Raman oscillation on a new vibrational mode setup in phosphosilicate binary glass systems

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Abstract: We demonstrate Raman oscillation at a wavelength of 1158 nm using a new vibrational mode in a phosphosilicate-glass system when pumped at a 1060-nm wavelength. The lower energy P-O vibration located at 640 cm^{-1} associated with pure phosphate glass system is comparatively weaker and is shifted to higher energy at 800 cm^{-1} in the phosphosilicate binary glass. Despite the relative weakness of this vibrational mode, we obtained an efficient Raman fiber laser with the use of fiber Bragg gratings used to select laser oscillation using this mode. The measured slope efficiency with respect to the launched pump power was 60.4% and a maximum laser power of 1.8 W was produced.

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1. Introduction

Stimulated Raman scattering is an efficient nonlinearity in germanosilicate or phosphosilicate glass optical fibre and can be used to effectively generate downshifted wavelengths. The long interaction length and large light intensity associated with the small core dimension of typical

optical fibres provides the conditions for efficient conversion. In particular, the phosphosilicate glass system is generally used to construct fibres for Raman fibre lasers (RFL's) [1-4] because of the large Stokes shift, which scatters an incident photon to lower energy by 1330 cm^{-1} [5-7]. In addition to the direct use of this high energy P-O vibration, many other wavelengths can be generated when the Si-O vibration and the P-O vibration are used consecutively [6,7].

For particular pumping applications, e.g., the fibre laser pumping of Ho^{3+}-doped silica fibre lasers [8,9] pump wavelengths of ~1150 nm are desired. One way of achieving this end is to utilize the lower energy P-O vibration relevant to phosphate glass in a RFL arrangement comprising of a single Stokes shift. In this letter, we show that in the binary phosphosilicate glass system, in contrast to the pure phosphate glass system, the lower energy P-O vibration (which is normally located at 640 cm^{-1}) is now comparatively weaker and is shifted to higher energy. We demonstrate Raman oscillation on this lower energy P-O vibration for the first time when the phosphosilicate glass is pumped at a wavelength of 1060 nm. In addition, other Stokes emissions, related to the Si-O vibration (at 420 cm^{-1} and 490 cm^{-1}) have been also been generated simultaneously in a Raman fibre laser arrangement.
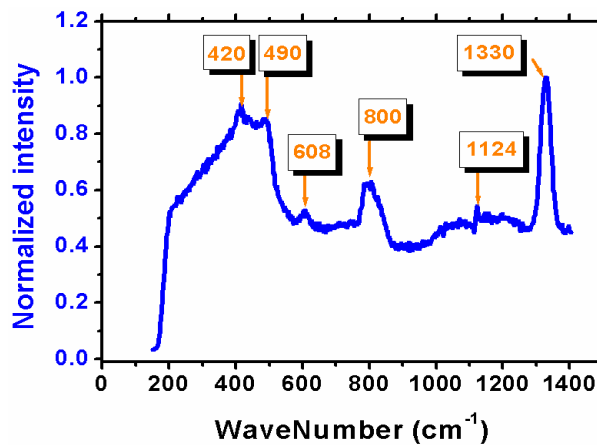

Fig. 1. Measured spontaneous Raman spectrum of the phosphosilicate preform.

2. Experiment

The preform used to make the fibre was fabricated by the standard MCVD technique. The phosphorous concentration was estimated to be 8 mol.% using the refractive index profile of the preform. The fibre used for the RFL experiments had a core diameter of 4.6 μm and a numerical aperture (NA) of 0.14 and therefore supported single mode operation down to 850 nm. The fibres used in the experiment have a length of 500 m or 1500m.

The spontaneous Raman scattering spectrum of phosphosilicate glass preform was measured with a Renishaw Raman Systems 2000 that used Argon ion laser excitation at 514 nm. Fig. 1 displays the normalized Raman spectrum. The Raman spectrum relating to the binary glass does not result from the linear superposition of the individual Raman spectra relating to the pure silica and pure phosphate glasses [10]. As compared to the vibration modes relevant to pure silica and pure phosphate glasses, there contains in the binary glass spectrum additional peaks at 608 cm^{-1} and 800 cm^{-1} and a small peak at 1124 cm^{-1}. The Raman vibration at 640 cm^{-1}, which exists in pure phosphate glass, however, is now not present. The peaks at 420 cm^{-1} and 490 cm^{-1} in the binary system relate to pure silica glass [7], however, the peak at 420 cm^{-1} is now narrower and more defined as compared to the case of pure silica glass. The Raman peak at 1330 cm^{-1} has a similar energy to the pure phosphate glass case, which is normally located at 1390 cm^{-1}. The correspondence of this vibration in the

phosphosilicate glass system with the pure phosphate glass system is not unexpected since this vibration relates to the double (terminating) bond between phosphorous and oxygen. The lower energy P-O vibration, however, relates to bonding to bridging oxygen atoms, which normally bond with other phosphorous atoms. In the phosphosilicate glass system these bridging oxygen atoms may bridge silicon with phosphorous and the phosphosilicate glass has additional and shifted Raman vibrations as compared to the pure glass systems.

Figure 2 shows schematically the experimental RFL configuration that used a diode-pumped Nd^{3+}-doped fibre laser as the pump source. The Nd^{3+}-doped fibre laser was pumped at a wavelength of 805 nm and a broadband dielectric mirror (labelled M) butted against the input end to the Nd^{3+}-doped fibre in conjunction with a Bragg grating (R=27%) which had a bandwidth of 0.4 nm at the central Bragg wavelength of 1060 nm (labelled λ_p) together formed the pump resonator. The maximum output power exiting from the pump source was ~5 W. The first Raman fibre laser cavity that was tested was created between the mirror M and the cleaved fibre at the output end of the phosphosilicate fibre (PSF). In a second arrangement, a pair of Bragg gratings were used, one with a high reflectivity (R>99.9%, FBG2) and one with a partial reflectivity (R=30%, FBG3) at the wavelength of 1158 nm (λ_s). In a third configuration, the output end was angularly cleaved to remove Fresnel back reflection. The optical spectrum of the output was measured with an Anritsu MS9710C spectrum analyser with a resolution of 0.05 nm.

In order to efficiently generate cascaded Raman fibre lasers, the fibre used in the experiments was made with a small effective core area of only 17 μm^2. The background loss was estimated to be ~3 dB/km in the wavelength range 1000 to 1190 nm. Silica-related Stoked emissions can be easily generated even without incorporating pairs of FBG's for the RFL resonator. On the other hand, 1158 nm emission, which relates to the ~800 cm^{-1} vibrational mode of the phosphosilicate glass system, can only oscillate with the use of higher reflectivity feedback components, i.e., by way of FBG's.
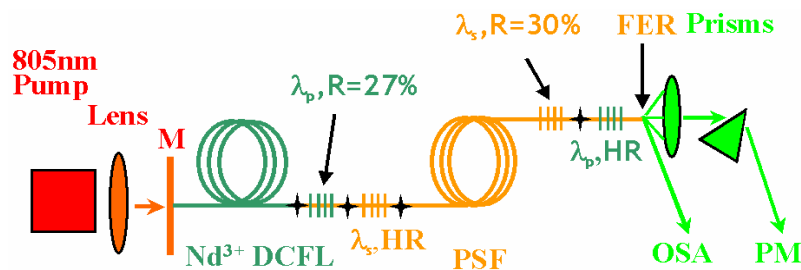

Fig. 2. Schematic diagram of the RFL system. M: dielectric mirror; DCFL: double-clad fiber laser; HR: high reflector; FER: Fresnel end reflector; OSA: optical spectrum analyzer; PM: power meter.

3. Results

The first experiment was conducted at low launched pump power levels of less than 3.8 W under a free running setup. In this arrangement, all the Raman emissions share the same resonator, i.e., between mirror M and fibre end reflector, FER. The evolution of the output spectrum as a function of launched pump power is shown in Fig. 3. The first Stokes emission that relates to the Si-O vibration at 420 cm^{-1} (this emission is labelled $S_{1,420}$), which is emitted at a wavelength of 1109 nm initially grows faster than the second Stokes emission at a wavelength of 1118 nm, which relates to the Si-O vibration at 490 cm^{-1}. As the pump power P_{1060} (the subscript indicates the wavelength in nm) is further increased, Stokes emission at 1118 nm begins to dominate the spectrum. The 1109 nm emission acts at the pump source for Stokes emission at 1118 nm in an amplifier type configuration. Stokes emission at 1158 nm was not observed with this setup.

The second experiment used FBG's for feedback and Fig.4 shows the output spectrum measured at 3.92 W launched pump power. In addition to the residual pump emission, P_{1060}, there appeared emissions at 1118 nm, 1158 nm ($S_{1,800}$), 1175 nm ($S_{2,420}$) and 1183 nm ($S_{2,490}$). It is clear that whilst gratings designed for 1158 nm were incorporated, competition between a numbers of Stokes emissions was evident when the cleaved output end of the PSF was perpendicular to the axis of the fibre.

With a 10^0 angle cleave placed at the output end of the PSF, the emissions at 1118 nm, 1175 nm and 1183 nm were not generated, and only 1158 nm resulted. Fig.5 shows the spectrum measured at the 3.80 W launched pump level and with a vertically logarithmic scale, and the inset indicates in detail the spectrum of 1158 nm emission with a FWHM of ~0.1 nm. Fig.6 shows the measured output power with a slope efficiency of ~60% as a function of the launched pump. The maximum output power generated at 1158 nm was pump limited at 1.8 W.
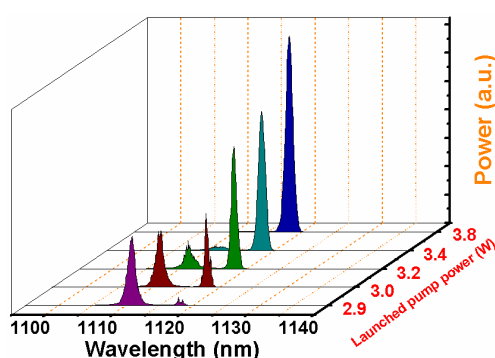

Fig. 3. The output spectrum evolution as a function of the launched pump power in the first setup.
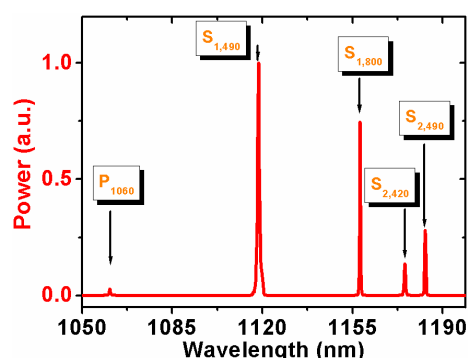

Fig. 4. The output spectrum measured at a launched pump power of 3.92 W in the second setup.

4. Discussion

Phosphosilicate glass is perhaps the most important material used for the creation of high power Raman fibre lasers. This results from the fact that the high-energy vibrational mode of phosphate glass produces a large downshift in the frequency and less FBG's are therefore required for a given wavelength, particularly when generating light in the 1.48 μm band. Using the silica related vibrations "fills the gap" between the large wavelength steps made by the high-energy phosphate vibration. In the present study, we have extended this work to the examination of the intermediate vibrations that are present in phosphosilicate glass and we have shown that they are also useful for the generation of downshifted wavelengths in RFL's that are developed with the minimization of the number of FBG's in mind.

The absence of the lower energy vibrational mode of pure phosphate glass at 640 cm^{-1}, which can be considered as a vibration mode involving a bridging oxygen and two phosphorous atoms (a P-O-P mode) indicates that in the binary phosphosilicate glass system there contains few oxygen atoms that bridge two phosphorous atoms. Little to no phase separation is present in this binary glass. The vibration modes of the phosphosilicate glass system at 608 cm^{-1} and 800 cm^{-1} are clearly the result of adding phosphorous to the silica glass system or silica to the phosphate glass system. One possible new vibration mode would involve an oxygen atom that bridges a phosphorous atom and a silicon atom (a P-O-Si mode). This may give rise to the vibrational mode at 800 cm^{-1} because the vibrations involving

bridging oxygen atoms in the pure phosphate glass are relatively strong compared to the vibrational mode relating to the double bond.

The large Raman scattering cross-section at 1330 cm^{-1} of phosphosilicate glass suggests that there should exhibit a strong Stokes emission at the wavelength of 1234 nm in the free-running arrangement. This emission however was not observed in the experiments. The absence of this Stokes emission can be attributed to the following facts. The estimated fiber loss of 6 dB/km at the wavelength of 1234 nm is nearly twice as high as the loss at wavelengths from 1000 to 1190 nm. In addition, the reflectivity of mirror M is ~18% at a wavelength of 1234 nm compared to the ~99% reflectivity for wavelengths 1000 to 1190 nm.
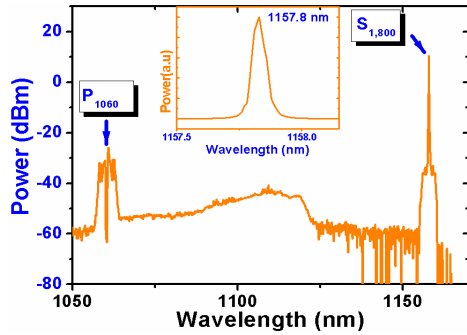

Fig. 5. The spectrum in the third setup at a 3.8 W pump power. The inset displays the 1158 nm only.
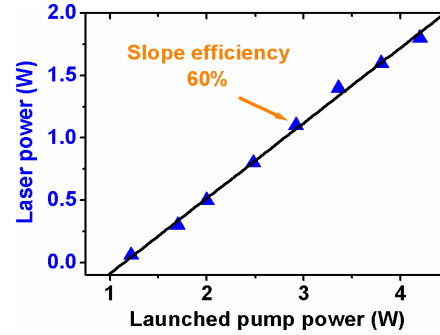
Fig. 6. The measured output power versus the launched pump power relevant to the third setup.

Table 1. Raman peak position and gain intensity in binary phosphosilicate fibre

Raman peak position (cm^{-1})	Normalised Peak Height	1st Stokes wavelength pumped at 1060 nm (nm)	Raman peak position (cm^{-1})[5]
			300
420	0.88	1109	420
490	0.84	1118	520
608	0.53	1132	710
800	0.62	1158	800
			1020
1124	0.54	1203	1145
1330	1.0	1234	1320

Table 1 lists the measured Raman scattering peak positions for our phosphosilicate glass system and the associated first-order Stokes emission wavelength positions when pumped with light at a wavelength of 1060 nm. The peak positions relevant to a similar study [5] are also shown. The intensity of the 800 cm^{-1} peak due to the P-O-P stretching vibration is comparatively stronger in our sample, as compared to the other study, however it is still weaker than the peaks at 420 cm^{-1} and 490 cm^{-1}. According to [4,5], the Raman gain coefficient is proportional to the phosphorous concentration in phosphosilicate fibre and, with a desire to optimize the gain to loss ratio for a RFL using the 800 cm^{-1} vibration mode, the Raman spectrum of the phosphosilicate glass system must be examined as a function of the

phosphorous concentration [4]. It is currently unclear why the silica-related vibration mode is split into two peaks at 420 cm^{-1} and 490 cm^{-1} in phosphosilicate glass as compared to the single peak at 444 cm^{-1} in high-purity silica glass. Clearly more work is required to fully understand the phosphosilicate glass system.

5. Conclusion

We have investigated and experimentally demonstrated Raman oscillations on a new vibrational mode that is setup in a phosphosilicate glass system. The lower energy P-O vibration at 640 cm^{-1} in pure phosphate glass is shifted to higher energy at 800 cm^{-1} in our binary phosphosilicate glass. Utilising this lower energy P-O vibration, oscillation at a wavelength of 1158 nm is generated for the first time when the phosphosilicate glass fibre is pumped at a wavelength of 1060 nm. We generated a maximum output power of 1.8W and measured a slope efficiency of 60.4% with respect to the launched pump power. With optimizing the experimental configuration, the output power of 1158 nm can be further scaled.

Acknowledgments