Regeneratively modelocked dual-wavelength soliton-pulse fibre-optical parametric oscillator in C- and L-bands

J. Lasri, P. Devgan, R. Tang, V.S. Grigoryan, W.L. Kath and P. Kumar

A self-starting regeneratively modelocked fibre-optical parametric oscillator that utilises four-wave mixing in a highly nonlinear fibre together with intra-cavity soliton formation to generate tunable, dual-wavelength picosecond pulses at 10 GHz rate simultaneously in the C- and L-bands, is demonstrated, believably for the first time. An electroabsorption-modulator-based optoelectronic oscillator is used as an ultra-low-jitter pump source that enables, by means of direct feedback injection locking, a significant reduction of the timing jitter of the obtained pulses.

Introduction: Many applications, particularly in high-speed optical communication systems, require tunable, multiwavelength, short optical pulses at high repetition rates and with low timing jitter. Among many potential sources, actively modelocked erbium fibre lasers (ML-EFLs) are attractive because they can produce single- or multiple-wavelength transform-limited (TL) soliton pulses with relatively short duration and low timing jitter in the 1550 nm spectral region [1–3]. In such fibre lasers, however, the tunability is limited to the erbium gain band. Moreover, modelocking is achieved with an electro-optic modulator, which significantly increases the loss inside the cavity. A modelocked (also called synchronously pumped) fibre-optical parametric oscillator (ML-FOPO), on the other hand, is beneficial for generating short optical pulses because the parametric process, which occurs through four-wave mixing (FWM) in fibres, in addition to providing the gain and fast modelocking mechanism [4], also leads to simultaneous production of multiple pulse streams (the oscillating signal, idler, and other cascaded FWM products) with tunability over wavelength ranges that may not be available otherwise [5].

In this Letter we report the first self-starting, 10 GHz-rate, dual-wavelength, regeneratively modelocked FOPO (RML-FOPO) that combines intra-cavity soliton formation with FWM in a highly nonlinear fibre (HNLF) to generate picosecond-duration, nearly TL, soliton pulses simultaneously in both the C- and L-bands. To maintain modelocked operation of the FOPO in the presence of environmentally-induced cavity-length fluctuations, we synchronise the FOPO with its pump source by direct feedback injection locking. Such regenerative feedback allows stable modelocked operation with significant reduction of the pulses' timing jitter.

Experimental setup: A schematic diagram for the RML-FOPO is shown in Fig. 1. It comprises a 1 km-long HNLF, a tunable optical-bandpass filter (OBF) with 3 nm-wide passband, a tunable optical delay line (ODL), and an isolator. The HNLF has a zero-dispersion wavelength at 1558 nm, dispersion slope of 0.018 ps/nm^2/km, and nonlinearity coefficient of $\sim$9 W^{-1}km^{-1}. The remaining 15 m fibre in the FOPO loop is standard SMF-28, which provides intra-cavity dispersion compensation. Two 5% couplers in the cavity provide the outputs. The first is placed after the HNLF to monitor the generated FWM products and to extract, using a 0.7 nm-passband tunable OBF, the generated idler pulses in the L-band. The second is located in the middle of the 15 m SMF span to extract the TL soliton (signal) pulses in the C-band. The 15 ps-wide, ultra-low-jitter (68 fs in the 100 Hz to 10 MHz range) pump pulses are obtained from a self-starting electroabsorption-modulator (EAM)-based optoelectronic oscillator (OEO) [6]. The pump is coupled into the FOPO via a 50/50 coupler. Regenerative modelocking is accomplished by feeding back a portion of the output pulse stream from the FOPO (via a high-speed photodetector) into the OEO.

Results and discussion: Upon pumping and adjusting the cavity length by means of the ODL, harmonic modelocking of the FOPO is obtained. Fig. 2*a* shows the optical spectrum recorded after the HNLF when the OBF was set near 1548 nm and the average pump power was 225 mW ($\sim$1.5 W peak power). The dashed trace shows the below-threshold case, where harmonic modelocking is not established; only the pump spectrum is observed along with spontaneous parametric fluorescence. The solid trace shows the modelocked spectrum, which is composed of peaks due to the pump, the oscillating signal at 1548 nm, the generated idler at 1572 nm, and cascaded FWM products. Figs. 2*b* and *c* show the autocorrelation traces and the optical spectra of the signal and idler pulses, respectively. The full width at half maximum (FWHM) of the signal's (idler's) autocorrelation trace is 6.0 ps (9.1 ps), yielding a 3.9 ps (5.9 ps) pulse duration for a sech^2 intensity profile. The signal's (idler's) optical spectrum has an FWHM of 0.71 nm (0.52 nm), yielding a time-bandwidth product of 0.35 (0.38) that is close to the transform limit. The left and right insets in Fig. 2*a* show the intra-cavity peak powers of the signal and idler pulses, respectively, against pump peak power coupled into the HNLF. An oscillation threshold is clearly seen when the pump peak power exceeds 1.25 W, where the signal gain per pass begins to exceed the 7 dB round-trip loss in the cavity. To obtain the peak power of the signal and idler pulses, we derived their width using the method described in [7], which allows extraction of the temporal profile of the pulses from autocorrelation measurements. Against pump power, the signal and idler pulse widths varied in the 2.7–3.9 ps and 5.2–5.9 ps ranges, respectively. The internal-efficiency slope, defined as the ratio of the signal (idler) peak power at the output of the HNLF to the pump peak power coupled into the HNLF, was calculated to be $\sim$50% ($\sim$30%). Differences between the measured parameters for the signal and idler pulse streams are due to their mutually conjugate nature and the different extraction points from the ML-FOPO cavity together with different passband characteristics of the OBFs. Fig. 3 shows tunability range for the signal and idler pulses for a fixed pump peak power of 1.5 W. By tuning the intracavity OBF from 1542 to 1555 nm the signal wavelength was varied in the C-band, while the idler was simultaneously tuned in the L-band from 1578 to 1565 nm. We note that use of HNLF with flattened dispersion profile would lead to wider tunability for the signal and idler pulses.

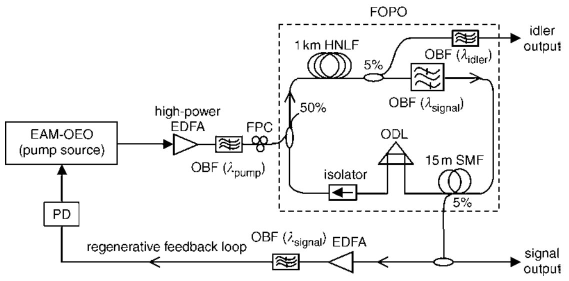

Fig. 1 *Experimental setup of RML-FOPO*

EAM-OEO: electroabsorption-modulator-based optoelectronic oscillator; EDFA: erbium-doped fibre amplifier; PD: photodiode; FPC: fibre polarisation controller

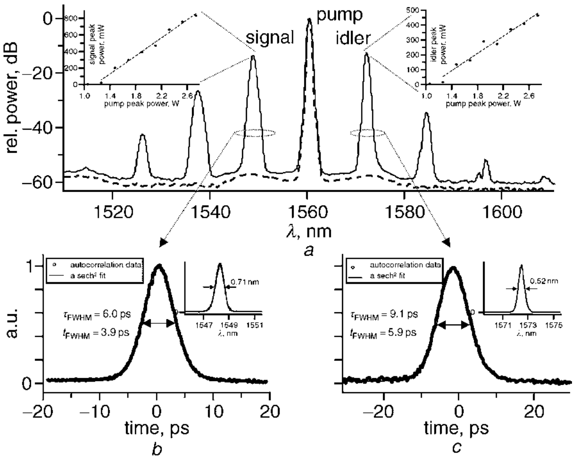

Fig. 2 *Optical spectrum after HNLF; and time autocorrelations and spectra of signal and idler pulses for 1.3 W peak pump power*

a Optical spectrum after HNLF
------ FOPO not modelocked
—— FOPO modelocked
Left and right insets: Peak power of output signal and idler pulses, respectively, against pump peak power
b and *c* Time autocorrelations and spectra (insets) of signal and idler pulses, respectively, for 1.3 W peak pump power

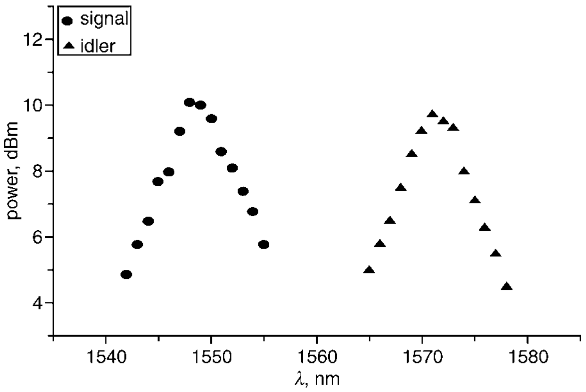

Fig. 3 *Measured tunability range for signal and idler pulses*

The RMS timing jitter of the FOPO output was determined by analysing the spectral content (in the 100 Hz to 10 MHz integration band) of the phase noise of the detected signal harmonics (10–40 GHz). Without regenerative feedback, the timing jitter was measured to be 0.71 ps. With regenerative feedback, however, the timing-jitter reduced to 0.23 ps.

Conclusions: We have developed a self-starting, dual-wavelength, modelocked fibre-optical parametric oscillator capable of efficiently generating picosecond soliton pulses at 10 GHz rate simultaneously in the C- and L-bands. We have demonstrated direct feedback injection locking of the self-starting optoelectronic oscillator used for pumping the parametric oscillator to achieve regeneratively modelocked operation with more than threefold reduction in timing jitter of the output pulses.

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