GigaHertz to TeraHertz Ultrashort Pulse Sources at 1555 nm

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Abstract *We experimentally study the generation of ultrashort pulses through multiple four wave-mixing in optical fibers. Well-separated transform-limited Gaussian pulses are generated at repetition rates ranging from 20 GHz to 1 THz around 1555 nm.*

Introduction

Laser sources emitting ultrashort pulses at very high repetition rate are now widely employed in several domains of physics, such as clock generation, ultrahigh-capacity optical communication systems or waveform measurements based on optical sampling. The most common technique for generating high repetition rate sources is based on the external amplitude modulation of a continuous laser source. However this method is limited by the electronic bandwidth and presently, the repetition rate can actually not exceed 80 GHz. To overcome this limitation, a host of all-optical techniques have been proposed, allowing the generation of pulse trains at very high repetition rates (100 GHz and more) [1].

One of these all-optical methods is based on the nonlinear compression of a sinusoidal beat-signal in an anomalous dispersion optical fiber through a multiple four wave-mixing (FWM) process [2]. This technique combines both stability and simplicity of the experimental set-up and has already been exploited to generate high quality pulse trains at repetition rates as high as 640 GHz [3]. In this work, we exploit the reliability of this efficient and attractive method to generate well-separated transform-limited Gaussian pulses at repetition rates ranging from 20 GHz to 1 THz and having a wavelength tunability over a 20-nm range.

Description of the experimental set-up

Figure 1 illustrates the experimental set-up used to generate all the GHz/THz pulse trains around 1555 nm. An initial beat-signal is obtained from the superposition of two continuous waves (cw) emitted by tunable external-cavity laser diodes. The central wavelength of the two cws was first fixed to 1555 nm but can be shifted over the entire Erbium-doped fiber amplifier (EDFA) bandwidth. Note that repetition rate of the pulse source is simply adjusted by detuning the frequency-separation between the two cws. The generated beat-signal is then amplified to the desired average power by means of an EDFA. A phase modulator was also used to increase the Stimulated Brillouin threshold well above the average power used in the experiments. After nonlinear compression in the optical fiber, the output pulse trains were characterized by means of an OSA, a background-free second-harmonic generation (SHG) autocorrelator and a SHG frequency resolved optical gating (FROG) set-up.

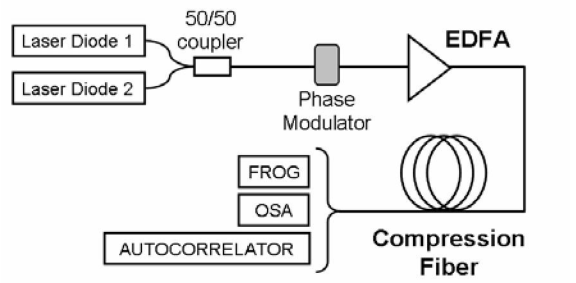

Fig. 1 : *Experimental set-up.*

Theoretical approach

Compression of the beat-signal in the optical fiber was numerically and analytically investigated using the usual nonlinear Schrödinger equation. Quite remarkably, we found that the initial beat-signal evolves towards a well-separated chirp-free Gaussian-pulse train during its propagation through the optical fiber only if the fiber length L_{opt} and the input average power P_{opt} obey the following relations :

$$L_{opt} = \frac{4\pi^2}{14|\beta_2|\Omega^2} \quad (1a)$$

$$P_{opt} = \frac{16|\beta_2|\Omega^2}{4\gamma\pi^2}, \quad (1b)$$

where β_2 is the fiber dispersion, γ the nonlinear coefficient and Ω the repetition rate of the pulse train. Note that these very simple rules allow the designers to have an easy and direct conception of any repetition rate pulse source, simply from the dispersion and nonlinearity parameters of the compression fiber.

Experimental results

All the pulse sources described below which repetition rate ranging from 20 GHz to 1 THz were designed thanks to expressions (1). Table I sums up all the parameters of the fibers as well as the optimum input average power used for each source.

TABLE I

Repetition rate	D (ps/nm/km)	γ ($W^{-1}km^{-1}$)	L (m)	P (mW)
20 GHz	17	1.3	7900	130
40 GHz	17	1.3	2100	380
80 GHz	6	1.7	1420	500
160 GHz	1	1.7	1000	525
320 GHz	0.69	10.5	720	150
640 GHz	0.69	10.5	200	450
1 THz	0.69	10.5	90	1300

Figure 2 represents typical experimental results obtained for the 1-THz pulse source. The nonlinear compression fiber was a 90-m long *OFS* DF-HNLF (Dispersion Flat Highly nonlinear Fiber) and the optimum average power was measured to 1,3 W. Fig. 2(a) shows the measured SHG-FROG trace at the output of the HNLF fiber whereas Fig. 2(b) represents the corresponding retrieved intensity. The intensity profile shows very well-separated Gaussian pulses with a 170-fs full width at half maximum (FWHM). The phase is also constant along the pulses indicating that they are nearly transform-limited while the output spectrum, Fig. 2(c), exhibits multiple generated FWM sidebands, characteristic of the compression process. Finally, Fig. 2(d) illustrates that a tunability of more than 20 nm can be achieved around 1555 nm which is essentially limited by the fact that the two pumps have to be in the spectral bandwidth of our EDFA.

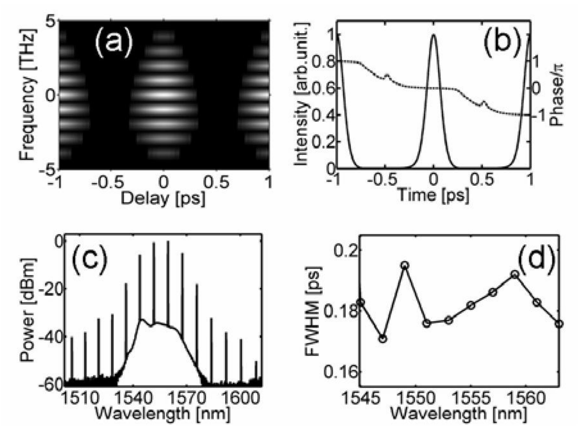

Fig. 2 *: Experimental results for the 1-THz pulse source **(a)** Experimental FROG trace. **(b)** Retrieved intensity and phase profile **(c)** Measured spectrum **(d)** FWHM as a function of central wavelength.*

Figure 3 illustrates two other results obtained for a repetition rate of 80 GHz, Fig. 3(a), and 320 GHz, Fig. 3(b). In each case, retrieved intensity and phase profiles show that very well-separated transform-limited pulses have been generated, proving the reliability of our method.

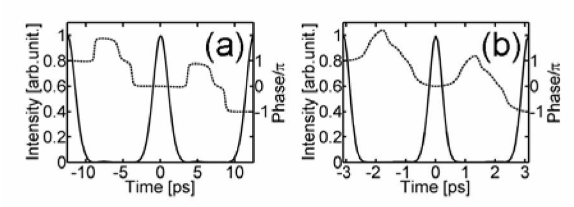

Fig. 3 *: Retrieved intensity and phase profiles of the 80-GHz **(a)** and 320-GHz **(b)** pulse source.*

Figure 4 represents the evolution of the pulse width as a function of the repetition rate of the source. At 20 GHz, the FWHM is close to 11 ps whereas it approaches 170 fs for a bit rate of 1 THz. Finally, for all repetition rates, we measured a duty cycle nearly equal to 5 and an extinction ratio between peak power and interpulse background better than 20 dB, stressing the high quality of the pulse source thus generated.

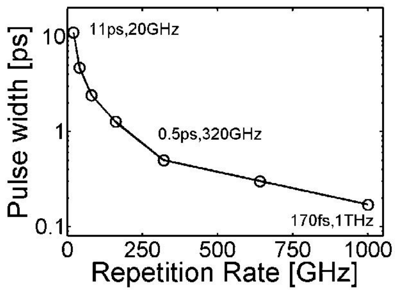

Fig. 4 *: Evolution of the FWHM pulse source as a function of repetition rate.*

Conclusion

In summary, we have numerically and experimentally studied the generation of pico- and femto-second pulse trains at very-high repetition rates using a highly efficient nonlinear compression technique. This method is based on the gradual transformation of a sinusoidal beat-signal into Gaussian pulses through a multiple four wave mixing process taking place into an anomalous dispersive optical fiber. The reliability of this simple and powerful technique was demonstrated for the generation of high-quality transform-limited Gaussian pulses from 20 GHz to 1 THz over a 20-nm wavelength range around 1555 nm. Finally, we provide simple design rules to obtain both the optimum fiber length and the optimum input average power as a function of the repetition rate of the source and fiber parameters. We believe that such simple rules and experimental efficiency could find a large number of applications in the field of optics.

References

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3. J. Fatome et al, Electron. Lett. 41 (2005), 1294-1295.