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1.9 µm Coherent Source Generation in Hydrogen-Filled Hollow Core Fiber by Stimulated Raman Scattering

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Abstract: A 1.9 µm fiber gas Raman converter is reported for the first time. A low loss hydrogen-filled hollow-core negative curvature fiber is pumped with a 1064 nm microchip laser, generating a 1907 nm output with quantum conversion efficiency >48%.

OCIS codes: (060.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (140.3550) Lasers, Raman; (140.4130) Molecular gas lasers.

1. Introduction

The nonlinear optical process of Stimulated Raman scattering (SRS) in gases is an effective method for generating new wavelengths with narrow linewidth. Historically, SRS has relied on high pump power, and has sometimes offered low conversion efficiency to the desired wavelength, and additional generation of other unwanted lines. Gas-filled hollow core photonic crystal fiber (HC-PCF) provides a near-ideal environment for SRS due to a very long effective interaction length, the high confinement of light in an small effective area, and the possibility of control of the effective gain spectrum [1,2]. High efficiency SRS has been observed in hydrogen-filled HC-PCF with a far lower pump power than previous experiments [1-9]. Nearly all the published papers have reported rotational SRS from hydrogen [2-9], even though the vibrational line from hydrogen is of special importance due to its large wavelength shift. The low loss at mid-IR wavelengths recently reported using negative curve hollow core fiber (NC-HCF) [10] makes it possible to exploit the large shift of vibrational SRS in hydrogen to generate longer wavelengths.

We demonstrate here, for the first time to our knowledge, a 1.9 µm fiber gas Raman wavelength converter using a hydrogen-filled low loss NC-HCF by vibrational SRS. A high quantum conversion efficiency >48% is obtained with a 6.5 m fiber at 23 bar pressure, and the corresponding output peak power is about 1500 W at the Stokes wavelength 1907 nm. This paper extends the range of Raman spectrum that can be obtained, and offers an effective scheme to generate narrow linewidth, high conversion efficiency Mid-Infrared coherent sources.

2. Experimental Setup and Results

The experimental setup is shown in figure 1. The hollow core fiber used for the experiment is a low loss NC-HCF, with a core diameter ~50 µm, the cross-section structure and the measured attenuation is shown in figure 2(A). The pump line (1064 nm) and the first-order vibrational Stokes line (1907 nm, Raman shift 4155 cm^{-1}) are in the second and the first transmission band respectively. The losses at some interested lines are shown in table 1. The hollow core fiber is filled with pressure (>10 bar) hydrogen using two gas cells, and is pumped with a passively *Q*-switched

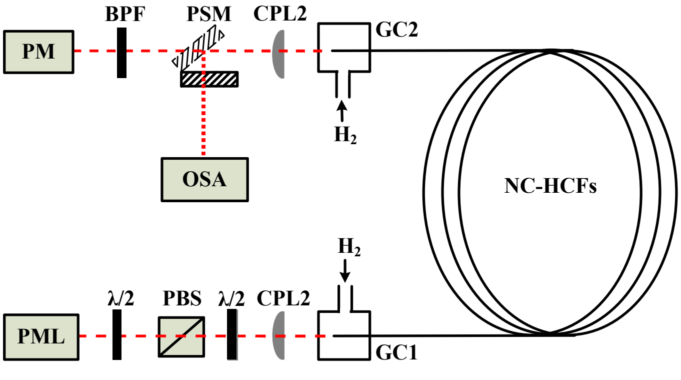

Fig. 1. Experimental . OSA, optical spectrum analyzer; PSM, protected silver mirror; CPL, convex-plane lens; BPF, band pass filter; GC, gas cell; PM, power meter; NC-HCFs, negative curve hollow core fibers; PBS, Polarization Beam Splitter; λ/2, half-wave plate; PML, pulse microchip laser.

Table 1. Fiber attenuations at some interested Raman lines

Wavelength (nm)	Frequency shift (cm^{-1})	Process	Fiber attenuation (dB/m)
738	+4155	Vibrational anti-Stokes	0.45
1001	+587	Rotational anti-Stokes	0.24
1064	0	Pump	0.12
1135	-587	Rotational Stokes	0.25
1907	-4155	Vibrational Stokes	0.35

frequency-doubled Nd:YAG microchip laser operating at 1064 nm. The pump characteristics are pulse duration ~0.9 ns, repetition rate 7.25 kHz, average power ~65 mW. The laser power is controlled using a half-wave plate and a polarization beam splitter (PBS) before coupled into the fiber through a plano-convex lens with a focal length of 50 mm. Another half-wave plate, positioned after the PBS, is used to optimize transmitted power through the fiber, because the fiber has polarization-dependent attenuation. After being collimated through another plano-convex lens with the same focal length, the output beam is sent to an broadband spectrometer by a rotatable silver mirror, or is directly sent to a thermal power meter passing through a band pass filter (Thorlab FB2000-500, central wavelength 2000 nm, FWHM 500 nm, measured transmission ~78% at 1907 nm wavelength, out-of-band transmission <1%, and measured attenuation > 40 dB at 1064nm wavelength).

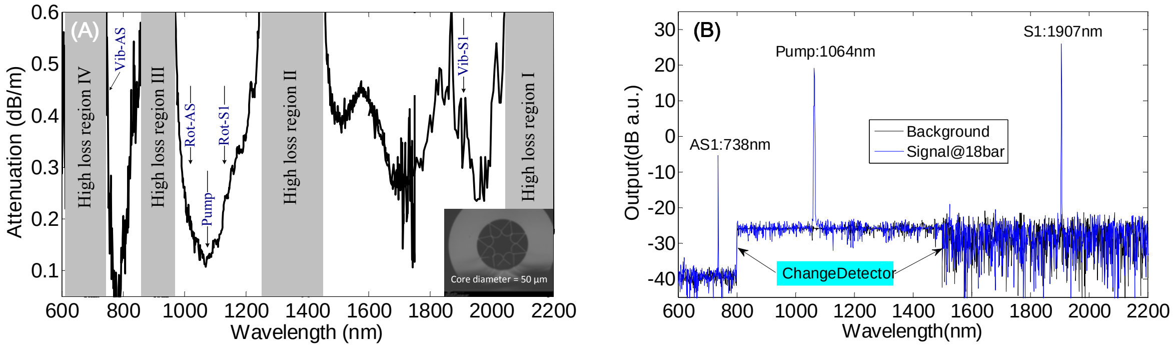

Fig. 2. (A) The measured attenuation of NC-HCFs used in experiments, Vib-S1: the first-order vibrational Stokes (1907 nm); Vib-AS, the first-order vibrational anti-Stokes (738 nm); Rot-S1, the first-order rotational Stokes (1135 nm); Rot-AS, the first-order rotational anti-Stokes (1001 nm); *inset*: cross-section micrograph of the fiber with a core diameter 50 µm. (B) Output optical spectrum at 18 bar H_2 pressure, 6.5 m length, and 36 mW coupled power, the black line is the background with no pump input, the changes of the noise level at 800 nm and 1500 nm are due to change of photo-detectors inside the optical spectrometer.

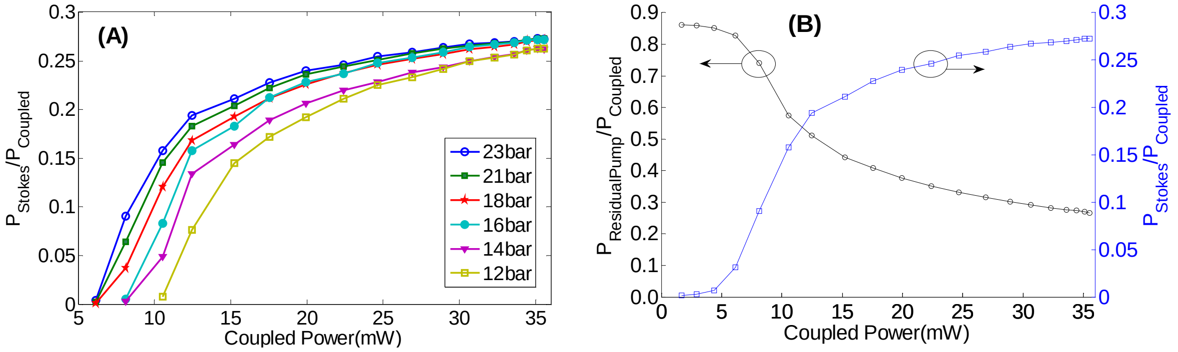

Fig. 3. (A) The ratio of output Stokes power to coupled pump power is plotted versus the coupled power at different hydrogen pressure. (B) The evolution of the residual pump (black open circle, left-hand vertical axis) and the Stokes (blue open square, right -hand vertical axis) with coupled pump power for a 6.5 m fiber at 23 bar hydrogen pressure.

The measured output optical spectrum for 6.5 m length, 18 bar pressure, and 36 mW coupled power is shown in figure 2(B). The first order vibrational Stokes 1907 nm is very strong, and the corresponding anti-Stokes 738 nm is also very clear (the relative intensities should be taken as indicative only). No rotational SRS signal was observed even though the corresponding wavelengths are in the transmission bands. Vibrational SRS has a higher gain than rotational SRS, and we used a linearly polarized laser and high hydrogen pressure (>10 bar) in experiments, which preferentially generates vibrational SRS. The changes of the noise level at 800 nm and 1500 nm are due to change of photo-detectors inside the spectrometer. We measured the output power with different input powers and hydrogen pressures, and the results are shown in figure 3. From figure 3(A), it can be seen that the output Stokes power increases rapidly with increasing pump, approaching saturation at higher pump powers. At a given input power, more Stokes is generated using higher pressures, although towards the upper end of the pump range investigated the outputs converge over the range of pressures shown. The evolution of the output power versus coupled power at 23 bar hydrogen pressure is show in figure 3(B). It can be seen, from the figure, that most of the output power is the pump laser when the input power is low, then the Stokes power will increase quickly with the increasing of input power due to more and more pump power is converted to Raman signal. The maximum power conversion efficiency ~27% is achieved with 36 mW power being coupled into the fiber.

3. Conclusions

A 1.9 µm Raman line has been generated with high efficiency in hydrogen-filled low loss NC-HCF by vibrational SRS. Rotational SRS is suppressed by linear polarization laser input and high pressure (>10 bar) operation. A quantum conversion efficiency >48% is obtained with a 6.5 m fiber operating at 23 bar hydrogen pressure. This investigation extends the range of narrow-band Raman lines that can be generated in fibers into the mid-IR, and demonstrates a route for generating further wavelengths potentially out to beyond 4 µm.

4. Acknowledgements

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