Quasi-CW purely rotational stimulated Raman scattering in H_2-filled hollow-core photonic crystal fibre

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Abstract: We report on low-threshold stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fibre using low-energy nanosecond pulses. Different purely rotational Raman transitions have been observed. The Raman gain dependence on pulse duration over long interaction lengths is also investigated.

1. Introduction

Hollow-core photonic crystal fibres (HC-PCF) can be extremely efficient stimulated Raman scattering (SRS) converters when filled with a Raman-active medium [1]. Their dramatically improved performance compared to any other conventional gas-based SRS converters is due to the very long interaction lengths and high intensities achievable with a HC-PCF. The first work on hydrogen-filled HC-PCF concentrated on the generation of vibrational SRS wavelengths guided in a fibre with a broad transmission spectrum. Recently [2], the use of an ultra-low loss photonic bandgap (PBG) HC-PCF with a narrower transmission window led to the generation of purely rotational SRS bands with extremely low pulse energy threshold (3nJ) and a high conversion efficiency (92%). The generated rotational SRS components can be used for such applications as pulse synthesis and compression.

In the present experiment a similar technique is used for quasi-CW SRS using long (up to 35ns) low-energy (~100nJ) pulses. The pulse width is varied in order to study the behaviour of the SRS gain for different time domains. This variation in the timescales involved together with the long interaction length available (15m in this case, made possible by the use of a low-loss PBG HC-PCF) open up a new and interesting regime for the study of the SRS process.

2. Experimental setup

The experimental setup is shown in Fig. 1(a). A *Q*-switched Nd:YVO_4 laser at 1047nm was used as the pump source. The repetition frequency of the laser could be varied from 1Hz – 50kHz. This also varied the pulse width from around 6ns – 34ns respectively. A half-wave plate on a rotating stage and a polarising beamsplitter were used to control the power of the pump beam, while a rotating quarter-wave plate was used to vary the pump polarisation from linear to circular. The pump beam was coupled into 15m of a hollow-core photonic crystal fibre (HC-PCF) filled with H_2 gas at 10bar pressure in the manner described in [1]. The input power was monitored just before the coupling lens and so was the power of the back-reflected light. The output spectrum was recorded on an optical spectrum analyser while the power and temporal profiles of the different spectral components were recorded with photodetectors by using interference filters to select different spectral bands.

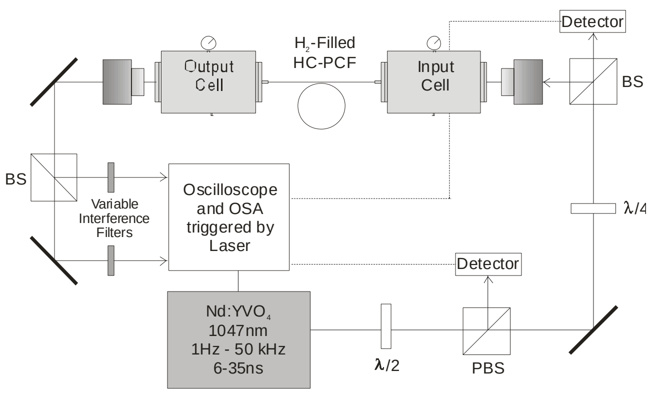

Fig. 1. Experimental setup

The transmission spectrum of the PBG HC-PCF used in the experiment was in the region 950-1200nm. The lowest loss occurs at 1060nm and is about 75dB/km. All the vibrational bands (Raman shift 4155cm^{-1}) generated in the SRS process lie outside the transmission spectrum of the fibre and will therefore be suppressed. Consequently only rotational SRS frequencies (Raman shifts 587 cm^{-1} and 354 cm^{-1}) can be guided in the fibre core. This overcomes the problem of efficiently generating purely rotational SRS spectra, which would otherwise require the use of focusing techniques to suppress the vibrational SRS bands [3,4].

3. Results

In the recorded output spectra [Fig. 2(a)] a maximum of eight different SRS lines were observed and identified. They are due to both the $S_{00}(1)$ rotational transition of ortho-hydrogen and the $S_0(0)$ rotational transition of para-hydrogen. In both cases there is a transfer of two units of angular momentum to the hydrogen molecule, which in turns make a transition from the J to the $J + 2$ state. For ortho-hydrogen $J = 1$ and for para-hydrogen $J = 0$ but, since their ratio is usually 3:1 respectively, the $S_{00}(0)$ transition is usually hard to observe. However due to the high efficiency of the hydrogen-filled HC-PCF as a Raman amplifier this transition was routinely observed in the experiments.

Near-field patterns of the transmitted modes at the end-face of the fibre were taken at the pump, first and second Stokes wavelengths. The modal profiles of the pump and first Stokes were those of the fundamental mode of the fibre, while the second-order Stokes mode had an annular profile.

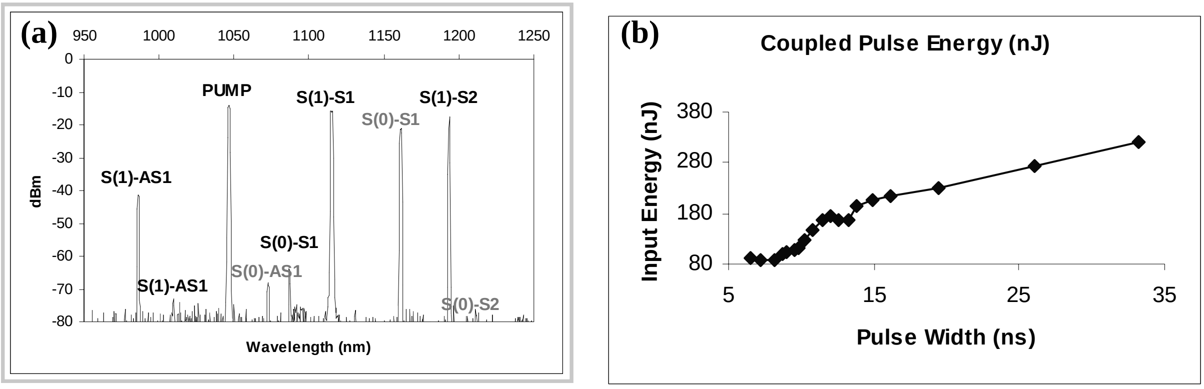

Fig. 2. (a) Output spectrum of the hydrogen- filled HC-PCF pumped by 7ns pulses at 1047nm. The SRS peaks marked with light grey are pumped by the 1st Stokes band at 1115nm. (b) Energy threshold versus pump pulse width for the generation of the first-order Stokes component. Theoretical calculations show a transition from transient to steady state around 10-15ns as was observed experimentally.

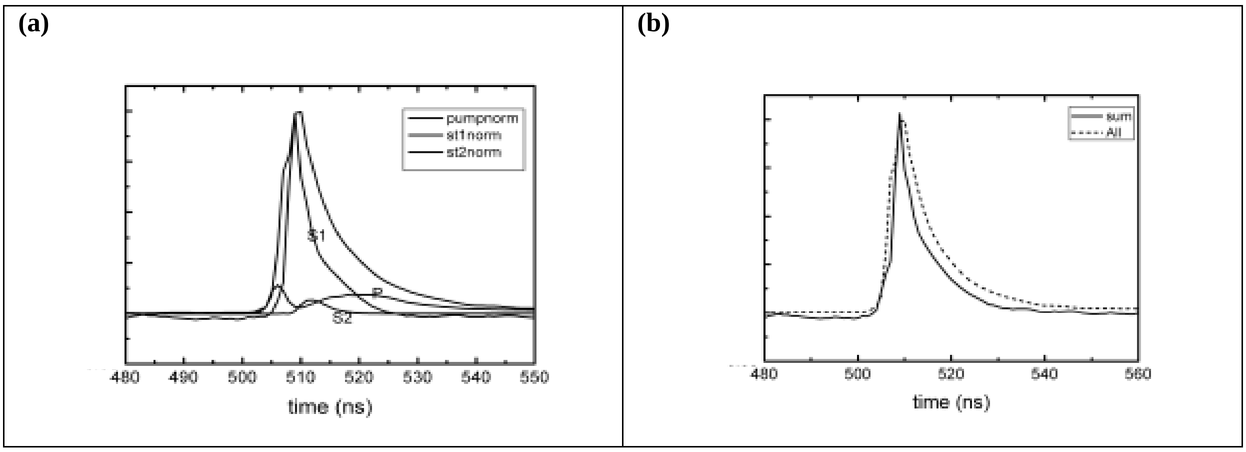

Fig. 3. (a) Pulse shapes of the co-propagating pulses at the pump (P), first (S1) and second Stokes (S2) frequencies together with the total output pulse at the output of the 15m-long HC-PCF. The pulse intensities have been normalised to account for variations in detector sensitivity with wavelength. (b) Comparison between the sum of the normalised SRS pulses from (a) and the recorded output pulse shape.

Extremely low threshold generation of the first $S_{00}(1)$ Stokes band was achieved (< 90 nJ) for the shorter pulses used). This is about five orders of magnitude lower than in previous publications [3,4]. The evolution of the SRS gain with pump pulse width was also examined. This was done by recording the threshold for the first $S_0(1)$ Stokes band for pulse widths in the range 6-34ns [Fig. 2(b)]. Using the transient SRS theory [5] we found that at the pump power level at threshold (~10W) there should be a transition from transient to steady state in the region between 10-15ns. This would mean a transition from a quadratic dependence of threshold energy on time to a linear one. Such a transition could explain the acquired plot of Fig. 2(a).

The temporal profile of the total output pulse was recorded [Fig 3(a)]. Using interference filters the pulses at the first-order, second-order Stokes and pump frequencies were also recorded. The peak of the first-order Stokes pulse occurs at the tail of the pump pulse due to the gain accumulation as the pump pulse builds up [6] and accounts for the dip in the profile of the transmitted pump pulse. The shape of the total output pulse was the result of the co-propagating pulses at the original frequency and the ones generated in the SRS process. This was experimentally demonstrated by almost exactly reconstructing the total output pulse by the constituent pulses [Fig. 3(b)].

4. References

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