Generation from continuous waves of frequency combs with large overall bandwidth and tunable central wavelength

B. Barviau, C. Finot, J. Fatome and G. Millot

It is experimentally shown that the combined effects of Raman soliton self-frequency shift with either compression of a sinusoidal beating or modulation instability leads to the generation of frequency combs with a spectral width higher than 100 nm and a central frequency shifted towards higher wavelengths.

Introduction: Generation of new optical frequencies in the 1.6–1.7 µm range is of great interest for a large variety of applications. In this context, starting from erbium-fibre based devices emitting in the 1.5 µm range, several techniques based on nonlinear effects in optical fibres could be used, such as wavelength conversion through four-wave mixing [1], generation of cascaded Raman Stokes waves [2] or spectral slicing of supercontinuums [3]. However, those various approaches can suffer from serious drawbacks. Indeed, in the first case, the pump energy is equally spread between lower and higher wavelengths, thus leading to non-optimal efficiency for the 1.6–1.7 µm range. For Raman emission, a restricted number of frequencies is allowed owing to the large and fixed spectral spacing resulting from the Raman gain of the propagation medium, e.g. silica or gas filling a hollow-core photonic bandgap fibre. On the other hand, when using a supercontinuum, initial energy is continuously spread out over a broad spectral range, thus leading to a relatively low spectral power density.

In this Letter, we experimentally evidence an alternative approach exploiting the soliton self-frequency shift (SSFS) in order to tune the central frequency of two continuous or quasi-continuous waves [4]. We first explain the principle of the method before detailing the experimental device and the results obtained by two different alternatives.

Method principle: An attractive and flexible solution for shifting the wavelength of an optical wave is the use of intrapulse Raman scattering under which the central frequency of a wave is progressively shifted towards lower frequencies [5]. However, since this process is only efficient for ultra-short pulses, it does not seem *a priori* suitable when continuous or quasi-continuous (nanosecond pulses) waves are considered. So, the issue was to find an easy way to convert two continuous waves into a train of subpicosecond pulses. Two approaches are then feasible. The first one is based on the compression of a sinusoidal beat signal into a train of Gaussian transform-limited ultra-short pulses [6]. For this technique, energy is initially equally divided between two wavelengths and harmonics develop through a multiple four-wave mixing process. In the second approach, energy is mainly concentrated on the pump wavelength, while a seed signal stimulates the generation of harmonics via induced modulation instability [7]. Once the train of ultra-short pulses is achieved, then it will be subject to the SSFS process. In both approaches, we generate at the fibre output a frequency comb with a central wavelength shifted towards higher wavelengths. The frequency spacing between the harmonics can be tuned by simply changing the frequency separation between the two initial continuous waves. It should be noted that the conversion of quasi-continuous waves into an ultra-short pulse train and the SSFS effect proceed in a single anomalous dispersive optical fibre.

Experimental setup: The general idea to combine modulation instability and SSFS was numerically suggested in 1990 by Mamyshev *et al.* [4] with the aim of filtering pedestals of ultra-short pulses. However, to date, no experimental implementation has been carried out. We detail here the two experimental setups that we have implemented. The first approach (see Fig. 1) is based on the sinusoidal beat signal created by two continuous laser diodes spaced by 9 nm (external cavity lasers (ECL)). An acousto-optic modulator makes it possible to slice long pulses (350 ns) which are then amplified by an erbium-doped fibre amplifier (EDFA) with an average power of 1 W. A phase modulator is used to avoid deleterious effects of Brillouin backscattering [6]. The continuous waves are then injected into a 900 m highly nonlinear fibre (HNLF – nonlinearity 10 W^{-1} · km^{-1}) with low anomalous dispersion (0.7 ps · nm^{-1} · km^{-1}), reduced dispersion slope of 0.0072 ps · nm^{-2} · km^{-1} and attenuation of 0.7 dB · km^{-1}. Our second approach (see Fig. 2) relies on the use of 10 ns flat top pump pulses delivered by an erbium-doped fibre laser. The pulse profile is super-Gaussian (Fig. 2*b*) and thus has the advantage of not presenting any notable rebound [8]. A peak power of 17 W enables us to use a shorter segment of dispersion-flattened HNLF (90 m – same parameters as the fibre used in the first approach) as well as a seed pulse shifted by 25.5 nm. Note that, for both approaches, in order to optimise the efficiency of the temporal compression of the initial modulation, we have used linearly polarised sources and carefully aligned the polarisations at the HNLF input.

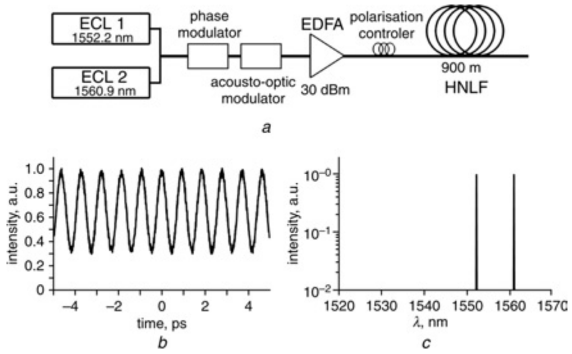

Fig. 1 *Method based on nonlinear compression of sinusoidal beating*

a Experimental setup
b Autocorrelation signal of initial beating
c Initial spectrum

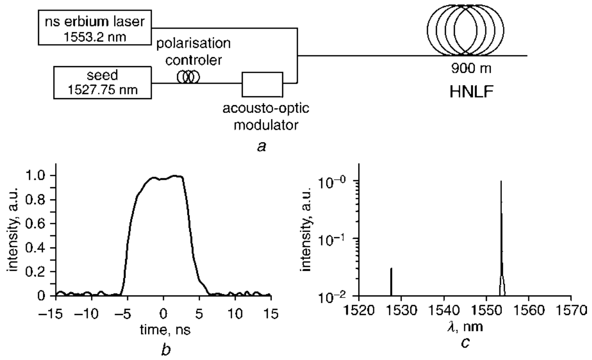

Fig. 2 *Method relying on induced modulation instability*

a Experimental setup
b Intensity profile of nanosecond initial pulse recorded on high-speed oscilloscope
c Initial spectrum

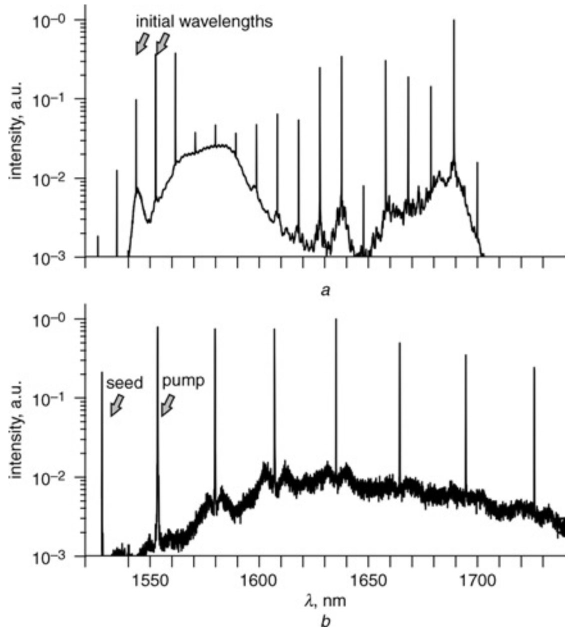

Fig. 3 *Experimental spectrum obtained after propagation in HNLF*

a Method based on nonlinear compression of sinusoidal beating
b Method relying on induced modulation instability

Results: The experimental results are presented in Fig. 3. In the case of the sinusoidal beat compression, 24 harmonics are generated between 1500 and 1710 nm, regularly spaced by 9 nm (Fig. 3*a*). In the approach based on induced modulation instability, 11 harmonics are obtained between 1450 and 1750 nm, regularly spaced by 25.5 nm (Fig. 3*b*). The signal-to-noise ratio measured with an optical spectrum analyser is higher than 17 dB. Thanks to the large spectral period of the comb, a single harmonic could be easily extracted with a bandpass filter in order to generate a frequency-shifted continuous (or quasi-continuous) wave. In both methods, the spectrum is shifted via intrapulse Raman effect towards higher wavelengths (dominating wavelengths of 1689 and 1635 nm for the first and second method, respectively). The central wavelengths of the combs can be easily tuned by adjusting both initial frequency separation and powers launched into the HNLF.

Numerical integration of the generalised nonlinear Schrödinger equation which governs the wave propagation has highlighted that the major effects limiting the performance achievable by both techniques are the third-order dispersion and the initial signal-to-noise ratio. Moreover, build up of Raman amplified spontaneous emission can also partly explain the degradation of the output optical signal-to-noise ratio.

Conclusions: We have experimentally studied the combined effects of the Raman soliton self-frequency shift with either beat signal compression or induced modulation instability. Two fully-fibered setups, relying exclusively on commercially available devices, have enabled us to generate frequency combs with a spectral width higher than 100 nm and a central frequency shifted towards higher wavelengths. The use of an additional contra-propagative Raman pumping would make it possible to extend the observed spectral shift [9].

31 May 2007
Electronics Letters online no: 20071608
doi: 10.1049/el:20071608

B. Barviau, C. Finot, J. Fatome and G. Millot (*Institut Carnot de Bourgogne, UMR 5209 CNRS-Université de Bourgogne, 9 Av. A. Savary, BP 47 870, F-21078, DIJON Cedex, France*)

E-mail: gmillot@u-bourgogne.fr

References

1 Nowak, G.A., Kao, Y.H., Xiao, T.J., Islam, M.N., and Nolan, D.A.: 'Low-power high-efficiency wavelength conversion based on modulational instability in high-nonlinearity fiber', *Opt. Lett.*, 1998, **23**, pp. 936–938

2 Benabid, F., Knight, J.C., and Russell, P.S.: 'Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber', *Science*, 2002, **298**, pp. 399–402

3 Abeeluck, A.K., and Headley, C.: 'Continuous-wave pumping in the anomalous- and normal-dispersion regimes of nonlinear fibers for supercontinuum generation', *Opt. Lett.*, 2005, **30**, pp. 61–63

4 Mamyshev, P.V., Chernikov, S.V., Dianov, E.M., and Prokhorov, A.M.: 'Generation of a high-repetition-rate train of praticaly noninteractiong solitons by using the induced modulational instability and Raman self-scattering effects', *Opt. Lett.*, 1990, **15**, pp. 1365–1367

5 Gordon, J.P.: 'Theory of the soliton self-frequency shift', *Opt. Lett.*, 1986, **11**, pp. 662–664

6 Fatome, J., Pitois, S., and Millot, G.: '20-GHz-to-1-THz repetition rate pulse sources based on multiple four-wave mixing in optical fibers', *IEEE J. Quantum Electron.*, 2006, **42**, pp. 1038–1046

7 Tai, K., Hasegawa, A., and Tomita, A.: 'Observation of modulational instability in optical fibers', *Phys. Rev. Lett.*, 1986, **56**, pp. 135–138

8 Kuzin, E.A., Mendoza-Vazquez, S., Gutierrez, J., Ibarra-Escamilla, B., Haus, J.W., and Roja-Laguna, R.: 'Intra-pulse Raman frequency shift versus conventional Stokes generation of diode laser pulses in optical fibers', *Opt. Express*, 2005, **13**, pp. 3388–3396

9 Chesnut, D.A., and Taylor, J.R.: 'Soliton self-frequency shift in highly nonlinear fiber with extension by external Raman pumping', *Opt. Lett.*, 2003, **28**, pp. 2512–2514