform oscillation is determined by the average 410 GHz spacing between pairs (Fig. 3(b)). To demonstrate fine scale waveform control, a π phase shift is applied to one pair of spectral lines while keeping the spectral amplitude essentially unchanged. The resulting time domain waveform should be out of phase compared with the waveform without the phase shift, exactly as seen in the zoomed figures. The finite contrast of the waveform oscillation minimum points, which should go to zero theoretically, is explained by the finite duration of the 400 fs reference pulses used for the measurement. These examples demonstrate an unprecedented capability for true line-by-line pulse shaping control, with waveform manipulation at both macro and micro scale simultaneously. It should also be noted that the pulse shaping technique affords control over both temporal intensity and phase, as is now well known [8], although our measurements here are sensitive only to intensity.

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Figure 4 shows another example of line-by-line pulse shaping control for O-AWG that highlights the fidelity of our method. Four spectral lines (five consecutive lines with the center line blocked, Fig. 4(a)) are selected within a relatively narrow bandwidth to ease comparison with a theoretical calculation. By applying the same amplitude modulation ([1 1 0 1 1]) but different phase modulation ([π 0 – 0 π] or [0 π – 0 π]), two distinct waveforms are generated. The intensity cross-correlation measurements are in almost perfect agreement with and are essentially indistinguishable from the calculations (black circles) based on the Fourier transform of the nominal amplitude and phase patterns imparted onto the spectral lines (Fig. 4(b-c)). The key point is that one can now synthesize optical waveforms with desired amplitude and phase, high fidelity, and 100% duty factor, by manipulating the individual spectral lines from a mode-locked frequency comb. It should also be noted that to clearly illustrate the relationship between the time and frequency domains, intensity and phase control are demonstrated in a binary fashion. As is well known, both intensity and phase gray level control can be readily achieved [8,21,25] using an LCM. Actually, the power spectra shown Figs. 2(a-c), visible on a linear scale in the insets, have been power equalized with the LCM, which is already an example of gray level intensity manipulation.

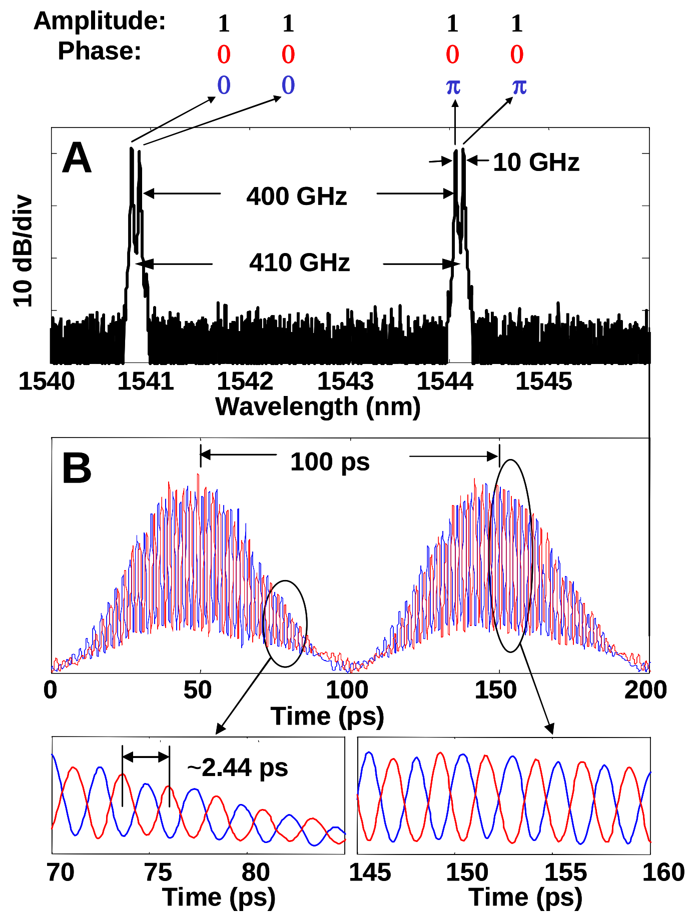

Fig. 3. Selecting four spectral lines, in which two lines in each pair are separated by 10 GHz and the two inner lines between the two pairs are separated by 400 GHz. The center to center separation of the line pairs is 410 GHz. The resulting waveforms have 100 ps macro period (corresponding to 10 GHz) and 2.44 ps micro period (corresponding to 410 GHz). The red and blue waveforms are controlled to be out of phase by applying π phase shift on one pair of spectral lines, as shown in the zoomed figures.

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One immediate application of line-by-line pulse shaping control for O-AWG is for generation of arbitrary radio-frequency electrical waveforms (RF-AWG). Figure 4(d-e) show sampling oscilloscope measurements of the electrical output generated when the optical waveforms of Figs. 4(b-c) drive a 50 GHz photo-diode. Such highly structured, high frequency, and broadband radio-frequency waveforms are impossible to implement using current electrical AWG technology which is typically limited to ~1 GHz [20]; however, the same waveforms are narrow-band from the optics point of view and can be implemented easily as shown here. The slight distortions of the RF waveforms compared with the driving optical signals are caused by the limited bandwidth of the photodiode and sampling scope, which could be precompensated (for example, to achieve two equal main peaks in Fig. 4(e)) by appropriately modifying the control signals to the optical driving waveforms. RF-AWG has the potential to impact fields such as ultrawideband (UWB) wireless [26], which uses subnanosecond electrical bursts for communications and sensing, and impulse radar, where the use of highly structured transmit waveforms designed to optimize discrimination between different scattering targets has been proposed [27].

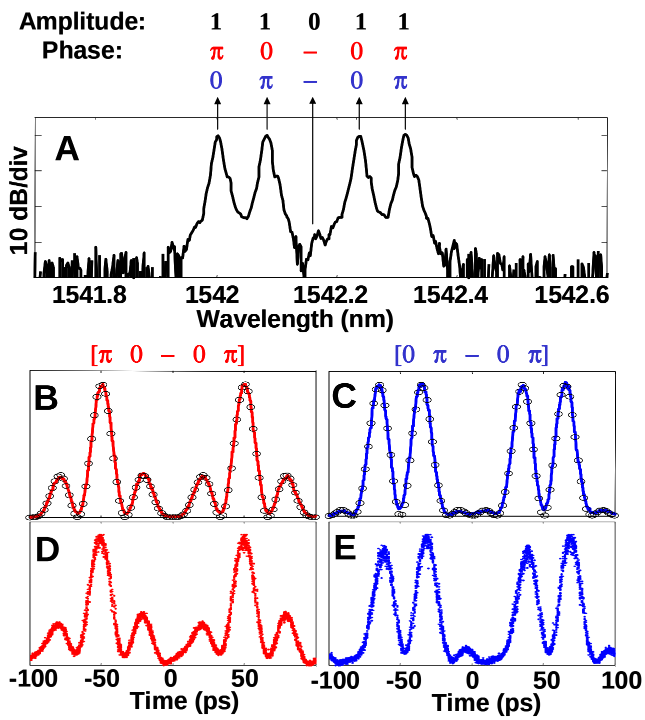

Fig. 4. Selecting four spectral lines (five consecutive lines with center line blocked). (B,C) Waveforms measured by intensity cross-correlation with different applied spectral phases (red and blue curves). Calculations (black circles) are essentially indistinguishable from the data, showing the high fidelity of the generated waveforms. (D,E) Waveforms are detected by a 50 GHz photo-diode and measured by sampling scope in persistent mode to demonstrate radio frequency arbitrary waveform generation (RF-AWG).

In the current experiments we performed line-by-line pulse shaping control for O-AWG relying only on sufficient passive spectral line stability of the mode-locked laser. We can anticipate further progress by performing similar line-by-line shaping experiments on state-of-the-art frequency-stabilized mode-locked sources, which will provide substantial advantages in long-term coherence. Current experiments are performed based on 3 ps or 400 fs pulses. Also of interest is to extend the optical bandwidth which is shaped to beyond 100 THz, a bandwidth already available from mode-locked lasers. This will require new modulator arrays

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with at least tens of thousands of pixels, a number which is well beyond current arrays specifically configured for pulse shaping (pixel counts up to 640 have been demonstrated in LCMs [28, 29], with similar level of control available from acousto-optic modulators [30]). Development of such large pulse shaping arrays should be plausible in view of the similarity to large array technologies that have been highly developed for computer displays. Finally, pulse shaping experiments to date, including those reported here, are generally constrained to generate waveforms periodic at the repetition rate of the mode-locked laser source. However, by fabricating optoelectronic or electro-optic modulator arrays which are in principle capable of being reprogrammed deep into the subnanosecond range, in the future it should be possible to change on subsequent mode-locked pulses to independent new waveform shapes, which could be stitched coherently together to yield arbitrary optical waveforms of unlimited length.

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