Subwatt Threshold cw Raman Fiber-Gas Laser Based on H_2-Filled Hollow-Core Photonic Crystal Fiber

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We report on what is, to our knowledge, the first cw pumped Raman fiber-gas laser based on a hollow-core photonic crystal fiber filled with hydrogen. The high efficiency of the gas-laser interaction inside the fiber allows operation in a single-pass configuration. The transmitted spectrum exhibits 99.99% of the output light at the Stokes wavelength and a pump power threshold as low as 2.25 W. The study of the Stokes emission evolution with pressure shows that highly efficient Raman amplification is still possible even at atmospheric pressure. The addition of fiber Bragg gratings to the system, creating a cavity at the Stokes wavelength, reduces the Raman threshold power below 600 mW.

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Since its first demonstration in 1963 [1], off-resonance stimulated Raman scattering (SRS) in gas-phase materials has been recognized as a potential and efficient means to obtain spectrally narrow and tunable laser sources. However, the large power required (~1 MW peak power) of the pump lasers limited drastically this prospect. In order to lift the reliance of SRS on high power laser sources, two directions were historically taken. The first option consisted of increasing the effective length of the Raman medium [2,3]. However, the laser beam diffraction limited the threshold reduction to a very modest level. The second route consisted of enhancing the power by placing the Raman gas in an optical resonant cavity. For example, Carlsten and coworkers used a high-finesse cavity resonant at both the pump and Stokes wavelength and filled with the Raman active gas hydrogen. Although an impressive ultralow power threshold was demonstrated by this technique, as illustrated in the development of cw pumped SRS hydrogen lasers [4,5], the conversion efficiency remained poor (only ~5%). Furthermore, the stringent locking of the cavity to the pump laser made its use limited.

A revival of the technique based on increasing the gas-laser interaction length arose from the advent of gas-filled hollow-core photonic crystal fiber (HC-PCF) [6] whereby gases and light are confined together over μm^2 scale mode areas while keeping them interacting on length scales a million times longer than the Rayleigh range. In fact, several demonstrations of the potential offered by these fibers have been reported, both for vibrational and rotational SRS in H_2 in the pulsed and quasi-cw regime [6–9]. These breakthroughs hinted not only that a cw rotational Raman laser in a single-pass configuration was achievable for the near-infrared but that a high conversion efficiency and a quasi–single-frequency output could concurrently be achieved [7]. Furthermore, the concomitant and recent development of high power, narrow linewidth cw fiber lasers [10] and the HC-PCF based all-fiber micronic gas cell [9] opens the prospect of all-fiber cw pumped Raman gas lasers. In this Letter we report, for the first time to our knowledge, the realization of a single-frequency, cw pure rotational Raman laser based on HC-PCF filled with H_2. Up to 99.99% of the output power is shown to be converted to the first Stokes radiation $S_{00}(1)$ in this single-pass configuration even at a pressure as low as 1 bar. The total Stokes output power corresponds to ~50% quantum conversion efficiency of the coupled pump power, due to linear loss along the 30 m long fiber sample and exhibit a narrow linewidth. The observed coupled pump power threshold of 2.25 W is further reduced to 600 mW by use of fiber Bragg gratings (FBGs) to form a cavity. These results open new prospects in compact gas lasers based solely on photonic and optical fiber solutions. Finally, and in contrast to the high-finesse cavity system, this type of fiber lasers offers a higher pump power dynamic range and a higher degree of immunity to parasitic effects such as optical bistability or thermal heating [11].

In designing the HC-PCF based Raman laser, we exploit the photon conversion map shown in Fig. 1(a). This map gives the photon conversion to the first rotational Stokes signal as a function of two experimentally variable parameters: the fiber length and the input pump power. The photon conversion is calculated using the Raman photon rate equations given in Ref. [12], where we limit the coupled equations to only the pump, the first and second Stokes, and first anti-Stokes lines. The Raman gain is taken to be 0.28 cm/GW at a pump wavelength of 1064 nm [13] for H_2 pressure inside the fiber of more than 5 bar and the Raman linewidth to be 250 MHz (including collisional dephasing due to the wall of the hollow core). The fiber's effective area is taken to be 20 μm^2 and its optical attenuations at the pump, first Stokes, second Stokes, and first anti-Stokes wavelength have been measured to be 100 dB/km, 140 dB/km, 400 dB/km, and 140 dB/km, respectively.

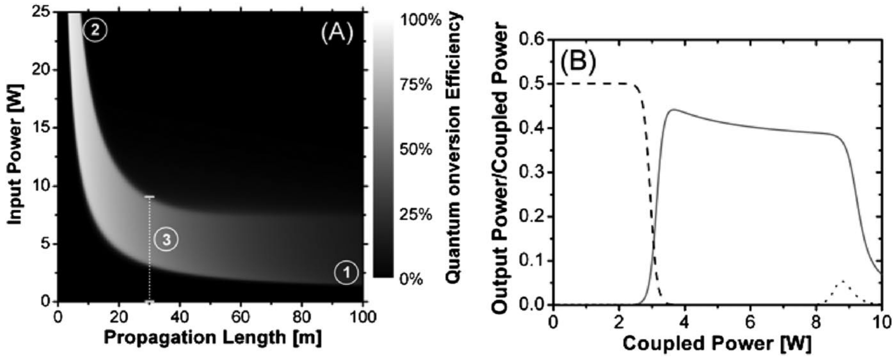

FIG. 1. (a) Theoretical conversion efficiency from the input pump power to the output power at the first rotational Stokes wavelength as a function of the propagation length and the input power. (b) Calculated output power ratio to the total input power at the pump (dashed line), first Stokes (solid gray line), second Stokes (dotted line) as a function of the coupled power for 30 m of HC-PCF. The anti-Stokes output power is 10^{-6} weaker than the pump and Stokes lines.

The results for the quantum conversion efficiency, given the parameters above, show that a low Raman threshold as low as 1.4 W is potentially achievable by using a 100 m long fiber sample [point 1 in Fig. 1(a)]. However, the conversion efficiency from the pump to the first Stokes is calculated to be only 0.05%. In contrast, 90% of the pump input power could be converted into a Stokes radiation when using a fiber length shorter than 10 m [point 2 in Fig. 1(a)], though the threshold power to achieve this conversion is higher than 10 W. In our case, given the experimentally available power coupled into the fiber [up to 8.5 W, represented by the dashed segment 3 of Fig. 1(a)], the best photon conversion efficiency one could hope for is ~50% at a HC-PCF length of 30 m. The theoretical evolution of the power of all Raman lines as a function of the coupled input power, shown in Fig. 1(b) for 30 m of HC-PCF, illustrates the fact that the fiber length and pump power are the sole parameters required to achieve a single-frequency Raman laser operation. For input pump powers less than ~2.5 W, no strong Raman amplification is observed and 50% of the input pump power is lost by linear attenuation of the fiber. Above a pump power of ~3 W, the pump power is dramatically depleted and more than 99% of the output light is expected to be converted into the first Stokes radiation at 1135 nm. The output power at this wavelength is predicted to be ~45% of the total input power. Four-wave mixing between the pump and the Stokes radiation generates the anti-Stokes radiation at 1005 nm, though, given the dispersion and the polarization of the fiber [7], this only accounts for 10^{-6} of the total output power. Conversion into the second Stokes line, at 1215 nm, starts above 8 W. However, due to the high attenuation of the fiber at this wavelength, most of the light is lost in the process.

Prior to the experiment, the 30 m sample of HC-PCF is flushed with nitrogen and heated to ~120 °C to remove impurities. As shown in the schematic of the experimental setup in Fig. 2(a), one fiber end is spliced to a few mm of

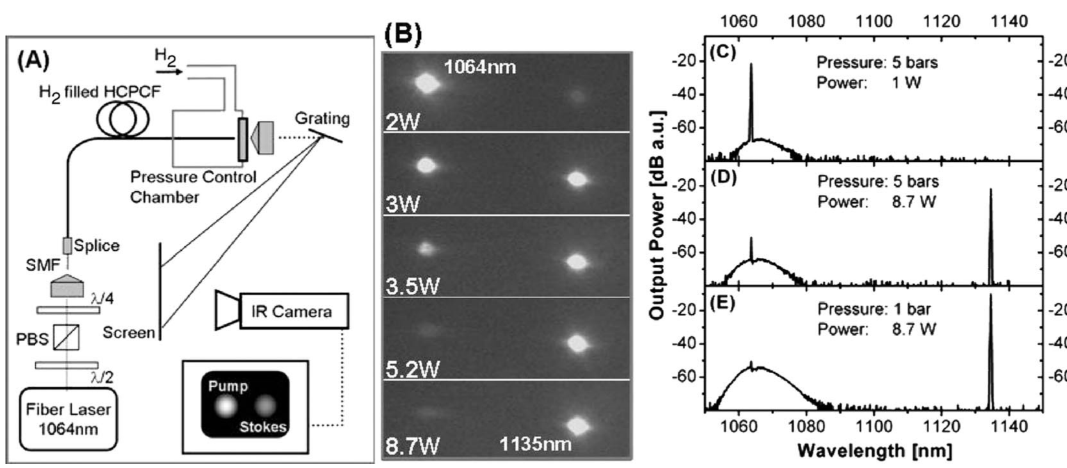

FIG. 2. (a) Experimental setup, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, PBS: polarization beam splitter, SMF: 980 nm cutoff single mode fiber. (b) Evolution of the dispersed output spectrum as a function of coupled input power: pump (left) and $S_{00}(1)$ (right) at 5 bar H_2 pressure. (c) Output optical spectrum for 1 W and (d) 8.7 W coupled input power at 5 bar H_2 pressure. Higher conversion efficiency is achieved at (e) 1 bar pressure. The broad spectral feature around 1064 nm is likely to be due to the residual fluorescence of the laser.

SMF28 to ensure the maximum coupling efficiency into the HC-PCF, while also hermetically sealing the fiber's hollow core [9]. The other end of the fiber is placed into a gas control chamber similar to the one used in Ref. [6] filled with H_2 at the required pressure. A continuous-wave fiber laser operating at 1064 nm, with a linewidth below 100 kHz and a variable power up to 25 W (IPG Photonics) is coupled into the spliced fiber using a microscope objective and a system of $\lambda/2$ plate, polarization beam splitter and $\lambda/4$ plate for control of the polarization. The coupling efficiency into the HC-PCF is estimated to be 35% of the laser output power, including the loss due to the splice. A quartz window at the front side of the control chamber allows for the fiber output beam to be collimated and dispersed onto a grating for direct observation of the Raman lines on a screen.

Figure 2(b) presents the profile of the dispersed output beam by a diffraction grating and its evolution with input pump power for a H_2 pressure of 5 bar. For powers less than 2 W, the profile consists of a single spot corresponding to the pump radiation (1064 nm). At a coupled power of 3 W, a large conversion from the pump into the first rotational Stokes line, $S_{00}(1)$ (1135 nm) is observed. Above 5.2 W, the pump is dramatically depleted and the majority of the output power is at the Stokes wavelength. No other Raman lines were observed using this technique. This illustrates dramatically the quasi-full conversion to the Stokes wavelength. Furthermore, thanks to the long interaction length and the small effective area (i.e., small Fresnel number) of the system, most of the Raman amplification happens in the forward direction, with only ~1% of the Raman light detected in the backward direction [14], believed to be a result of reflections at the fiber ends. To quantify the Raman conversion, the output light of the HC-PCF was collected onto a multimode fiber linked to an optical spectrum analyzer (OSA). The optical spectrum at a coupled input power of 8.7 W for a pressure of 5 bar is given in Fig. 2(d). A reference spectrum below threshold is shown in Fig. 2(c) for comparison. The output $S_{00}(1)$ line is 30 dB stronger than the residual pump line, corresponding to 99.9% of the total output light. This trend of full pump power depletion in favor of near total conversion to Stokes radiation was observed for pressure as low as 1 bar, as shown in Fig. 2(e). Moreover, in this configuration, the Stokes part of the total output power increases to 99.99%. This is, to our knowledge, the first report on the generation of SRS in hydrogen at this low pressure and with such high quantum conversion.

To corroborate these results with the predicted evolution of Stokes radiation as a function of the input power, Fig. 3(a) presents the measured ratio between the output and coupled input power at the pump and Stokes wavelength, together with the theoretical prediction calculated using the experimental parameters. As expected, 50% of the pump reaches the output of the fiber due to the 3 dB linear loss along the HC-PCF. The measured threshold power of 2.25 W and the ~50% conversion efficiency are in very good agreement with the theory. Also in line with the model predictions, no second Stokes is experimentally observed for the pump power range explored and a weak anti-Stokes line is detected at the limit of the dynamic range of the OSA and only accounting for 10^{-6}% of the total output power, so it is not represented on the graph. Because of the low birefringence and the long length of HC-PCF used in the experiment, no significant polarization dependence of the threshold of the conversion is observed.

Similarly to the output Stokes-pump ratio, the power threshold is also expected to vary with pressure. Figure 3(b) presents the measured Stokes threshold power versus H_2 pressure, together with the theoretical value based on the pressure dependence of the Raman gain [13]. Although both experimental and theoretical results show a sharp power threshold increase at low pressure, Raman amplification can still be observed at atmospheric pressure. The Stokes radiation linewidth was measured using a scanning Fabry-Perot spectrometer for a 4 bar H_2 pressure inside the fiber. The expected Raman linewidth is of the order of 400 MHz [15]. However, the measured

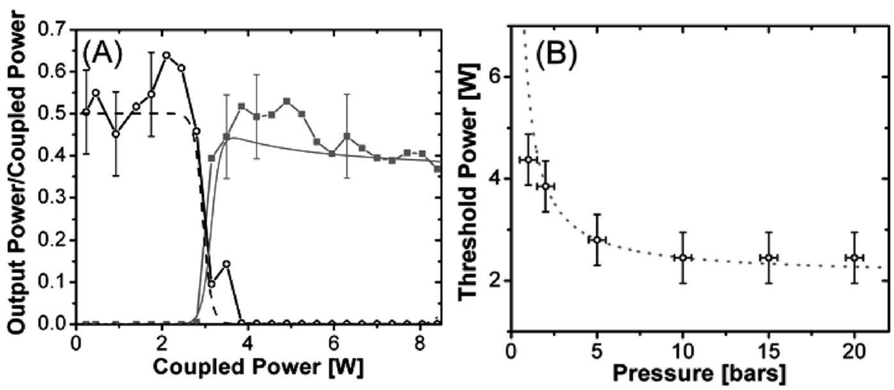

FIG. 3. (a) Experimental output-input power ratio for the pump (circles and black line) and $S_{00}(1)$ (gray squares and line) at 5 bar H_2 pressure. Theoretical calculations are also given for comparison for the pump (dashed line), the first Stokes (solid gray line), and the second Stokes (short dotted line). The anti-Stokes radiation is too weak to be represented. (b) Experimental (circles) and theoretical (dotted line) evolution of $S_{00}(1)$ threshold power with H_2 pressure.

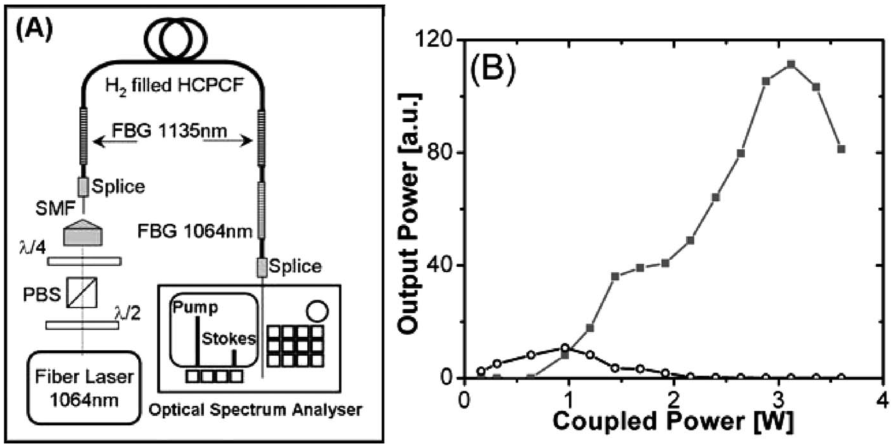

FIG. 4. (a) Low threshold, all-fiber cw Raman laser experimental setup. FBG: fiber Bragg grating. (b) Output power versus coupled input power for the pump (circles and black line) and $S_{00}(1)$ (gray squares and line) when using FBGs to form a cavity. The drop in Stokes intensity above 3 W is due to conversion to second Stokes.

spectral width of the Stokes line is below the 200 MHz resolution of the spectrometer, indicating a strong gain spectral narrowing [16].

To improve the conversion efficiency and reduce the threshold power, FBGs are introduced in the experiment. This technique has already been reported to reduce the Raman threshold power of a HC-PCF gas cell used with a pulsed laser [17]. As shown schematically in Fig. 4(a), a 99% reflective FBG at the pump wavelength (1064 nm) is spliced at the output end of a 10 bar gas-filled HC-PCF, while a cavity is formed at the Stokes wavelength by the addition of a 1135 nm 99% reflective FBG on each side of the HC-PCF. Figure 4(b) shows the output power at the pump and Stokes wavelength as a function of the coupled input power. The measured threshold is reduced to 600 mW, ~6 times less than the single pass corresponding qualitatively to the finesse of the formed cavity [17]. A reduction of the HC-PCF or conventional fiber splice loss could produce high conversion efficiency Raman lasers below the 100 mW barrier.

To conclude, we have reported, for the first time to our knowledge, on a single-pass cw Raman laser based on H_2-filled HC-PCF with 2.25 W power threshold and 50% conversion efficiency into the Stokes line. The fiber proved an excellent Raman converter, with up to 99.99% of the output power at the Stokes wavelength, even at atmospheric pressure. A further reduction of the threshold to 600 mW was made possible by the addition of FBG at the pump and Stokes wavelength. Further improvement on HC-PCF and splice loss would bring higher conversion efficiency and further reduce the threshold power. The present results open prospects on a new type of Raman gas lasers. The low operating pressure of the reported cw laser could be of interest in using SRS in coherent and quantum optics applications [14].

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