High beam quality cw 1.5 W $BaWO_4$ Raman laser using Nd:YLF as laser active medium

Jonas Jakutis Neto[1,2], Jipeng Lin[1], Andrew J. Lee[1], Huaijin Zhang[3], Jiyang Wang[3], Niklaus Ursus Wetter[2] and Helen Pask[1]

1. *MQ Photonics Research Centre, Department of Physics, Macquarie University, Sydney, NSW 2109, Australia*
2. *Instituto de Pesquisas Energéticas e Nucleares, CNEN/SP, Universidade de São Paulo, CEP 05508-000, São Paulo/SP, Brazil*
3. *State Key Laboratory of Crystal Materials and Institute of Crystal Materials, Shandong University, Jinan, 250100, PR China*

jonas.jakutis-neto@mq.edu.au

Abstract: 1.5 W of 1st Stokes, 1167 nm, cw output power was produced using a Nd:YLF laser crystal associated to a $BaWO_4$ Raman crystal. The laser built provided a M^2 of 1.51 and 1.43, vertical and horizontal, respectively. This high beam quality and Watt level power laser was built in a long cavity, demonstrating the advantages of Nd:YLF, which will ultimately enable low amplitude noise Raman lasers and allowing long length cavity geometries, such as “V” shape, for better conversion efficiencies. A preliminary result for a cw 583 nm laser has delivered 0.61 W of output power.

1. Introduction

CW solid state Raman lasers have been explored during the past 6 years due to their capacity to reach new wavelengths in the near infrared as well as in the yellow-orange visible spectrum range [1-3]. Also, such lasers have demonstrated a great versatility in terms of multiple wavelength generation when further cascaded into higher stokes orders [4]. Given that, and the fact that these lasers, in general, use similar design to the most common and efficient Nd lasers, we decided to explore different approaches in order to improve their engineering.

The main problem reported for these lasers is the strong thermal lens found in crystals like Nd:$GdVO_4$, Nd:YVO_4 extensively used in self-Raman configurations [1,3,5,6]. This stronger thermal lens is mostly built up from the combination of pump thermal loading and the inelastic Raman shifting process, which generates phonons during the wavelength conversion. As an alternative, Nd:YAG presents a higher thermal conductivity than Nd:YVO_4 and Nd:$GdVO_4$, weaker thermal lens, but it does not have polarized emission, also required for an efficient Stokes shifting.

In this paper, we explore the performance of Raman lasers using Nd:$LiYF_4$ (Nd:YLF). Nd:YLF provides a naturally polarized emission and a weak thermal lens. Nd:YLF has a negative dn/dT which partially compensates the positive lens generated in the crystal’s face bulging. In addition, π and σ emissions have different wavelengths 1047 nm and 1053 nm, respectively, both shorter than the more conventional 1063 nm and 1064 nm, thereby providing a new range of Stokes wavelengths. A disadvantage of this crystal is the low thermal fracture limit, which limits the maximum absorbed pump power. This can be partly mitigated by using a direct pumping system, by means of a diode emitting at 881 nm instead of the usual 806 nm and 797 nm, which are the other main absorption peaks of Nd:YLF. In this case one non-radiative decay is eliminated in the lasing process, reducing the thermal loading.

In this paper we reported a high beam quality cw Nd:YLF/$BaWO_4$ Raman laser system, emitting at 1167 nm with a maximum output power of 1.5 W for 17 W of absorbed power. In addition, we have demonstrated second harmonic generation (SHG) of the laser, obtaining 0.61 W cw at 583 nm.

2. Experimental setup

We used a Nd:YLF crystal, 1.0 at% Nd^{3+}-doped, a-cut with dimensions of 4x4x15 mm^3. The length and relatively high doping concentration were chosen in order to absorb more at the direct pumping wavelength, 881 nm. Furthermore, this crystal oscillated at 1053 nm, favored by the mirrors and crystal coatings. Such line presents the weakest thermal lens compared to the 1047 nm transition, providing better stability and good beam quality for the laser even under high pump powers.

As Raman active crystal $BaWO_4$ was chosen because of its high Raman gain of ~8.5 cm/GW compared to KGW (~4.4 cm/GW), $GdVO_4$ (>4.5 cm/GW) and YVO_4 (>4.5 cm/GW) [7]. This crystal was a-cut and 25 mm long since in the steady-state regime, the Stokes field increases exponentially with the interaction path along the crystal. The Raman shift provided by $BaWO_4$ is 926 cm^{-1}, so then, the shift of 1053 nm is to 1167 nm.

The best cavity configuration was found to be the one using a high reflectivity (HR) flat mirror as the pump mirror and a 250 mm of radius of curvature (ROC) as the output coupler. Both mirrors have a reflectivity at 1053

978-0-9775657-7-1

nm higher than 99.9%, while the pump mirror has similar high reflectivity at 1167 nm and the output coupler has 0.4% of transmission at 1167 nm. The cavity was 240 mm long, as shown in the Figure 1.

In order to estimate the focal length of the thermal lens, the Nd:YLF was set in a high Q cavity with the same mirrors, apart the output coupler, which in this case had a 300 mm of ROC and HR(R>99.9%) at 1053 nm and 1167 nm. Given this cavity, the output coupler was translated so as to vary the cavity length from 18 mm to 265 mm and the 1053 nm output power measured.

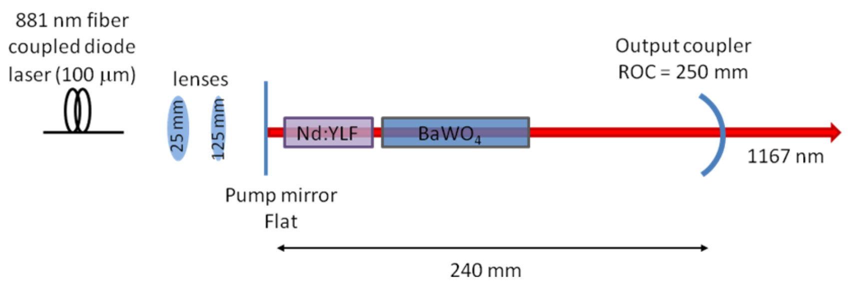

Fig. 1. Nd:YLF/$BaWO_4$ Raman laser setup.

This pump focusing optics delivered a pump beam waist (radius) of 250 μm and the fundamental resonator mode was slightly smaller than the pump.The mode in the Raman crystal was about 400 μm of diameter.

Finally, we tried to obtain some yellow conversion by SHG in a 4x4x10 mm^3, type I, LBO crystal cut for non-critical phase matching. As a first test, we modified the cavity to one with HR mirrors, R>99.99% at 1053 nm and 1167 nm and high transmission at 583 nm (T>95%). Also, we changed the curvature of the mirrors, to achieve a small mode size in the doubling crystal. The pump mirror used had a ROC of 400 mm and the output coupler a ROC of 200 mm, and the cavity was 80 mm long. An intracavity mirror, antireflection coated (AR) at 1053 nm and 1167 nm and with T>95% of reflectivity at 583 nm, was used to reflect the backward propagating yellow beam to the output of the laser.

3. Results and discussions

Figure 2(a) shows the output power at the fundamental for different, high Q, cavity lengths. The results show that the thermal lens of Nd:YLF under high Q condition is longer than 250 mm, since no rollover was noticed for a cavity of 265 mm. Hardman et. al. found a thermal lens for 1053 nm of more than 1 m when lasing for 12 W of incident pump power [8]. In our case, we could expect a slightly shorter focal length than 1 m because we pumped the crystal up to 17 W, but using a direct pumping wavelength, 881 nm, which reduces the thermal loading.

Figure 2(b) shows the output power at 1167 nm as a function of absorbed power. The Raman laser provided a maximum output power of 1.5 W operating in CW regime. The beam quality was measured using a beam scope (Beamscope P8, GENTEC) when the laser was pumped with 15 W. The result is a M^2 of 1.43 in the horizontal and 1.51 in the vertical, Figure 2(c).

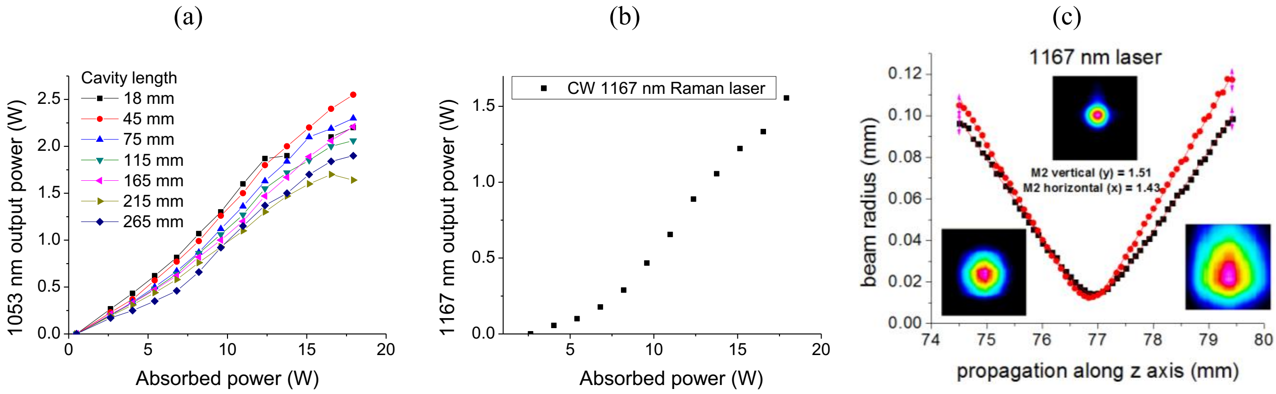

Fig. 2. (a) high Q cavity 1053 nm output powers for different cavity lengths, (b) CW 1167 nm output power as function of absorbed pump power and (c) M^2 measurement of the Raman laser with beam profiles in the near field, focus and far field.

The cavity used to produce 1.5 W at 1167 nm is considered a long cavity for Raman lasers, since the most efficient ones were based on self-Raman configurations [3,6,9], and in those cases, a strong thermal lens takes place, demanding the use of very short cavities. The advantage of a long cavity is in fact its capacity to provide more longitudinal modes, which is a feature that plays an important role for low amplitude noise lasers. Furthermore, Nd:YLF has a gain bandwidth of 358 GHz at 1053 nm compared to 344 GHz for Nd:GdVO$_4$, 254 GHz for Nd:YVO$_4$ and 119 GHz for Nd:YAG [10,11], providing naturally more longitudinal modes than the others.

The preliminary SHG test resulted in 0.61 W at 583 nm, and the corresponding laser characteristics is shown in Figure 3. A competitive oscillation between 1053 nm and 1047 nm, which was not observed when operated at 1167 nm. It happened due to the fact that now, an extra loss is introduced by the SHG to the 1053 nm line.

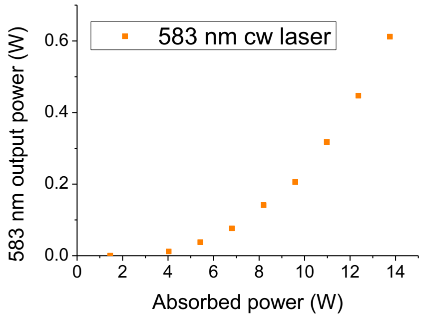

Fig. 3. 583 nm cw laser performance.

The pure oscillation of 1053 nm was possible only up to 14 W of pump power. Above 14 W, the 1047 nm line starts to oscillate, reducing the 583 nm output power. One way to overcome this problem is to introduce more losses to the 1047 nm line, as an example, a Brewster window or any low loss polarizing optics, since 1053 nm and 1047 nm have orthogonal polarizations. By solving this issue, we expect to be able to power scale the yellow emission in order to achieve multi-Watt yellow powers.

4. Conclusion

We have proved the capacity of Nd:YLF crystal to operate in long Raman laser cavities without lose stability, high power and good beam quality. Our ongoing work is aimed at obtaining very low amplitude noise Raman lasers and higher conversion efficiencies for Raman shift, second harmonic generation and sum frequency by means of “V” shaped cavities. We have also showed some preliminary cw yellow laser generation, reaching 600 mW, but limited by competition between fundamental transitions.

Acknowledgements

We are grateful to CAPES for supporting Jonas, CAPES scholar: Proc nº 5381/09-6.

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