Optical arbitrary waveform processing of more than 100 spectral comb lines

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Pulse-shaping techniques, in which user-specified, ultrashort-pulse fields are synthesized by means of parallel manipulation of optical Fourier components, have now been widely adopted[1–6]. Mode-locked lasers producing combs of frequency-stabilized spectral lines have resulted in revolutionary advances in frequency metrology[7–11]. However, until recently, pulse shapers addressed spectral lines in groups, at low spectral resolution. Line-by-line pulse shaping[12], in which spectral lines are resolved and manipulated individually, leads to a fundamentally new regime for optical arbitrary waveform generation[13], in which the advantages of pulse shaping and of frequency combs are exploited simultaneously. Here we demonstrate programmable line-by-line shaping of more than 100 spectral lines, which constitutes a significant step in scaling towards high waveform complexity. Optical arbitrary waveform generation promises to have an impact both in optical science (allowing, for example, coherent control generalizations of comb-based time–frequency spectroscopies[10]) and in technology (enabling new truly coherent multiwavelength processing concepts for spread-spectrum lightwave communications and light detection and ranging, lidar).

Bringing the concepts of pulse shaping and frequency combs together allows the generation of waveforms with both controllable ultrafast time structure and long-term coherence. Two-photon absorption experiments in cold atoms have already shown that simple chirping of a frequency comb enables coherent control techniques to enter a new regime with natural linewidth resolution[14]. Fully general waveform control through optical arbitrary waveform generation (O-AWG) should allow more complex manipulation of quantum-state excitations in such systems. Applications in new, high-sensitivity, broadband spectroscopy techniques based on femtosecond comb enhancement cavities[15] and massively parallel readout[11] may also be anticipated, where O-AWG may allow generation of interrogation fields optimized for detection of particular species. In engineering applications, spread-spectrum[16] techniques bring well-known advantages such as multiple-access capability and covertness to communications and radar systems. In ultrafast lightwave communications, however, demonstrated spread-spectrum receiver technologies[17] only partially capture the full coherent processing power of analogous electronic systems. The long-term timing stability of optical combs now allows consideration of new receiver structures[18] that use synchronized ultrashort-pulse local oscillators for multi-line homodyne detection in lightwave systems, with sensitivity gains that scale similarly to those obtained in traditional coherent systems. Related multi-line processing schemes are also being investigated in laser radar[19]. Combining such concepts with pulse shaping or O-AWG may enable a new field of truly coherent, ultrashort-pulse spread-spectrum processing.

Previous pulse shapers operated in the group-of-lines regime, which yields waveform bursts that are isolated in time. For true O-AWG, the phases and intensities of individual spectral lines should be controlled, which leads to waveforms spanning the full time period between mode-locked pulses. Recently, line-by-line pulse shaping at ~10-GHz line spacing has been demonstrated in a free-space apparatus[12,13]; however, only a small number of spectral lines (~5) was fully controlled for O-AWG (ref. 13). Line-by-line shaping in integrated planar lightwave circuit technology has also recently been reported at line spacings between 10 and 40 GHz; however, the number of lines remains small (10–20), and waveform fidelity is compromised due to phase errors and crosstalk[20,21]. Moreover, the number of lines controlled by these devices is limited by their free spectral range, and it is difficult to extend device resolution to below 10 GHz. As the number of lines determines the degrees of freedom available for O-AWG, scaling to a larger number of spectral lines is highly desirable. In this letter we use a free-space platform to scale high-resolution, line-by-line pulse shaping to obtain independent programmable control of >100 lines at 5-GHz line spacing, while maintaining excellent waveform fidelity.

Optical frequency combs are usually generated by mode-locked lasers emitting periodic trains of ultrashort pulses. Highly stable, frequency-stabilized, mode-locked lasers, such as self-referenced Ti:sapphire lasers[22], are available at repetition rates (comb spacings) of ~1 GHz and below. Unfortunately current pulse shapers are unable to cleanly resolve such closely spaced spectral lines. Therefore, combs with larger line spacings are desired for line-by-line shaping; such combs also have the practical advantage of placing proportionally more power in individual lines. There are several alternative approaches for obtaining higher-repetition-rate combs. Harmonically mode-locked lasers are well known, but often exhibit optical frequency instabilities, which lead to serious pulse-shape noise when used for O-AWG. Examples of frequency-stabilized, harmonically mode-locked lasers have been demonstrated, but only with complicated control or compromised frequency tunability[23,24] or both. Approaches based on optical cavities are also relevant. For example, a Fabry–Pérot cavity with free spectral range set to N

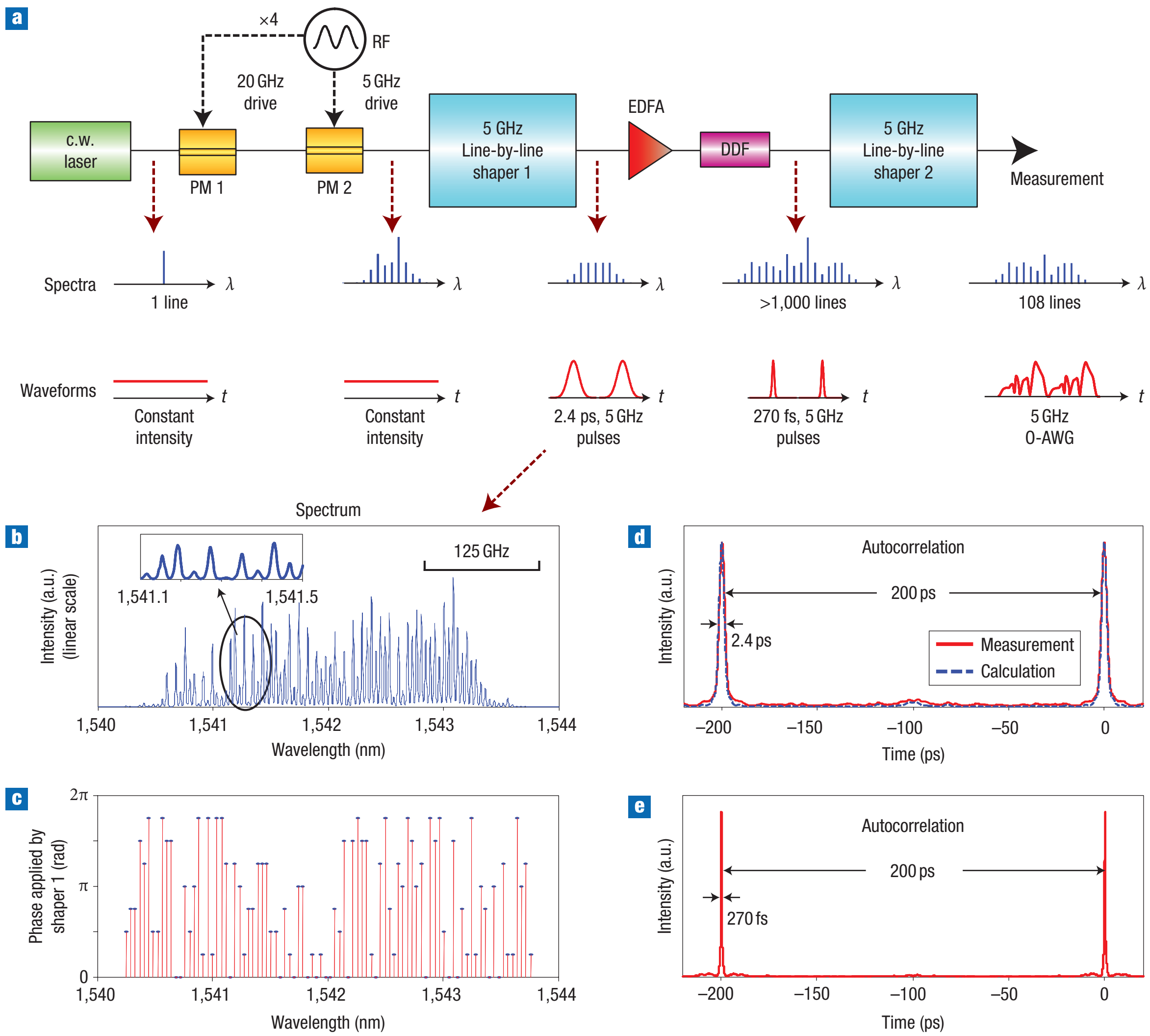

Figure 1 Experimental set up and high-rate ultrashort pulse generation. **a**, Schematic diagram. **b**, Spectrum (in linear scale) after shaper 1 with partial spectral intensity equalization to remove large spectral spikes. The discrete-line feature of the spectrum is clear in the inset figure. **c**, Spectral phases applied by shaper 1. **d**, Pulse intensity autocorrelation after shaper 1. The theoretical autocorrelation, calculated using the measured power spectrum and assuming a flat spectral phase, is also shown for comparison. **e**, Pulse intensity autocorrelation after DDF with 20.4-dBm optical power at the DDF input. PM: phase modulator; RF: radio frequency; EDFA: erbium-doped fibre amplifier.

times the comb spacing acts as a periodic transmission filter that passes only one of every N lines from an input comb source[11]. One may also generate a well-defined frequency comb by imposing a strong periodic modulation onto a continuous-wave (c.w.) laser, either without[25,26] or with[27] the aid of a cavity. This 'modulation-of-c.w.' scheme has the significant advantage that the frequency offset of individual lines is controlled by the input c.w. laser and decoupled from the pulse-generation process. We adopt such a modulation-of-c.w. source with additional spectral broadening by means of nonlinear fibre optics[27] as the input for our O-AWG demonstrations.

Figure 1a shows our experimental set up. A c.w. laser with a specified 1-kHz linewidth centred at 1,542 nm is modulated by two phase modulators, driven synchronously (with adjustable delay) by 20-GHz and 5-GHz cosine waveforms. The phase modulator driven at 20 GHz contributes to the broad bandwidth, because the generated bandwidth is proportional to the modulation frequency. The modulator driven at 5 GHz determines the comb spacing and temporal periodicity. The resulting comb is manipulated by spectral line-by-line pulse shaper 1 to convert the broadband constant-intensity waveform to a pulse train. Our fibre-coupled pulse shaper[1] incorporates a 2×128 pixel liquid-crystal modulator (LCM) array and can be programmed for independent grey-level intensity and phase control. Our experiments are the first to resolve comb lines spaced by only 5 GHz in a pulse-shaping apparatus.

Figure 1b shows the measured spectrum after shaper 1; the discrete lines making up the spectrum are clear in the inset. Figure 1c shows the discrete spectral phases applied by shaper 1 onto the individual lines, in order to convert the phase-modulated but constant-intensity field into bandwidth-limited 2.4 ps full-width at half-maximum (FWHM) pulses (intensity autocorrelation shown in Fig. 1d). Although not yet demonstrating true O-AWG, such high-rate pulse generation starting from a c.w. source is already a powerful application of line-by-line pulse shaping[28]. The 2.4-ps pulses are then amplified

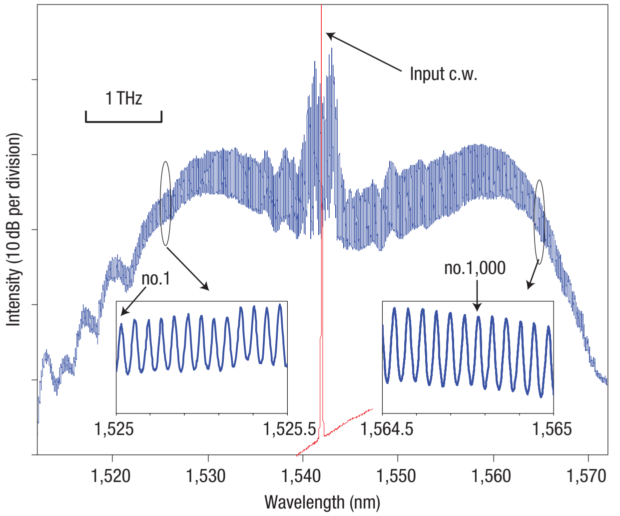

Figure 2 Generation of over 1,000 stable spectral lines starting from one single line. The input c.w. (one single line) is also shown for comparison, with 22.0-dBm optical power at the DDF input, showing over 1,000 lines between 1,525 nm and 1,565 nm. The spectral intensity dynamic range for 1,000 lines is 20 dB. If one excludes the middle 4.5-nm portion, the comb's intensity dynamic range is below 8 dB. This is important for application to line-by-line shaping so that the intensities of different comb lines may be equalized with acceptable power loss. The frequency stability of the comb is much better than the line spacing, which is critical for high-quality line-by-line pulse shaping.

by a fibre amplifier and directed into a dispersion-decreasing-fibre (DDF) soliton compressor. The interplay of self-phase modulation and dispersion in the DDF yields pulse compression to durations as short as 270 fs (Fig. 1e). Pulse compression is accompanied by strong spectral broadening. Figure 2 shows the spectrum after DDF compression obtained with slightly higher optical power coupled into the DDF. Over 1,000 lines are generated between 1,525 nm and 1,565 nm.

Such a comb, created from a single c.w. laser, is highly useful for line-by-line pulse-shaping studies. In the following O-AWG demonstrations we use a second line-by-line pulse shaper following the DDF (Fig. 1a) to select and individually manipulate a set of 108 lines centred around 1,537.5 nm and spanning a 540-GHz bandwidth. The spectrum is shown in Fig. 3a. An intensity cross-correlation measurement of the resulting pulse train, demonstrating transform-limited 1.65-ps pulses at a 5-GHz repetition rate, is also shown. In this and subsequent measurements, temporal intensity waveforms are obtained by means of cross-correlation with high-quality, pedestal-free, 1.02-ps reference pulses. Figure 3b demonstrates a simple example of line-by-line intensity control, where the LCM is programmed to block every other comb line. The resultant doubling of the comb spacing leads in the time domain to a doubling of the pulse repetition rate to 10 GHz.

We demonstrate the capability of line-by-line phase control for O-AWG by exploiting the relation $\tau(\omega) = -\partial\Psi(\omega)/\partial\omega$, where $\tau(\omega)$and $\Psi(\omega)$ are the frequency-dependent delay and spectral phase, respectively. In the simplest case we apply linear spectral phase, which results in pure delay as shown in Fig. 4. Note that the delay is scanned across the whole repetition period T (200 ps), which is only possible when individual spectral comb lines are independently manipulated. The waveforms remain clean, with only very small satellite pulses. This is further evidence that we are in the line-by-line regime. In the group-of-lines regime, a strongly stepped masking function gives rise to significant satellite pulses, with satellite intensity becoming equal to main pulse intensity at phase steps of π per pixel[29].

Figure 5 shows examples of O-AWG with very complex waveforms: each pulse is split into two pulses per period, one of which is delayed and the other of which has cubic spectral phase. Each pulse corresponds to one half of the spectrum. Figure 5a shows such an example with the two pulses still non-overlapping. The cubic spectral phase corresponding to quadratic

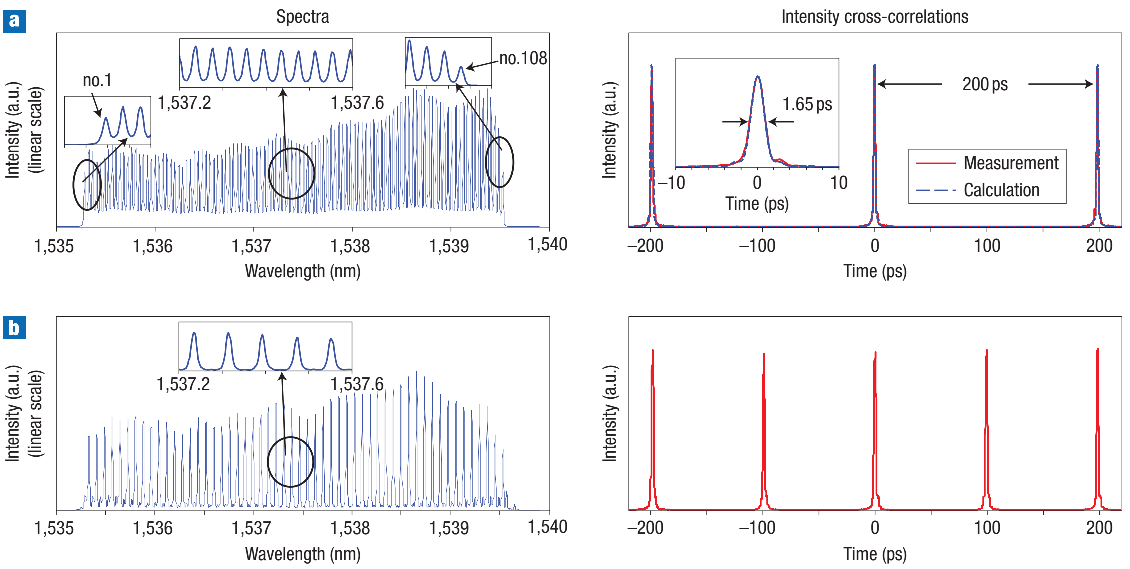

Figure 3 Spectral line-by-line shaping of 108 lines: spectral intensity control. a, Spectrum (linear scale) and intensity cross-correlation for the selected 108 lines, with 20.4-dBm optical power at the DDF input. Calculated intensity cross-correlation for transform-limited pulses (using measured spectrum and assuming zero spectral phases) is also shown for comparison, which agrees very well with the measured cross-correlation. This confirms that the pulses are transform-limited. **b**, Spectrum and intensity cross-correlation obtained by blocking every other line.

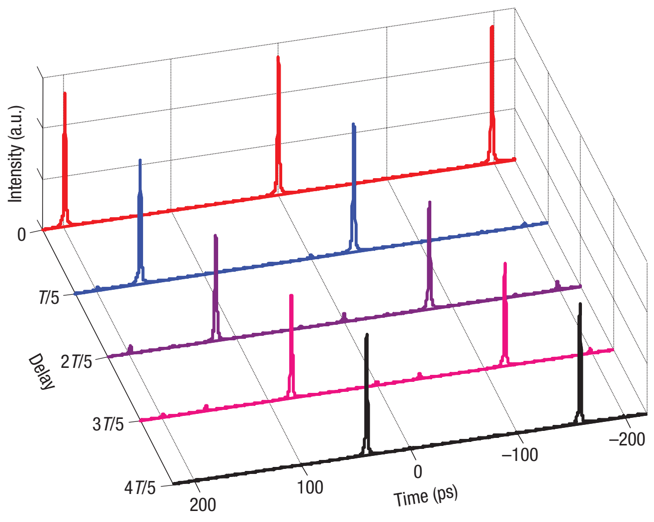

Figure 4 Spectral line-by-line shaping of 108 lines: spectral phase control. In a series of experiments, the pulse shaper applies various linear spectral phase ramps, resulting in delays proportional to the slope of the applied phase ramp. Intensity cross-correlation measurements are plotted for pulse trains delayed by 0, $T/5$, $2T/5$, $3T/5$ and $4T/5$, by applying phase changes of 0, $2\pi/5$, $4\pi/5$, $6\pi/5$ and $8\pi/5$ per pixel, respectively. Note that the delay is scanned across the whole repetition period T (200 ps), which is only possible when the individual spectral comb lines are independently manipulated.

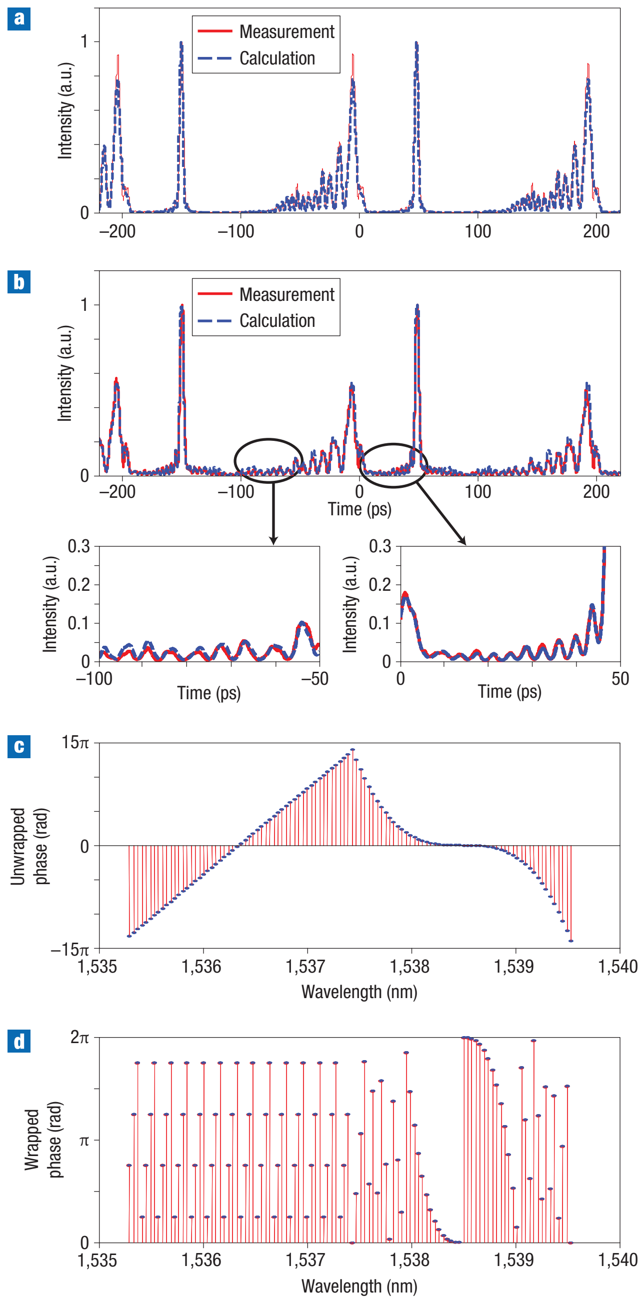

Figure 5 Line-by-line shaping of 108 lines: complex O-AWG. a, The intensity cross-correlation shows an example of O-AWG with a very complex waveform: each pulse is split into two pulses per period, one of which is delayed and the other of which has cubic spectral phase. Each pulse corresponds to one half of the spectrum. The two pulses are still temporally separated. **b**, Similar to **a**, but with a larger cubic phase on one pulse. Features of the two pulses now begin to merge, and such temporal overlap is a feature of line-by-line shaping. The agreement between measurement and calculation for both **a** and **b** shows the high fidelity achieved in these O-AWG experiments. The red solid line indicates measured intensity cross-correlation and the blue dashed line calculated intensity cross-correlation. **c**, The unwrapped spectral phases applied to shaper 2 for waveform **b**. **d**, The wrapped spectral phases applied to shaper 2 for waveform **b**.

frequency-dependent delay yields a strongly oscillatory tail in the time domain. Figure 5b shows an example with larger cubic spectral phase. Here the waveform oscillations span the whole period with 100% duty cycle, which is one of the hallmarks of line-by-line pulse shaping. To confirm O-AWG fidelity, the calculated intensity cross-correlations are also shown for comparison. The agreement is excellent everywhere, even in the lowest intensity oscillations. Figure 5c and d shows the unwrapped and wrapped discrete spectral phases applied to the 108 lines by shaper 2 in order to generate waveform Fig. 5b. The linear and cubic spectral phases are clearly visible on the respective halves of the spectrum. At some locations the phase change per pixel is π or more—again a hallmark of operation in the line-by-line regime.

One important aspect of this set up is that it is scalable in both spectral-line generation and spectral-line manipulation. Our comb generator already provides $>$1,000 frequency-stable spectral lines available for future O-AWG investigations, and further nonlinear spectral broadening should be possible. By developing pulse shapers based on novel two-dimensional spectral dispersers[30], a radically increased number of control elements should be possible, considering the large-array technologies in use for two-dimensional display applications.

METHODS

PULSE-SHAPER SET UP

Both 5-GHz line-by-line pulse shapers are fibre-coupled Fourier-transform pulse shapers constructed in a reflective geometry. A fibre-pigtailed collimator and subsequent telescope take the light out of the fibre and magnify the beam size to $\sim$18 mm in diameter on the 1,200 grooves per millimetre 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 a lens with 1,000-mm focal length. A fiberized polarization controller (PC) is used to adjust for horizontal polarization on the grating. A 2×128 pixel LCM array is placed just before the lens focal plane to independently control both the amplitude and phase of individual spectral lines. The LCM in our experiment is fully integrated with control electronics and software. The individual pixels of the LCM are arranged on 100-μm centres. The LCM layers with liquid-crystal axis configured as $\pm 45^{\circ}$ introduce phase shift and thus modify the polarizations of the input light. Combined with a polarizer, grey-level intensity control can be achieved with a maximum extinction ratio up to ~20–25 dB by the LCM. The loss of the LCM is ~0.5–1 dB. A retro-reflecting mirror leads to a double-pass geometry, with all the spectral lines recombined into a single fibre and separated from the input by means of an optical circulator. The fibre-to-fibre insertion loss of the pulse shaper is 13 dB (including circulator loss), which includes all-optical component losses as well as loss incurred in focusing back into the 9-μm fibre mode after the pulse shaper. In our set up, the two phase modulators have a total loss of 7 dB and the loss of the DDF is 2 dB. The input c.w. power is 16 dBm and optical amplifiers are added at appropriate locations to compensate for the components' loss, as mentioned above.

MEASUREMENT TECHNIQUES

In order to convert the phase-modulated c.w. to 2.4-ps short pulses as shown in Fig. 1d, spectral phases from the phase-modulated c.w. have to be strongly corrected. This requires an algorithm to determine the spectral phases. Here we adopt a simple approach assisted by line-by-line pulse shaping, maximizing the second-harmonic yield of an autocorrelator at zero delay (the yield is maximized for bandwidth-limited pulses) by adjusting the spectral phases of individual spectral lines. We use the pulse-shaper line-by-line intensity control capability to add one line at a time and line-by-line phase-control capability to optimize its phase (with $\pi/4$ phase resolution). After adding all spectral lines we keep the spectral intensity unchanged and finely optimize spectral phases in a line-by-line fashion once more. The resulting phases programmed onto the LCM are shown in Fig. 1c. We also calculate intensity autocorrelation for transform-limited pulses using the measured spectrum and assuming zero spectral phases, and compare them to measured intensity autocorrelation as shown in Fig. 1d. The agreement between them shows that the pulses are close to transform-limited and this also allows us to correctly calculate the pulsewidth.

To generate high-quality, pedestal-free reference pulses for intensity cross-correlation measurements, the DDF output is split and bandpass filtered between 1,532.2 nm and 1,540 nm by another high-resolution pulse shaper. After dispersion compensation for this spike-free spectral band, 1.02-ps transform-limited pulses are generated. A procedure similar to that for the 2.4-ps pulses above is applied to confirm the reference pulses are transform-limited.

In Fig. 3a, we calculate intensity cross-correlation for transform-limited pulses using the measured spectrum (108 spectral lines) and assuming a flat spectral phase. The agreement with the measured results again shows that the pulses are transform-limited and the pulsewidth can be correctly calculated as 1.65 ps.

All shown spectral plots are acquired with an optical spectrum analyser (OSA) at 0.01-nm resolution. To provide a more meaningful check of the frequency stability of the comb in Fig. 2, we beat various portions of the comb with a second, tunable c.w. laser. The resultant beat note is limited by the ~20-MHz linewidth of the tunable laser for all regions of the comb. This confirms that the frequency stability of the comb is much better than the line spacing, which is critical for high-quality line-by-line pulse shaping.

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References

1. Weiner, A. M. Femtosecond pulse shaping using spatial light modulators. *Rev. Sci. Instr.* **71,** 1929–1960 (2000).
2. Weiner, A. M., Leaird, D. E., Wiederrecht, G. P. & Nelson, K. A. Femtosecond pulse sequences used for optical manipulation of molecular-motion. *Science* **247,** 1317–1319 (1990).
3. Dudovich, N., Oron, D. & Silberberg, Y. Single-pulse coherently controlled nonlinear Raman spectroscopy and microscopy. *Nature* **418,** 512–514 (2002).
4. Brixner, T., Damrauer, N. H., Niklaus, P. & Gerber, G. Photoselective adaptive femtosecond quantum control in the liquid phase. *Nature* **414,** 57–60 (2001).
5. Levis, R. J., Menkir, G. M. & Rabitz, H. Selective bond dissociation and rearrangement with optimally tailored, strong-field laser pulses. *Science* **292,** 709–713 (2001).
6. Bartels, R. *et al.* Shaped-pulse optimization of coherent emission of high-harmonic soft X-rays. *Nature* **406,** 164–166 (2000).
7. Jones, D. J.*et al.* Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. *Science* **288,** 635–639 (2000).
8. Udem, T., Holzwarth, R. & Hansch, T. W. Optical frequency metrology. *Nature* **416,** 233–237 (2002).
9. Ma, L. S.*et al.* Optical frequency synthesis and comparison with uncertainty at the 10^{-19} level. *Science* **303,** 1843–1845 (2004).
10. Marian, A., Stowe, M. C., Lawall, J. R., Felint, D. & Ye, J. United time–frequency spectroscopy for dynamics and global structure. *Science* **306,** 2063–2068 (2004).
11. Diddams, S. A., Hollberg, L. & Mbele, V. Molecular fingerprinting with the resolved modes of a femtosecond laser frequency comb. *Nature* **445,** 627–630 (2007).
12. Jiang, Z., Seo, D. S., Leaird, D. E. & Weiner, A. M. Spectral line-by-line pulse shaping. *Opt. Lett.* **30,** 1557–1559 (2005).
13. Jiang, Z., Leaird, D. E. & Weiner, A. M. Line-by-line pulse shaping control for optical arbitrary waveform generation. *Opt. Express* **13,** 10431–10439 (2005).
14. Stowe, M. C., Cruz, F. C., Marian, A. & Ye, J. High resolution atomic coherent control via spectral phase manipulation of an optical frequency comb. *Phys. Rev. Lett.* **96,** 153001 (2006).
15. Thorpe, M. J., Moll, K. D., Jones, R. J., Safdi, B. & Ye, J. Broadband cavity ringdown spectroscopy for sensitive and rapid molecular detection. *Science* **311,** 1595–1599 (2006).
16. Proakis, J. G. *Digital Communications* 3rd edn (McGraw-Hill, New York, 1995).
17. Jiang, Z. *et al.* Four user, 2.5 Gb/s, spectrally coded O-CDMA system demonstration using low power nonlinear processing. *J. Lightwave Technol.* **23,** 143–158 (2005).
18. Lee, W., Izadpanah, H., Delfyett, P. J., Menendez, R. & Etemad, S. Coherent pulse detection and multi-channel coherent detection based on a single balanced homodyne receiver. *Opt. Express* **15,** 2098–2105 (2007).
19. Swann, W. C. & Newbury, N. R. Frequency-resolved coherent lidar using a femtosecond fiber laser. *Opt. Lett.* **31,** 826–828 (2006).
20. Miyamoto, D. *et al.* Waveform-controllable optical pulse generation using an optical pulse synthesizer. *IEEE Photon. Technol. Lett.* **18,** 721–723 (2006).
21. Takiguchi, K., Okamoto, K., Kominato, I., Takahashi, H. & Shibata, T. Flexible pulse waveform generation using silica-waveguide-based spectrum synthesis circuit. *Electron. Lett.* **40,** 537–538 (2004).
22. Cundiff, S. T. Phase stabilization of ultrashort optical pulses. *J. Phys. D* **35,** R43–R59 (2002).
23. Gee, S., Quinlan, F., Ozharar, S. & Delfyett, P. J. Simultaneous optical comb frequency stabilization and super-mode noise suppression of harmonically mode-locked semiconductor ring laser using an intracavity etalon. *IEEE Photon. Technol. Lett.* **17,** 199–201 (2005).
24. Yoshida, M., Yaguchi, T., Harada, S. & Nakazawa, M. A 40 GHz regeneratively and harmonically mode-locked erbium-doped fiber laser and its longitudinal-mode characteristics. *IEICE Trans. Electron.* **E87C,** 1166–1172 (2004).
25. Murata, H., Morimoto, A., Kobayashi, T. & Yamamoto, S. Optical pulse generation by electrooptic-modulation method and its application to integrated ultrashort pulse generators. *IEEE J. Sel. Top. Quant. Electron.* **6,** 1325–1331 (2000).
26. Hisatake, S., Nakase, Y., Shibuya, K. & Kobayashi, T. Generation of flat power-envelope terahertz-wide modulation sidebands from a continuous-wave laser based on an external electro-optic phase modulator. *Opt. Lett.* **30,** 777–779 (2005).
27. Imai, K., Kourogi, M. & Ohtsu, M. 30-THz span optical frequency comb generation by self-phase modulation in an optical fiber. *IEEE J. Quant. Electron.* **34,** 54–60 (1998).
28. Huang, C.-B., Jiang, Z., Leaird, D. E. & Weiner, A. M. High-rate femtosecond pulse generation via line-by-line processing of a phase-modulated CW laser frequency comb. *Electron. Lett.* **42,** 1114–1115 (2006).
29. Weiner, A. M., Leaird, D. E., Patel, J. S. & Wullert, J. R. Programmable shaping of femtosecond optical pulses by use of a 128-element liquid crystal phase modulator. *IEEE J. Quant. Electron.* **28,** 908–920 (1992).
30. Wang, S. X., Xiao, S. & Weiner, A. M. Broadband, high spectral resolution 2-D wavelength-parallel polarimeter for dense WDM systems. *Opt. Express* **13,** 9374–9380 (2005).

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Competing financial interests

The authors declare no competing financial interests.