320/640 GHz high-quality pulse sources based on multiple four-wave mixing in highly nonlinear optical fibre

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Ultra-high repetition rate quality pulse trains have been generated in a highly nonlinear optical fibre through the compression of a dual-frequency beat-signal based on a multiple four-wave mixing process. FROG analyses show that 500 and 300 fs transform-limited pulses have been generated at 320 and 640 GHz, respectively, over a 20 nm wavelength range.

Introduction: The development of simple and flexible optical pulse train sources with high repetition rates has become of great interest for time-division multiplexing and clock generation in future ultrafast telecommunication systems [1]. Since current electronic-based and direct modulation technologies make difficult the generation of pulses at a repetition rate higher than 40 GHz, the compression of a dual-frequency beat-signal seems an attractive and efficient way to generate such high repetition rate pulse trains. The main idea is to reshape the initial sinusoidal beat-signal into well-separated pulses through a nonlinear process taking place in an optical fibre [2–7]. This reshaping can be achieved by an adiabatic compression in a dispersion decreasing fibre [2], through an adiabatic Raman amplification in a standard optical fibre [3] or in a comb-like or step-like dispersion profiled fibre [4]. However, these techniques often require a relatively complicated experimental setup and require careful management of the chromatic dispersion all along the fibre length. More recently, the multiple four-wave mixing (MFWM) technique was proposed as a very simple and efficient way to compress the initial beat-signal into well-separated pulses [6, 7]. This technique has been experimentally demonstrated through the generation of a 1.3 ps high-quality pulse train at 160 GHz [7]. In this Letter, we propose an extension of this method and demonstrate its reliability for ultra-high repetition rates through the generation of 320 and 640 GHz pulse trains in a dispersion-flat highly nonlinear optical fibre (DF-HNLF). Frequency resolved optical gating (FROG) analyses [8] show that 500 and 300 fs nearly transform-limited pulses are generated at 320 and 640 GHz in a 720 and 200 m DF-HNLF, respectively. On the other hand, the ultra-high repetition rate sources are tunable over a 20 nm wavelength range around 1555 nm.

Experimental setup: Fig. 1 shows the experimental setup used to generate the 320 and 640 GHz pulse trains. The initial beat-signal is obtained from two continuous waves delivered by two external-cavity lasers (ECL) frequency-separated by 320 or 640 GHz, respectively, and combined by a 50:50 coupler. The generated beat-signal is then amplified to the desired average power by means of an erbium-doped fibre amplifier (EDFA). A $LiNbO_3$ phase modulator is also used to increase the stimulated Brillouin scattering threshold well above the power used in our experiment. The central wavelength of the laser diodes was fixed to 1555 nm and all the injection setup is made of polarisation-maintaining (PM) fibres in order to maximise the FWM process in the compression fibre. The beat-signal is then injected into a DF-HNLF from OFS with the following parameters at 1550 nm: linear losses $\alpha = 0.72$ dB/km, dispersion $D = 0.69$ ps/nm/km, slope $S = 0.0072$ ps/nm^2/km and nonlinear coefficient $\gamma = 10.5$ W^{-1} km^{-1}. We stress that the key point here is the use of a dispersion-flat fibre with a small third-order dispersion (TOD) which is the main limiting effect of the pulse quality at ultra-high repetition rates [9]. The DF-HNLF output field was finally characterised by means of an optical spectrum analyser (OSA), a background-free second-harmonic-generation autocorrelator and a FROG setup [7, 8].

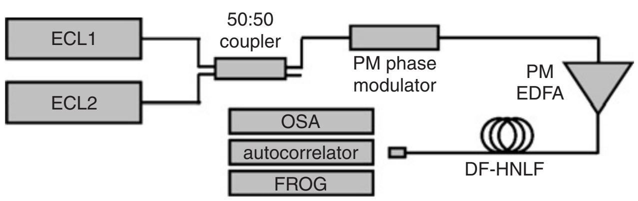

Fig. 1 *Experimental setup*

320 GHz results: Fig. 2 represents the experimental results obtained at 320 GHz for a fibre length of 720 m. Fig. 2*a* shows the retrieved intensity and phase profiles. The retrieval error, defined as the rms between the experimental and retrieved FROG traces, was found to be 3.3×10^{-3}. The intensity profile (solid line) shows very well separated pulses with remarkably no pedestal. Maximum compression is obtained for an input average power of 150 mW leading to a full width at half maximum (FWHM) of 500 fs, in excellent agreement with numerical simulations (circles). The retrieved phase (dashed line) is almost constant over the compressed pulses, indicating that pulses are nearly transform-limited. Moreover, phase difference between neighbouring pulses is π, also in good agreement with numerical predictions. The degree of tunability of the 320 GHz source has also been evaluated by studying the variation of the FWHM against the central wavelength. Fig. 2*b* shows that a tunability of more than 20 nm is achieved around 1555 nm. Let us note that the main limitation of the wavelength tunability comes essentially from the fact that the two pumps have to be in the spectral bandwidth of our EDFA. Finally, as shown in Figs. 2*c* and *d*, the autocorrelation and spectrum both derived from the retrieved pulse train (circles) are in excellent agreement with the independent direct experimental measurements (solid lines), thus confirming the reliability of the experimental FROG setup.

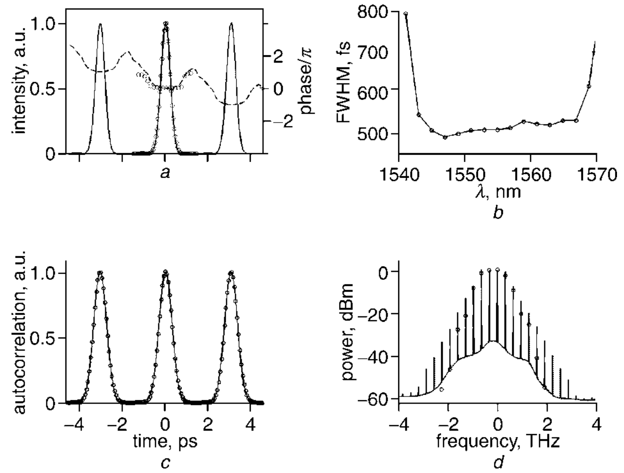

Fig. 2 *FROG results for 320 GHz pulse train*

a Retrieved intensity profile (solid line), retrieved phase (dashed line), simulation results (circles)
b Output pulse width against wavelength
c Autocorrelation function, experimentally measured (solid line) and calculated from retrieved intensity and phase (circles)
d Optical spectrum, experimentally measured (solid line) and calculated from retrieved intensity and phase (circles)

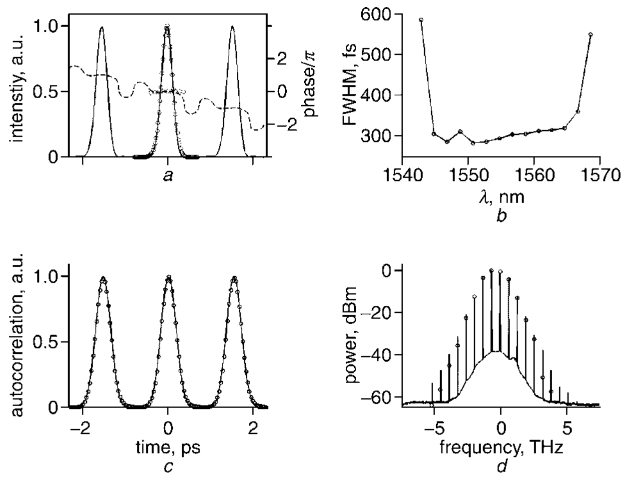

Fig. 3 *As Fig. 2 but for 640 GHz pulse train*

640 GHz results: Fig. 3 represents the experimental results obtained at 640 GHz for a DF-HNLF length of 200 m. These results present the same features as those of Fig. 2. The FROG retrieval error is 2.4×10^{-3}. The retrieved intensity profile (Fig. 3*a*, solid line) shows very well separated pulses with an FWHM of 300 fs obtained for an input average power of 450 mW, in excellent agreement with numerical simulations (circles). Moreover, the retrieved phase (dashed line) displays a π-jump between neighbouring pulses and is almost constant over the compressed pulses, indicating that they are nearly transform-limited. Fig. 3*b* stresses a wavelength tunability of more than 20 nm around 1555 nm. Finally, Figs. 3*c* and *d* show excellent agreement between the retrieved (circles) and the measured (solid lines) autocorrelation and spectrum, respectively.

Conclusions: We have extended the multiple four-wave mixing compression technique for the generation of 320 and 640 GHz pulse trains. To achieve such ultra-high repetition rates, we have used a highly nonlinear optical fibre with a small dispersion slope to avoid large asymmetry in the pulse profile due to the TOD effect. FROG characterisations finally show that 500 and 300 fs nearly-transform-limited pulses are generated at 320 and 640 GHz, respectively. We believe that such a powerful and simple technique could find a large number of applications for time-division multiplexing or clock generation in future ultrafast telecommunication systems.

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