Wavelength conversion and temporal compression of pulse train using dispersion oscillating fibre

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The generation of a picosecond pulse train is demonstrated taking advantage of the cross-gain occurring in a dispersion-oscillating fibre. The resulting frequency-converted signal is detuned by more than 20 nm from the pump and can be temporally compressed by a factor of 2 compared with the input sinusoidal pump wave.

Introduction: To alleviate the bandwidth limitations of optoelectronic modulations or the complexity of modelocked fibre lasers, the generation of high-repetition pulse sources has strongly benefited in the past from various strategies relying on the use of the Kerr effect of silica to convert a sinusoidal signal into a train of well-separated optical pulses. For example, multiple four-wave mixing in anomalous dispersion fibres or nonlinear reshaping in normally dispersive fibres followed by a linear compensating segment are two efficient ways to achieve such a transformation [1]. A more recently demonstrated technique relies on the nonlinear reshaping of a sinusoidal beating into a train of Akhmediev breathers [2]. A very different approach takes advantage of the parametric gain experienced by a continuous seed under sinusoidal pumping: the exponential and instantaneous gain leads to a very high level of amplification in the most intense areas of the sinusoidal profile of the pump, whereas the signal remains quasi-unamplified around its temporal minima. The efficiency of this approach has been demonstrated in a parametric amplifier [3] based on a fibre with constant longitudinal anomalous dispersion.

In this Letter, we show that other parametric processes can also be suitable for frequency conversion and pulse train generation applications. More specifically, we demonstrate that it is possible to take advantage of newly developed fibres having a longitudinally oscillating dispersion profile. Given the periodic variation of their properties, such fibres exhibit new gain regions that we exploit here [4, 5].

Experimental setup: The experimental setup that has been developed is illustrated in Fig. 1. The pump is made of a continuous wave at 1540 nm delivered by a distributed feedback laser that is intensity modulated by a niobate lithium modulator driven by a sinusoidal clock operating at a frequency of 10 GHz. The sinusoidal pump waveform is first amplified and then sliced by a second optical modulator to decrease the repetition rate of the source down to 2.5 GHz. An optical bandpass filter (OBPF) is then used to prevent excessive build-up of amplified spontaneous emission before the light is launched into a high-power erbium-doped fibre amplifier with an output power of 28 dBm (corresponding to a peak power of 6 W). The pump is combined by a 90/10 coupler with a seed signal at 1563.2 nm delivered by a second external cavity laser that is amplified in order to reach the mW level. Next, the pump and signal are launched in a 400 m-long dispersion oscillating fibre (DOF) with the following parameters: spatial period of the sinusoidal dispersion profile $\Lambda = 20$ m, peak-to-peak amplitude of the dispersion change $D_{Amp} = 1.2$ ps/km/nm, a normal average value of dispersion $D_{Av} = -0.4$ ps/km/nm at the pump wavelength and nonlinear coefficient of 10 W^{-1}/km^{-1}. More details on the index profile and drawing techniques of this fibre can be found in [6, 7]. At the output of the fibre, an OBPF is used to isolate the generated idler (wavelength 1518 nm). The idler temporal and spectral profiles are monitored on a 70 GHz photodiode associated with a high-speed-sampling oscilloscope (bandwidth 70 GHz) and on an optical spectral analyser.

Spectral analysis: We have plotted in Fig. 2 the initial spectrum of the pump wave launched into the fibre (dotted dark grey line). From the spectrum recorded at the output of the fibre in the absence of filtering and seed signal, we can clearly point out the growth of resonant gain sidebands from the spontaneous amplified emission (grey solid line) [8, 9]. These sidebands exhibit a gain in excess of 40 dB, and are detuned by more than 20 nm from the pump that lies in the normal dispersion regime of the DOF [6]. However, these sidebands are narrower than the ones typically observed in anomalous fibres, which may limit the tunability of the conversion efficiency as well as the spectral extent of the pulse that can be processed. From the output spectrum, we can also note the generation of additional regularly spaced sidebands, originating from multiple four-wave mixing between the pump and the resonant sidebands [6]. A continuous signal seed within the resonant gain bandwidth at 1563.2 nm undergoes both amplification as well as spectral broadening through parametric-gain and cross-phase modulation, respectively.

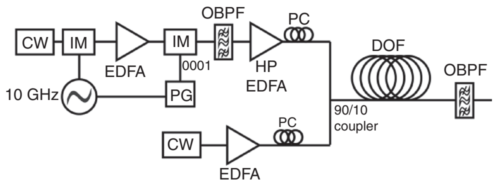

Fig. 1 *Experimental setup*

CW: continuous-wave laser; IM: intensity modulator; EDFA: erbium-doped fibre amplifier (HP: high power); PG: pattern generator; OBPF: optical bandpass filter; PC: polarisation controller; DOF: dispersion oscillating fibre

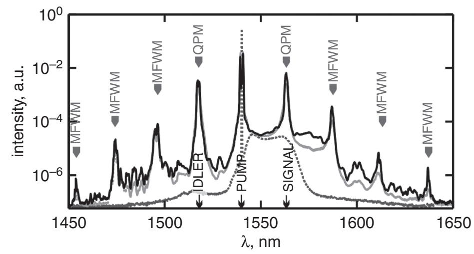

Fig. 2 *Optical spectra of pump wave (dotted dark grey line) compared with spectra at output of DOF with and without seeds (black and light grey solid line, respectively)*

Gain sidebands linked to resonant gain are designated by QPM, whereas those linked to multiple four-wave mixing between pump and resonant sidebands are marked MFWM

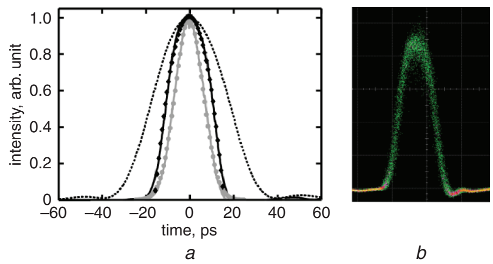

Fig. 3 *Temporal intensity profiles (Fig. 3a) of pump (dashed black line) compared with profile of idler wave obtained (after OBPF) for amplifier running in unsaturated and saturated regimes (solid grey and black lines, respectively). Full grey circles and full black diamonds represent a Gaussian and parabolic fits of temporal intensity profile, respectively. Oscilloscope trace in persistent mode of idler wave for amplifier running in saturated regime (Fig. 3b)*

Temporal analysis: The temporal profile of the pump pulse is plotted in Fig. 3*a* and is compared with the idler wave obtained after propagation in the DOF and optical bandpass filtering. Both saturated and unsaturated regimes are investigated and in both cases a background-free pulse train with significant temporal narrowing is observed (with temporal durations of 21 and 15 ps, respectively, i.e. temporal compression factors of 1.7 and 2.4 compared with the initial duration of 37 ps). As we shall see, the regime of amplification, as well as the central wavelength of the signal, also influences the temporal waveform of the idler [10]. Indeed, the idler pulse intensity profile is close to a Gaussian shape (full grey circles) in the unsaturated amplification, whereas the idler pulse becomes parabolic-like in the saturated regime (full black diamonds). Let us also point out that the regime of operation crucially affects the stability of the converted pulse train, so that a trade-off between short duration and stability was experimentally found based on an empirical basis. Indeed, due to the exponential amplification experienced in the unsaturated regime, the intensity noise of the pump converts into major fluctuations of the amplified waves [11]. On the contrary, saturation of the amplifier efficiently limits those detrimental shot-to-shot fluctuations as illustrated in Fig. 3*b*. Let us finally add that due to the cross-phase modulation induced by the pump on the signal, the recorded pulses are not transform limited (the corresponding time-bandwidth product is equal to 4).

Conclusion: We have demonstrated in this Letter that the wavelength-conversion/generation of GHz trains of picosecond pulses through parametric gain is not restricted to the usual case of parametric amplification in a fibre with anomalous dispersion. Using a pump lying in the normal dispersion regime is also possible, thanks to a resonant quasi-phase matched process induced by the periodic sinusoidal modulation of the dispersion profile. When compared with the other possible schemes such as phase matching induced by the fourth-order dispersion coefficient, we expect that our proposed technique is more tolerant with respect to the longitudinal stochastic fluctuations of the fibre properties. We also believe that improvements in the drawing process may enable in the future shorter spatial periods of dispersion oscillation, so that the larger wavelength shifts would become feasible.

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One or more of the Figures in this Letter are available in colour online.

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