Erratum

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Author's correction

The author list should have appeared as follows:

Lim, H., Ilday, F.O., Buckley, J., Chong, A., and Wise F.W.

Fibre-based source of femtosecond pulses tunable from 1.0 to 1.3 μm

H. Lim, J. Buckley, A. Chong and F.W. Wise

Tunable short-pulse generation in the spectral range 1030–1330 nm with an all-fibre source is demonstrated. A compact system with a femtosecond Yb fibre oscillator and a photonic crystal fibre relies on the soliton self-frequency shift to cover the wavelengths of primary interest to biological/biomedical imaging deep in tissue. Continuous tuning of <100 fs pulses with energies in the range 0.1–0.5 nJ is accomplished by adjusting the pulse energy.

Introduction: The soliton self-frequency shift (SSFS) is a phenomenon in which a soliton with a sufficiently broad spectrum undergoes a downshift from intrapulse Raman scattering. Since the first observation [1] and the theoretical explanation [2] of the SSFS in 1986, the process has been studied intensively, mostly in the context of a convenient facilitator of short pulse wavelength tuning.

Advances in fibre technology, notably photonic crystal fibre (PCF) [3], have renewed attention in this process. The novel properties of PCF include: 1) the possibility of anomalous group-velocity dispersion (GVD) at wavelengths between ~0.7 and 1.3 μm [4], and 2) the enhanced nonlinear coefficient, $\gamma = n_2/A_{eff}$ (n_2 is the nonlinear refractive index and A_{eff} is the effective area). The first feature allows solitons to form (an obvious prerequisite to the SSFS) at wavelengths below 1.3 μm. A few groups have demonstrated the use of this process in PCF to implement tunable femtosecond pulse sources, with either bulk solid state lasers [5–7] or a Yb fibre amplifier [8]. These instruments will be valuable, as they provide access to wavelengths desired for biological and medical applications, among others. The second property of PCF enables the design of compact devices, because nonlinear effects become appreciable at much lower powers in PCF than in ordinary single-mode fibres (SMF). For example, a substantial spectral downshift of few nJ pulses was obtained in a PCF of length as short as 15 cm [5], which is orders of magnitude shorter than the SMF required for a similar effect. However, the benefit of highly-nonlinear PCF is not fully exploited in the previous demonstrations [6–8], where the use of either a bulk solid-state source of femtosecond pulses or a complicated Yb-doped PCF amplifier increases substantially the size and expense of the tunable source. A natural solution would be to use a femtosecond fibre laser as the first stage, but compact, integrated devices capable of supplying the required pulse energies at wavelengths near 1 μm have only recently been demonstrated.

Here we report the generation of Raman solitons from a recently developed 1 μm fibre laser that routinely generates a few nJ energy and 100 fs pulses [9]. Sub-100 fs Raman solitons are generated typically between 1.03 and 1.33 μm by changing the input pulse energy. In particular, at 1.33 μm, stable pulses of 68 fs duration and 0.5 nJ energy are obtained. The femtosecond device is based on a fibre oscillator only, and thus one can envision an all-fibre route to a compact, tunable source in the near-infrared range.

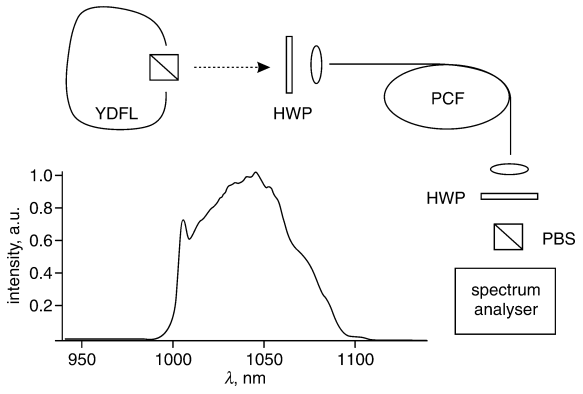

Fig. 1 *Experimental configuration and typical output spectrum from ytterbium-doped fibre laser (YDFL)*

HWP: half-wave plate, PBS: polarising beam splitter
For details of Yb fibre oscillator see [9]

Experimental results: The experimental setup is depicted in Fig. 1. The pump pulses are produced from a stretched-pulse modelocked ytterbium fibre laser [9]. The laser is self-starting owing to the unidirectional ring cavity. Nonlinear polarisation evolution (NPE) initiates and stabilises the modelocked operation. The net cavity GVD is near zero. The linearly-polarised output rejected by the polarising beam splitter consists of positively-chirped pulses with approximately 2 nJ energy at 60 MHz repetition rate. The pulse duration is approximately 2 ps. A commercially-available PCF is used in the experiment (1.5 m length, 2 μm core, 1.4 μm pitch and 0.7 average pitch-to-hole size ratio, supplied by Crystal-Fibre A/S). The GVD of the fibre goes through zero near 780 nm and is anomalous at 1030 nm, with a value of −40 ps^2/km. The PCF is intrinsically birefringent, with beat length (measured by a spectral transmission method) of ~1 mm. The birefringence is sufficiently large to prevent nonlinear coupling between the orthogonal polarisations [10]. About 30% of the incident pulse is coupled into the PCF. We measured the pulse duration with an interferometric autocorrelator based on two-photon absorption in a GaAs diode.

During the first stage of propagation in the PCF, the positive chirp on the incident pulse is compensated. This is followed by soliton compression, and finally the frequency shift occurs. As a guide to the experiments, numerical simulations of the pulse propagation were performed. The scalar nonlinear Schrödinger equation that governs the propagation includes terms for the Raman response in addition to the third-order dispersion (TOD) of the PCF. Inclusion of the complete Raman gain spectrum is essential for an accurate description of the process [7, 11]; however, we were satisfied to use a simplified model [12, 5] and found that it produced qualitative and semi-quantitative agreement with the experimental results.

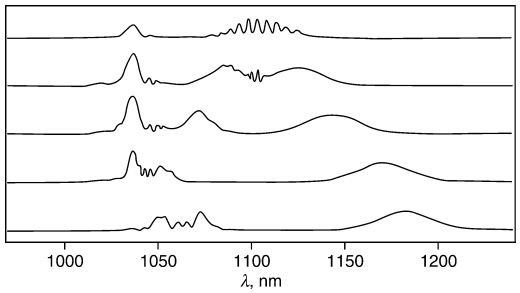

Fig. 2 *Wavelength tuning with input polarisation control*

Spectra were recorded with a Rees spectrum analyser with 0.4 nm resolution

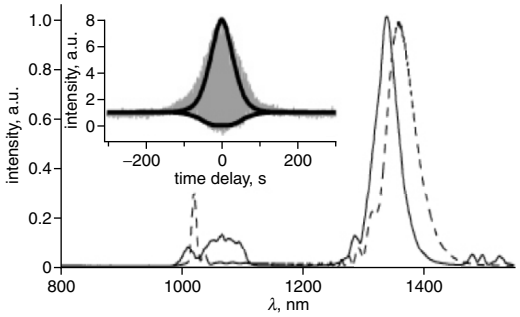

Fig. 3 *Measured spectrum of pulse at 1.33 μm and result from numerical simulation*

– – – – measured
——— numerical simulation

Spectra were recorded with an Agilent 86140B spectrum analyzer with 0.06 nm resolution
Inset: measured interferometric autocorrelation and the zero-phase Fourier transform from the measured power spectrum

Illustrated in Fig. 2 are typical traces of the pulses that are generated around 1.1 μm. The two Stokes components correspond to Raman solitons polarised along the two orthogonal axes of polarisation. Depending on the orientation of the linearly-polarised input, Raman solitons are excited along the axes with different energies, and therefore they exhibit different wavelength shifts. A polariser placed at the output end of the PCF projects the two pulses onto a single linear polarisation. The modulation on the top spectrum (Fig. 2) is from interference of the two pulses at the polariser. Alternately, tuning can be accomplished by attenuating the input pulse, or by varying the length of the PCF.

With higher pulse energy from the oscillator along a single polarisation axis of the PCF, maximum tuning range is achieved. As an example, tuning to 1.33 μm is presented (Fig. 3). After a long-pass filter to remove residual pump energy at 1030 nm, average power of the Raman soliton is approximately 25 mW (0.5 nJ pulse energy). The autocorrelation measurement (inset) indicates a full-width at half-maximum pulse duration of 68 fs (assuming a $sech^2$ profile), which is ~25% larger than the duration retrieved from the zero-phase Fourier transform (solid line, inset) of the measured power spectrum (1150 ~1570 nm). We attribute the small deviation from transform limit to pulse broadening in bulk optical elements after the PCF. The spectrum of the Raman soliton agrees well with the numerical calculation (Fig. 3, dashed). As a secondary point, we note that the generated Raman solitons confirm the high quality of the pulses produced by the fibre oscillator [9].

The ability to tune to even longer wavelengths would be desirable. Further tuning is limited presently by a strong absorption at 1.4 μm that originates in OH^- ions in the PCF. 'Water-free' synthesis of SMF has been demonstrated and it is reasonable to expect that analogous PCF will be available in the future. Such fibres would be likely to allow the technique presented here to reach much longer wavelengths.

Conclusions: We have demonstrated a compact femtosecond pulse source that is tunable from 1.03 to 1.33 μm. To our knowledge this is the first demonstration of Raman solitons in this near-infrared range, produced directly with a femtosecond fibre oscillator. The source is stable and reliable, with the pulse characteristics (energy, wavelength, and duration) sustained over hours. We anticipate that the presented scheme will find numerous applications, particularly in the realm of biological and medical imaging.

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