Introduction: The generation of optical solitons in single-mode optical fibres has primarily relied on the direct injection of radiation into the fibre at a power level which corresponds to, or is greater than, the fundamental soliton power. However, it is possible to generate high-energy solitons from quantum noise through stimulated Raman scattering in gases, as first proposed theoretically by Vidyadhar and Sercel and subsequently demonstrated experimentally in the pulsed regime by Dianov et al. and by Guerra-Neto et al. for CW mode-locked Nd:YAG laser operated at 1.32μm.

For this, sufficiently intense radiation at a frequency ω2 generates stimulated Raman radiation at ω1 = ω2 − ω1 = 440 cm⁻¹ for SiO₂-based fibres, which lies in the region of negative group velocity dispersion. The generation of optical solitons at the Stokes frequency is attributed to the combined effects of self-phase modulation, negative group velocity dispersion and stimulated Raman scattering amplification. The broad Raman gain bandwidth should in principle be capable of supporting pulses of <100fs.

In this letter we report on the generation of pulses of 130fs duration at 1.5μm using a single-pass generation technique that is similar to that used in the second Stokes band, but pumped by a CW mode-locked Nd:YAG laser at 1.32μm. The solitons at the second Stokes wavelength (1.5μm) were generated through a cascade Raman soliton-like shaping and amplification process.

Experiment: The experimental configuration for the soliton was a basic minimum. A CW mode-locked Nd:YAG laser at 1.32μm was used as the fundamental source of radiation. This laser generated 100-ps pulses at a 100 MHz repetition rate with an average power of 2 W (300 W peak). The pump radiation was coupled into and out of the fibre using a fibre optics polarization-maintaining microscope objective. The silica-based fibre was non-polarisation-preserving, single-mode at 1.32μm, and of a multiple index design, with a central graded core of 7 μm diameter. In the spectral region 1.2-1.65 μm the loss was less than 0.4 dB/km, with an exception of 5.2 dB/km around 1.39 μm where the loss rose to 2.4 dB/km. The low OH content was essential to prevent attenuation of the first Stokes band. The fibre was tapered to have its dispersion minimum at 1.46 μm, which ensured an efficient cascade Raman generation and negative group velocity dispersion in the required 1.5μm regime. Dispersion values of 5 pm/nm/km and -2.5 pm/nm/km were exhibited at 1.4μm and 1.5μm, respectively. Pumping at 1.32μm, the first Stokes band occurs around 1.4μm in the region of positive group velocity dispersion. For a walk-off of 100ps between pump and Raman, a fibre length of 290 μm is required; hence efficient conversion to the first Stokes band is possible, which can subsequently act as the pump source in cascade for the generation of the second Stokes component. A scanning autocorrelator incorporating a 2-mm-thick LiIO₂ crystal in an interferometric free-space configuration was used to measure the generated pulsewidths. Spectra were recorded using a 1.4μm spectrophotometer with an operating resolution of 5nm in conjunction with a Ge photodiode.

Fig. 1: Spectra of pulses in a 600μm fibre at average pump (1.3μm) powers of (a) 450 mW and (b) 550 mW

A low-intensity signal at 1.5μm was observed, indicating the inefficiency of the generation of the second Stokes band in cascade for an average power of 450 mW. At this power level and wavelength no subpicosecond pulses were recorded on the autocorrelator. For a pump power of approximately 530 mW (53 mW peak), however, a very intense broad Raman band centred on 1.5μm was observed as shown in Fig. 1b. Direct measurement showed that 30% of the total power coupled out of the fibre resided in the second Stokes band, corresponding to an average power in the band of ~160 mW. As the second Stokes band was in the negative group velocity dispersion regime, the radiation at 1.5μm experienced a soliton-like shaping mechanism.

The autocorrelation trace of Fig. 2 shows 130fs soliton pulses generated at 1.5μm. However, as can be seen from this Figure, the soliton pulses were riding on a pedestal corresponding to 4.5% of the autocorrelation intensity. As measured from streak camera records, the pedestal extended for 30ps; hence approximately 30% of the average energy resided in the soliton, corresponding to a peak power of 3kW. The presence of the dispersive nonsoliton pedestal is attributed to the chirp inherent in the Raman pulse from cross-phase modulation between the pump and Stokes pulses. The use of the intensity-dependent polarisation rotation effect in fibres should allow the removal of these pedestals.

It should also be noted that the bandwidth at 1.5μm was approximately 74 nm wide, which, assuming transform-limited operation, is capable of supporting soliton pulsewidths of >21fs. The measured pulsewidth of 130fs showed that clearly not all the bandwidth was associated with the soliton, indicative of an inherent chirp, and as a consequence the pulses on propagation in fibres would be expected to broaden temporally, with an associated increase in the dispersive pedestal.

Conclusions: We have demonstrated, for the first time to our knowledge, the generation of pulses as short as 130fs with 3kW peak power at 1.5μm in a single span of single-mode, dispersion-shifted optical fibre. For this single-pass case, high pump powers were required (>55 W peak) to generate stable pulses. In a synchronously pumped dye laser configuration, much less pump power would be necessary for the generation of equivalent duration and powered pulses. This is at present under active investigation in our laboratories.
Fig. 2 Noncollinear autocorrelation trace of 10 fs pulses generated around 1.5 μm through s-polarized cascaded Raman soliton-like shaping mechanism in 40 m of fiber.

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