Grating-free *n*th order cascaded Raman fibre lasers using highly Ge-doped low loss fibre

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Abstract: Pumped by a narrow band Nd^{3+}-doped fibre laser, a grating-free three-wavelength Raman fibre laser has been demonstrated. More than 1.3W output power at the third Stokes line of 1230 nm, a bandwidth of 1.8nm and a slope efficiency of ~28% was measured. A four-wavelength Raman fibre laser was also demonstrated using a different resonator that consisted of a 4% fibre end reflector, a dielectric mirror and a single fibre Bragg grating. This method is simple, versatile and cheap compared with conventional methods employing fibre Bragg gratings used to resonate all Stokes wavelengths.

OCIS codes: (140.3510) Fiber lasers; (140.3550) Raman lasers; (160.4330) Nonlinear optical materials; (290.5910) Stimulated Raman scattering

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1. Introduction

Stimulated Raman scattering (SRS) is a nonlinear scattering process that involves the scattering of photons by the atomic vibrations of molecules. These inelastically scattered photons have frequencies that are lower or higher than the incident pump frequency. The SRS process, which occurs quite effectively in optical fibres, has allowed the production of broadband Raman amplifiers and tunable Raman lasers. Raman fibre amplifiers (RFAs) in

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particular have been attracting increasing attention in recent years due to the low noise, the ability to provide gain over a wide wavelength range and the wavelength flexibility [1] these devices offer. Multi-wavelength Raman fibre lasers (RFLs) on the other hand are promising pump sources for optical amplification systems [2]. Multi-wavelength Raman fibre-ring lasers based on intra-cavity multi-wavelength filters have also been reported [3]. Higher order Raman Stokes radiation was generated in a phosphosilicate fibre resonator formed by two pairs of Bragg gratings [4] and the highest reported Raman fibre laser output is 10 W generated at a maximum slope efficiency 84.2% and operated with a bandwidth of 0.2 nm [5]. Theory and numerical simulation of cascaded Raman fibre lasers showed that wider frequency downshift is possible with high Raman gain fibre, such as GeO_2 or P_2O_5 doped fibres [6].

In this paper, we present a grating-free three-wavelength Raman fibre laser pumped with a Nd^{3+}-doped fibre laser that employs highly Ge-doped optical fibres. This is in contrast to previous demonstrations of cascade Raman fibre lasers, which generally employ fibre Bragg gratings in order to resonate the individual Stokes wavelengths [7]. A four-wavelength Raman fibre laser was also demonstrated using a 4% fibre end reflector, a dielectric mirror and a single fibre Bragg grating used for the 4^{th} Stokes wavelength. Experimental results show that our grating-free cascaded Raman laser configuration is effective. The simplicity, overall efficiency and versatility of this Raman fibre laser make it highly practical for a number of applications including Raman amplification and distributed sensing systems.

2. Theory

A schematic diagram of the experimental arrangement is shown in Fig. 1. The Nd^{3+}-doped fibre laser [8] consisted of an 805 nm pump laser, a high reflectivity (~100% at 1060 nm) broadband dielectric mirror M butted against the input end to the double clad Nd^{3+}-doped fibre and a fibre Bragg grating FBG1 with reflectivity of 27% and a bandwidth 0.4 nm at the centre Bragg wavelength of 1060 nm. The cascaded Raman fibre laser uses the same mirror M and the ~4% Fresnel reflection at the end of the Ge-doped silica fibre as the resonator.

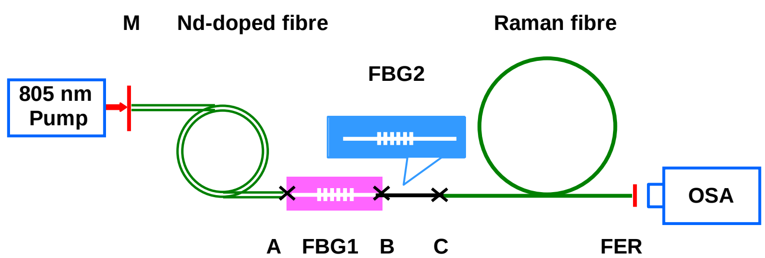

Fig. 1. Schematic configuration of cascaded Raman fibre laser. M: dielectric mirror; FBG: fibre Bragg grating; FER: fibre end reflector; OSA: optical spectrum analyzer.

Germania glass has the highest Raman cross-section amongst the widely used vitreous Raman materials SiO_2, GeO_2, B_2O_3 and P_2O_5 [9]. We fabricated a high (18 mol%) concentration germano-silicate fibre as the Raman fibre to increase the Raman gain per unit length of fibre. The Raman fibre had a small mode-field-diameter (MFD) of 3.87μm and its effective area was A_{eff}=12 μm^2 at the 1300 nm wavelength. The estimated loss and Raman gain coefficient were measured to be ~3.3 dB/km and ~10.1 dB/km W respectively at 1230 nm. The cascaded Raman fibre laser was pumped by a Nd^{3+}-doped fibre laser operating at 1060 nm which delivered up to 8.6 W launched pump power to the single mode Ge-doped fibre.

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3. Experiments and results

The first experiment was conducted with the experimental setup as shown in Fig. 1. In this configuration, all the Raman frequencies use the same resonator, i. e., between the mirror M and fibre end reflector FER. We observed that the number of Stokes frequencies increases as the power increases. The relationship between the Stokes spectra and pump power for a length of 2 km of fibre is shown in Fig. 2. The second and third Stokes lines were observed at a launched pump power of 3.8 W and 5.6 W, respectively. As can be noted from these two figures, higher order Stokes lines appear at higher power pump for constant fibre length. Although the pump bandwidth is 0.4 nm, the bandwidths of the first, second and third Stokes lines are wider at between 1.8 nm and 2.2 nm.

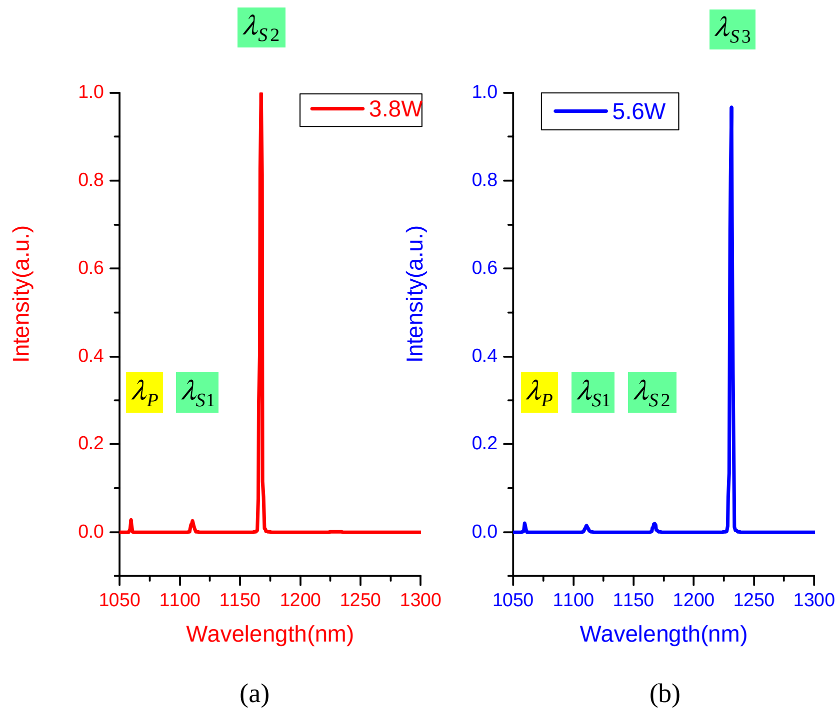

Fig. 2. Raman laser output spectrum measured at different launched pump powers for a 2 km long Raman fibre.

In another experiment, the Raman fibre length was varied whilst the pump power was maintained at a constant value. The output spectrum is shown in Fig. 3. It can be observed that higher order Stokes lines appear at longer fibre length for constant pump power. This results because the Raman gain is proportional to fibre length and longer lengths of fibre therefore provide more opportunity for lower order Stokes lines to produce higher order Stokes lines.

A comparison between the Stokes output powers for different fibre lengths is shown in Fig. 4. As can be seen, the overall slope efficiency decreases with the increase in the fibre length; this is because longer lengths of fibre have more intrinsic loss than shorter lengths. If we assume a linear response, the slope efficiencies are ~28%, ~19%, ~4%, respectively for L=0.5km; L=1km and L=2km. Beyond the optimum length, the threshold also increases with the decrease in the fibre length, because a shorter length of fibre has less Raman gain than a longer length of fibre.

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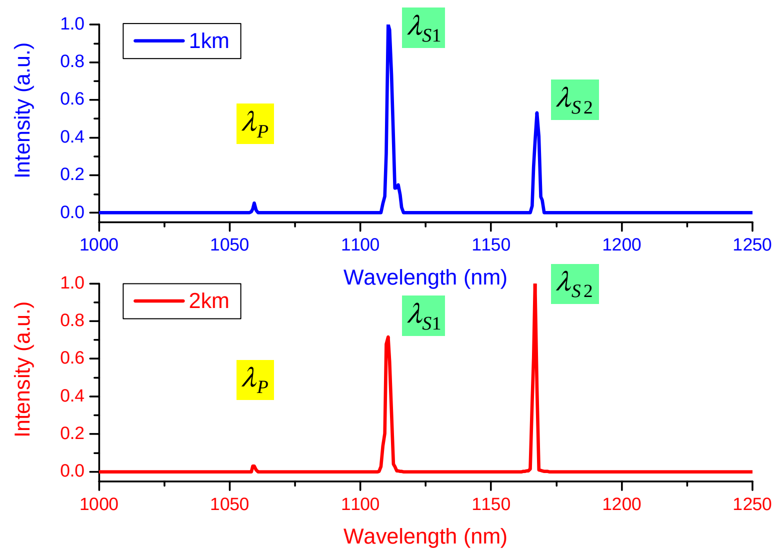

Fig. 3. Raman laser output spectrum at different Raman fibre length for 2.5 W pump.

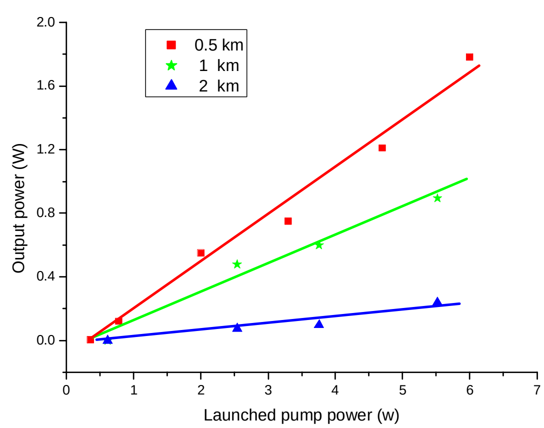

Fig. 4. Total Stokes output powers versus launched power for different fibre lengths.

Fibre Bragg gratings can be used to narrow the linewidth of the output. A fibre Bragg grating FBG2, which was fabricated by Redfern Optical Components (ROC) Pty Ltd, with a bandwidth of 0.4 nm at 1308 nm, was inserted in the cavity between point B and point C as shown in Fig. 1. The resonator for the fourth order Stokes frequency therefore comprises of FBG2 and FER. The laser operates in a cascaded mode and has two types of cavities for the different Stokes frequencies. The laser spectrum for this arrangement is shown in Fig. 5. Overall CW output powers of up to 0.8 W have been obtained from the laser at the output wavelength of 1308nm. The corresponding pump power is 8.5 W and the fibre length was 1km. The dependence of the total Stokes output power versus pump power is shown in Fig. 6. The total output of 1.8 W was generated at an average slope efficiency of ~22%. The power distribution amongst the four Stokes lines are ~0.6%, ~3.4%, ~51.7% and ~44.3%, respectively for the first, second, third and fourth Stokes. We believe the dip in the total

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Stokes power between the 3W and 7W is due to the high loss of the dominating Stokes line caused by the low reflectivity of the dielectric mirror.

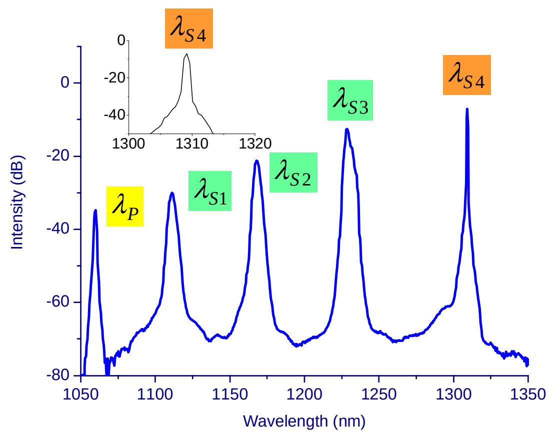

Fig. 5. Raman laser output spectrum for 1km Raman fibre with FBG2.

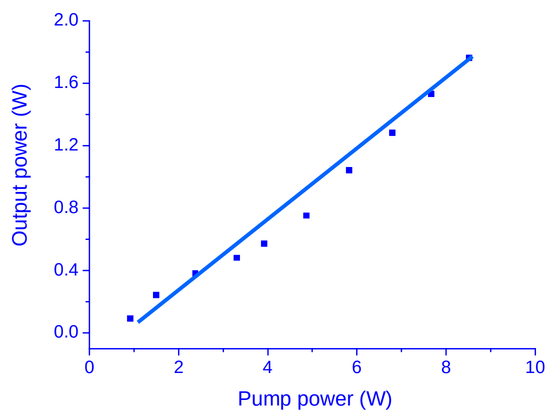

Fig. 6. Raman laser output characteristics for 1km Raman fibre with FBG2.

The Raman frequency shift of the Ge-doped fibre is 13.2 THz, conversion from 1060 to 1300 nm occurs through cascaded Raman processes up to fourth order via three intermediate Stokes shifts at centre wavelengths of 1110, 1170 and 1230 nm. The laser cavity consisting of mirror M and fibre end reflector FER resonates the first, second and third Stokes. Dielectric mirror M has a ~100% transmission at 805 nm. The reflectivity of mirror M is ~99%, ~18% and ~12% at 1040-1190, 1230 and 1310 nm Stokes frequencies, respectively, and the mirror reflectivity obviously affects the laser threshold of each Stokes line. Ideally M should be ~100% reflectivity for all Stokes lines, λ_{S1}, λ_{S2}, λ_{S3} and λ_{S4}, and consequently a weaker FBG can be placed at the output end in order to narrow the linewidth of the final Stokes emission. In our case, we did not have a mirror with ~100% reflectivity for all Stokes lines, and we used FBG2 instead. The use of a single broadband dielectric end reflector has advantages in terms of compactness and simplicity.

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Since no narrowband filters are included for the first, second and third Stokes shifts, their 3dB bandwidths are wider than 1 nm. To compare the lasing characteristics, a spectrum is shown in Fig. 7 for the same condition with Fig. 5 but without FBG2 in place. The fourth Stokes power was increased over ~20dB because of the high reflectivity of the fibre grating. Since we did not use FBGs for wavelength selection, the output wavelength is a function of pump power and fibre length. If a narrowband output is required from the laser, then a FBG at the output wavelength is all that is required and nesting FBGs is not necessary. This greatly reduces the complexity of cascade Raman fibre lasers.

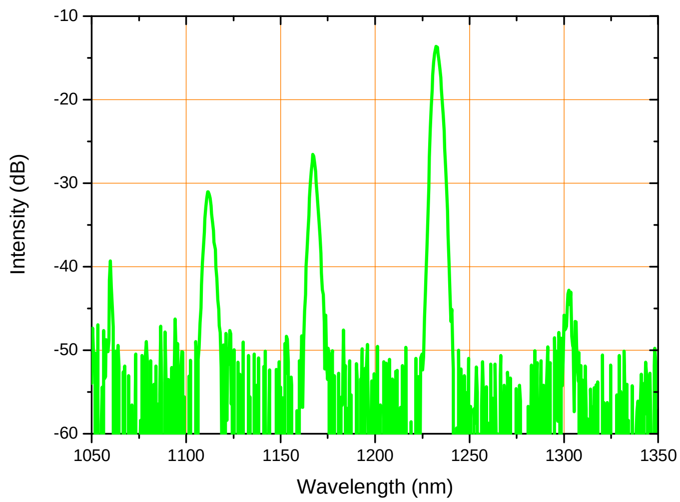

Fig. 7. Raman laser output spectrum for 1 km Raman fibre without FBG2.

4. Conclusion

In conclusion, we have experimentally demonstrated a grating-free cascaded Raman fibre laser that uses Fresnel reflection and a broadband dielectric mirror in order to produce *n*th-order Stokes output. Since we did not use pairs of gratings to force the output wavelength, for a fixed pump power, the Stokes lines can be adjusted by setting the length of fibre. The fibre length and pump power play an important role in determining the Raman laser output when broadband reflection is used. For narrow band output, we have shown that a single FBG centered at the desired output wavelength is all that is required. Fourth order Stokes output of ~0.8 W at a bandwidth of ~0.4 nm was produced at a slope efficiency of ~22% with respect to the launched pump power. The cascaded grating-free multi-wavelength Raman laser is versatile and cheap. The simplicity of this configuration combined with its overall high efficiency makes this laser very attractive as a pump source for a number of applications including Raman amplifiers.

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