High-rate femtosecond pulse generation via line-by-line processing of phase-modulated CW laser frequency comb

C.-B. Huang, Z. Jiang, D.E. Leaird and A.M. Weiner

Generation of a high repetition rate femtosecond pulse train by line-by-line phase and amplitude shaping applied to over 40 lines from a phase-modulated CW laser is demonstrated. Resulting pulses with FWHM duration of 2.76 ps at 9 GHz repetition rate are reported. 324 fs pulses are obtained at 9 GHz after soliton compression.

Introduction: High repetition rate optical pulses in a few picosecond range and below are playing an increasingly important role in high speed optical fibre communication systems. Such high repetition rate short pulses are routinely generated by harmonically modelocked lasers [1], but with the following limitations: (i) complicated feedback control is required; (ii) the modelocked frequency comb has limited tunability; (iii) at high repetition rates, these frequency combs often suffer from frequency instability. Alternatively, applying a strong periodic temporal phase modulation to a CW laser can generate a well-defined, broad frequency comb [2], which can support short pulse generation after appropriate control. For example, a modulated CW laser followed by singlemode fibre or other dispersion control components has been demonstrated for pulse generation [3–5]. Recently we demonstrated spectral line-by-line pulse shaping on frequency comb derived from a modulated CW laser to generate ~12 ps pulses at 9 GHz [6]. Line-by-line pulse shaping significantly extends the capability of optical processing with a modulated CW laser since the intensity and phase of all individual spectral lines can be independently controlled [7]. Very recently an arrayed waveguide grating device was used to manipulate ~20 spectral lines also generated from a modulated CW laser, resulting in pulses as short as 4.7 ps [8]. The number of spectral lines to be controlled is one of the most important parameters for all applications: (i) for short pulse generation, more spectral lines correspond to shorter pulses; (ii) generally for optical arbitrary waveform generation [9], the number of spectral lines determines the degree of complexity of the generated optical waveforms. In this Letter we report line-by-line pulse shaping on a phase-modulated CW laser to generate and control over 40 lines, resulting in 2.76 ps pulse generation at 9 GHz repetition rate. These pulses are further compressed down to 324 fs using a commercially available dispersion decreasing fibre. Compared with harmonically modelocked lasers, short pulses generated in this way have significant advantages including simple control, low cost, and a tunable and a stable optical frequency comb.

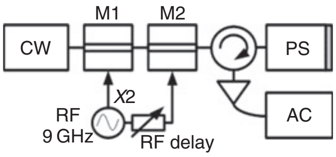

Fig. 1 *Schematic of experimental setup*

PS: reflective line-by-line pulse shaper; AC: autocorrelator; M1: low V_π phase modulator; M2: phase or intensity modulator

Experiments and results: Fig. 1 shows the schematic for our experimental setup. A CW laser with a specified linewidth of 3 kHz at 1542 nm is used as an input source to provide for a stable generated comb. A low V_π lithium niobate phase modulator (20 GHz bandwidth, V_π of ~3 V at 1 GHz) is modulated at 18 GHz (obtained by sending the 9 GHz RF signal to a ×2 RF frequency multiplier) with a driving voltage of ~4.8 V_π peak-to-peak to provide wider comb bandwidth than our previous report [6]. A second lithium niobate phase modulator (12.5 GHz bandwidth, V_π ~ 5 V at 10 GHz) is driven at 9 GHz (~1.6 V_π peak-to-peak) to obtain a comb with spacing equal to the fundamental 9 GHz driving frequency. The first phase modulator driven at 18 GHz provides a broader spectral bandwidth, while the second modulator driven at 9 GHz fills in the missing lines while doubling the number of lines. Relative RF drive phases are adjusted by tuning an RF delay line to balance the power distribution among the 18 and 9 GHz comb lines. The comb lines are manipulated by our reflective high-resolution grating-based line-by-line pulse shaper [9]. The modified comb lines are amplified via an erbium-doped fibre amplifier and sent to a non-collinear autocorrelator for pulse measurement and to an optical spectrum analyser (OSA) for optical spectrum measurement with a resolution of 0.01 nm.

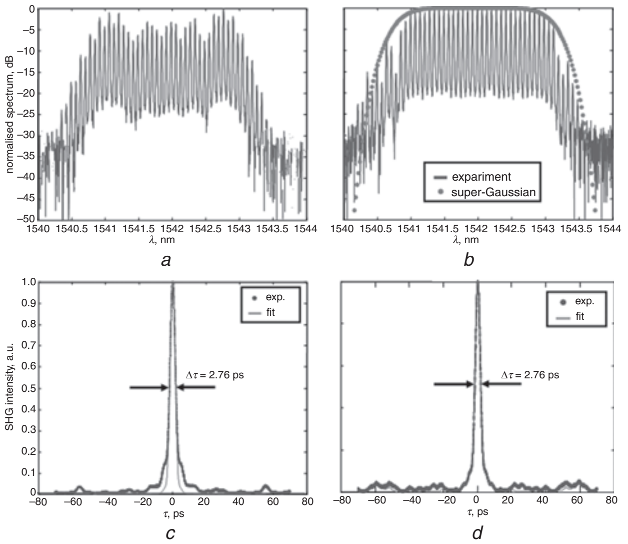

Fig. 2 *Frequency comb and generated pulses*

a Frequency comb without line-by-line control
b Intensity equalised and phase corrected frequency comb (solid); designed super-Gaussian apodisation function (dots)
c Autocorrelation trace (dotted: experimental; solid: calculated from frequency comb) of phase corrected output pulse, using two-line-beating phase measurement
d Autocorrelation trace (dotted: experimental; solid: calculated from frequency comb) of phase corrected output pulse, with phase adjusted to maximise SHG yield

Fig. 2*a* shows the frequency comb without line-by-line control. Limited in part by the RF driving power to the second phase modulator, there is ~7 dB power variation among the central 30 lines. Fig. 2*b* shows the resulting frequency comb with both intensity equalisation and phase correction from the line-by-line pulse shaper. The comb lines are shown with solid lines while the designed apodisation function (a super-Gaussian of eighth order) is shown with dots. Fig. 2*b* indicates our capability of equalising the intensities of the lines by demonstrating 28 lines within 1 dB, 35 lines within 10 dB, and 44 lines within 20 dB power levels off the peak, respectively. Relative phase differences between various pairs of spectral lines are determined by monitoring the relative temporal delays of the time-domain waveform on a sampling scope [10]. In an automated process, the line-by-line shaper is programmed to pass only two adjacent lines at a time; the resulting time-domain cosine waveforms on the sampling scope are recorded for delay calculations, and hence the relative spectral phase between each pair of two lines can be deduced. Fig. 2*c* shows normalised experimental (dotted) and theoretical (solid) autocorrelation traces for the frequency comb shown in Fig. 2*b*. The theoretical trace uses the experimental power spectrum but assumes flat spectral phase after the pulse shaper. Generated pulses have deconvolved FWHM duration of 2.76 ps (using a deconvolution factor of 1.43 appropriate for our super-Gaussian apodisation function) and time periodicity $T = 111$ ps. Although the central portions of the curves match well, we observe discrepancies in the wings which we attribute to phase errors in this experiment. In another experiment, the second phase modulator in Fig. 1 is replaced with an intensity modulator with similar specifications. The generated frequency comb is comparable to that shown in Fig. 2*b*. Autocorrelation traces of the compressed pulses obtained after phase correction are shown in Fig. 2*d*. Here the phase corrections are determined by maximising the second-harmonic generation (SHG) yield at zero delay position while adding one spectral line at a time. In this case, although the deconvolved FWHM duration is the same (2.76 ps), the agreement between the experimental (dotted) and theoretical (solid) autocorrelation, the latter again calculated assuming no phase errors, is improved.

The 2.76 ps pulse train obtained in Fig. 2*c* is sent to a 2 km dispersion decreasing fibre soliton compressor (Pritel FP-400). Fig. 3*a* shows the autocorrelation of the compressed pulse train with a repetition rate of 111 ps (9 GHz). A zoom-in of the compressed pulse is shown in the inset, indicating a FWHM of 324 fs (assuming sech^2). Fig. 3*b* depicts the compressed spectrum, indicating stable frequency comb generation with over 100 lines within 12 dB of the peak. Zoomed-in views for the compressed comb of Fig. 3*b* are shown in Fig. 3*c* (circle) and Fig. 3*d* (rectangle). Figs. 3*c* and *d* reveal excellent comb structure and quality after soliton compression even in the spectrally broadened regions. We compared the widths of the individual comb lines against OSA measurements of the initial CW linewidth and observed no broadening of individual lines, even to the very edges of the spectrum (limited by the OSA resolution).

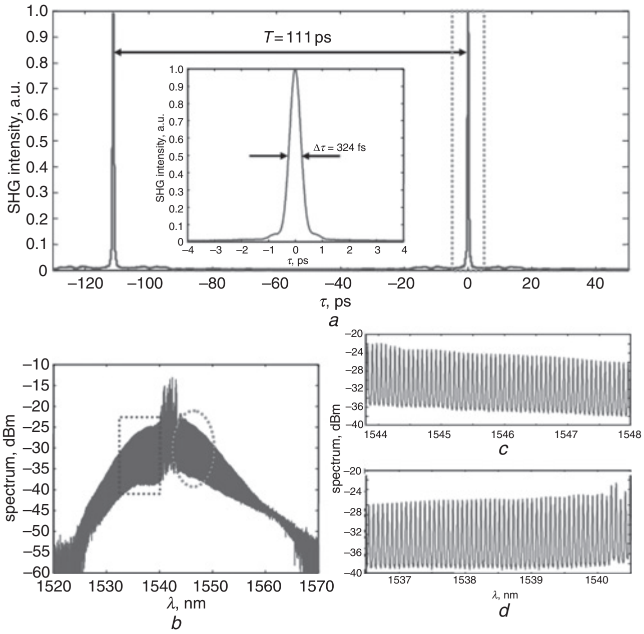

Fig. 3 *Compressed pulses and frequency comb*

a Autocorrelation showing pulse train
Inset: Zoomed in on single pulse
b Frequency comb after soliton compression
c Zoomed-in view of circle portion of *b*
d Zoomed-in view of rectangular portion of *b*

Conclusions: We have demonstrated 9 GHz, 2.76 ps pulse generation using spectral line-by-line processing of a >40 spectral line frequency comb derived from a phase-modulated CW laser. The pulses have comparable pulse width with harmonically mode-locked lasers at similar repetition rate, but with simplified control, easy spectral tunability and excellent spectral stability. The generated pulses are further compressed to 324 fs by soliton compression.

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