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Nd:YLF/KGW intracavity Raman laser in DBMC configuration at 1147 and 1163 nm in TEM_{00}

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ABSTRACT

A Nd:YLF / KGW intracavity Raman laser in DBMC (double-beam-mode-controlling) configuration has been investigated in this work. The fundamental wavelength laser was generated using a Nd:YLF crystal pumped in DBMC configuration generating an emission wavelength of 1053 nm in σ-polarization. A VBG (volume-Bragg-grating) equipped diode emitting at 797 nm was used as pump source. The KGW crystal has two strong Raman lines, 768 cm^{-1} and 901 cm^{-1}, generating two Raman wavelengths at 1147 nm and 1163 nm, respectively. The DBMC technique allows to produce TEM_{00} stable output in a side-pumped configuration with no requirement to introduce any additional mode selection technique, thus achieving high efficiency for fundamental TEM_{00} operation. The high power density of the fundamental laser combined with intracavity Stokes conversion produces an efficient Raman laser. Allying both techniques, the Nd:YLF in DBMC configuration and the intracavity Raman generation, it was possible to generate an output power at 1163 nm of 3.2 W corresponding to a diode-to-Raman conversion efficiency of 8% with slope efficiency of 8.8 %. For the emission at 1147 nm, 3.5 W of output power was achieved with a diode-to-Raman conversion efficiency of 11% and slope efficiency of 9%. The beam quality was M^2 =1.9 and 1.1 in the horizontal and vertical direction, respectively. This is, to our knowledge, the first report of a side-pumped Nd:YLF/KGW intracavity Raman laser in DBMC configuration.

Keywords: Raman lasers, intracavity Raman lasers, near-IR lasers, diode pumped lasers, side-pumped lasers.

1. INTRODUCTION

The first Raman laser employing a Nd:$LiYF_4$ (Nd:YLF) fundamental laser crystal was reported by Savitski et al.[1]. The authors used a Nd:YLF laser module operating at 1047 nm to pump a diamond crystal for Raman generation, obtaining 5,1 W at 1217 nm (M^2~1.1). They also used this same system to pump a KGW crystal, obtaining 6.1 W at 1139 nm (M^2~5.5). The corresponding diode to Stokes conversion efficiency was 4%. The second Nd:YLF based Raman laser was reported by Bu et al.[2], also operating at the π-polarized 1047 nm emission which was Stokes shifted by a $SrWO_4$ crystal and frequency-doubled in a LBO crystal generating a laser source at 579 nm with 889 mW output power with a conversion efficiency of 5.8%. The most recent work was reported by Neto et al.[3] composed of a Nd:YLF/KGW continuous-wave (CW) Raman laser system in a longitudinal pump configuration. They achieved results at near IR, yellow and lime-green wavelengths with 14% conversion efficiency at 552 nm and 1.56 W output power at 1163 nm (quasi-CW operation) with M^2~1.49 and conversion efficiency of 7.4%. At the wavelength of 1147 nm, 1.2 W of (quasi-CW) output power was achieved with M^2~1.44 and 6% conversion efficiency.

The benefits of using Nd:YLF as the fundamental laser crystal in intracavity Raman lasers are that it provides for a naturally polarized emission and a weak thermal lens[4]. The π and σ polarized emissions at wavelengths of 1047 nm and 1053 nm, respectively, are shorter than the typical 1064 nm emission of many other Nd^{3+} doped laser crystals, thus providing an unusual range of Stokes wavelengths and corresponding visible wavelengths. As a disadvantage, it has a low thermal fracture limit, which restricts the maximum absorbed pump power during cw operation. The main benefit for our laser set-up is that this crystal has a slightly smaller absorption cross-section than e.g. $GdVO_4$ or YVO_4, which is well suited for a Brewster angle incidence, side-pumped configuration as shown in Figure 1 [5]. This means that no coating is necessary on the entrance and exit facet of the crystal, which is crucial for the generally loss-dominated, low-gain Raman lasers. Additionally, the high intracavity intensities combined with the demanding coating specifications require very specific coatings that only few companies are capable of delivering.

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Another characteristic that inspires side-pumped set-ups is the possibility of power scaling [6]. Diode-end-pumped configurations show limited power scalability because of two principal challenges, which are the coupling of high-power pump beams to the TEM_{00} mode of the laser resonator and second, managing the strong thermally induced lensing. Furthermore, increasing the power of fiber-coupled diode pump sources is typically accompanied by increased spectral bandwidth as well as an exponential increase in costs if reasonable beam quality is required. This makes the pump source an item of disproportional cost within the otherwise economical Raman laser device. Also, fiber-coupled pump sources are generally not polarized which, in connection with birefringent gain media, may cause further overall efficiency loss. An alternative, cost-effective approach is to use the herein proposed side-pumping scheme with Brewster angle incidence geometry.

The KGW was chosen as the Raman-active crystal because it has a similar Raman gain to vanadate crystals of ~ 4.5cm/GW[7] with two strong Raman lines at 768 cm^{-1} and at 901 cm^{-1} that can be accessed separately, just by the orientation of the KGW. Therefore, it is possible to obtain two different first Stokes emissions with this system of 1147 nm and 1163 nm. Consequently, hereafter, many visible lines from the green to the yellow-orange range of the visible may be achieved by second harmonic generation (SHG) or sum-frequency generation (SFG). From the Stokes wavelengths of 1147 nm and 1163 nm one can to achieve, through SHG and SFG, the wavelengths 549 nm, 552 nm, 573 nm and 581 nm.

The double-beam-mode-controlling (DBMC) technology[6,8,9] adjusts the modal behavior inside the cavity by controlling the waist size and the distance between the two beams inside the crystal that undergo total internal reflection at the pump surface, preventing thereby higher order modes from oscillating. This loss-less mode selection mechanism together with a good overlap between the two laser beams and the pump region inside crystal allows for the generation of efficient, stable, and high-quality TEM_{00} laser operation. It has been demonstrated that this side-pumped technology can be much more efficient than longitudinal pumping[10].

Here we report for the first time, to our knowledge, a diode-side-pumped Nd:YLF as a fundamental laser in an intracavity Raman laser.

2. MATERIALS AND METHODS

In the DBMC configuration, the mode waist size inside the crystal is chosen large enough such that a good overlap with the pump inversion is guaranteed and, at the same, the distance between the two beams must be small enough in order to impede higher order mode from oscillating. It has been demonstrated that the bigger the absorption coefficient of a crystal or the larger the size of the laser beam fundamental mode, the higher is the threshold for additional oscillation of the next higher mode (generally TEM_{10}) [9] aside from the already oscillating TEM_{00} mode. For the cavity set-up of this work operating at the maximum incident pump power, we simulated a minimum necessary waist size inside the Nd: YLF crystal of equal to or slightly greater than 500 µm [11]. Given the Brewster angle incidence of the beam (index of refraction of Nd:YLF is 1.45 at 1053 nm), this corresponds to a beam waist of approximately 350 µm outside the crystal. The optimal beam separation for the highest output power in TEM_{00} had already been determined in previous works [10] and was maintained in 2 mm. An image of the aligned cavity can be seen in figure 2.

In order to be able to achieve good Stokes conversion, it is necessary to produce a much smaller beam waist of the order of 100 µm in the resonator at the position of the KGW crystal. Several simulations were performed using the LasCad software before selecting a z-cavity coupled to the DBMC configuration as shown in Figure 1. This cavity has 5 mirrors composed of two plane mirrors and two curved mirrors of radius of curvature R = 75 mm, all highly reflective for all wavelengths involved (HR(0°,1020-1200nm)>99.99% and R (0°, 808-980nm)<2%), and a flat output coupler optimized for the desired laser output. The output coupler (OC) for the fundamental emission at 1053 nm had 15% transmission and the OC for the Stokes emissions had a highly reflective coating for 1053 nm and ~ 2% and ~ 0.7 transmission at the Raman wavelengths of 1163 nm and 1147 nm, respectively. The KGW Raman crystal (Castech Inc.) with dimensions of 5x5x10 mm^3 had AR coatings for 1064-1180 nm, and 880/808nm. The Raman crystal was positioned between the two curved mirrors M3 and M4 (Figure 1) which allowed us to almost independently tune the beam waist in the KGW without changing the beam waist in the Nd: YLF crystal.

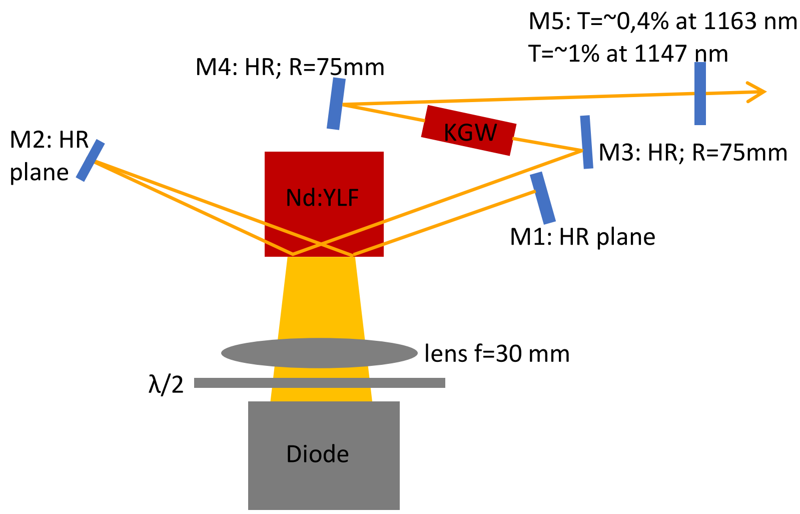

Figure 1: Configuration of the DBMC Nd:YLF/KGW Raman laser DBMC. Mirrors M1 to M4 are highly reflective (HR) for the fundamental and the Raman wavelengths; M5 is HR at the fundamental wavelength partially transmissive at the Stokes wavelengths.

For measuring the fundamental laser output, the cavity was maintained as in Figure 1 removing the KGW crystal and changing the output coupler to 15% transmission at 1053 nm. All other cavity mirrors had a highly reflective film in the range of 1020-1200 nm.

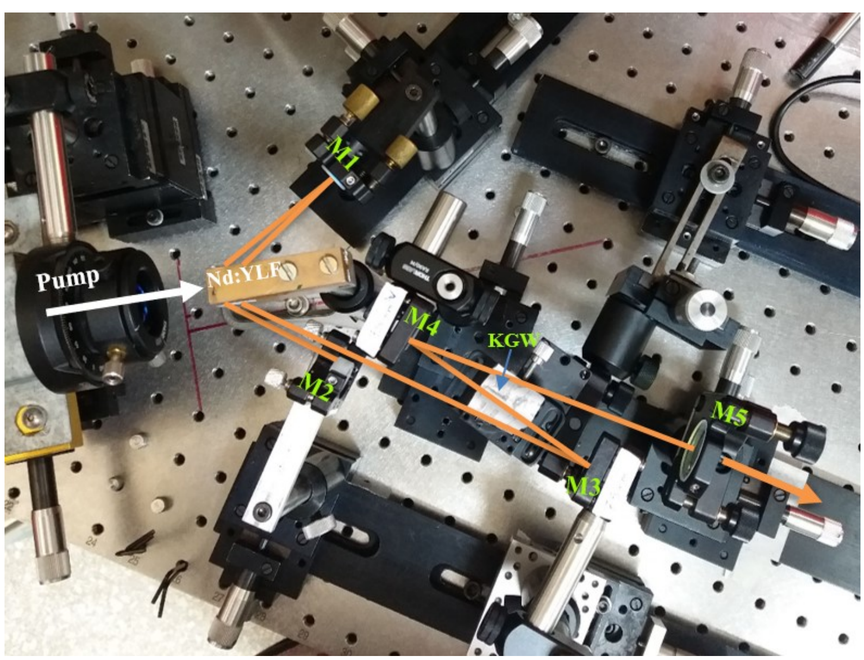

Figure 2: Photo of the Raman laser in DBMC geometry with overlay of the intracavity beam path.

Cavity alignment of this configuration needed to be performed in several steps, aligning parts of the cavity at a time. First, an alignment laser was positioned behind the M2 flat mirror and the alignment is made for one single bounce between M1 and M2. Then the alignment laser is moved behind mirror M3 and the cavity is aligned for a simple DBMC configuration using only M1, M2 and a flat output coupler instead of mirror M3. Next, the mirror M3 is tilted in such a way that the reflection of the alignment laser on its rear face forms an angle of 20 ° with respect to the entering alignment laser. This ensures that the resonant beam incidence angle is 10 °. Next, the alignment laser is positioned behind the coupling mirror M5 to align the rest of the cavity. After optimizing the cavity for maximum emission at the fundamental wavelength, the KGW crystal is introduced into the cavity. Ideally the KGW position is centered between the curved mirrors, however the pump power had to be limited in order to avoid damage to the coatings.

Throughout all experiments the laser was operated at a repetition rate of 5.Hz and with a pulse duration of 350 µs.

3. RESULTS AND DISCUSSION

Using the 15% output coupler and the DBMC configuration, the following results were achieved for the fundamental laser (figure 3).

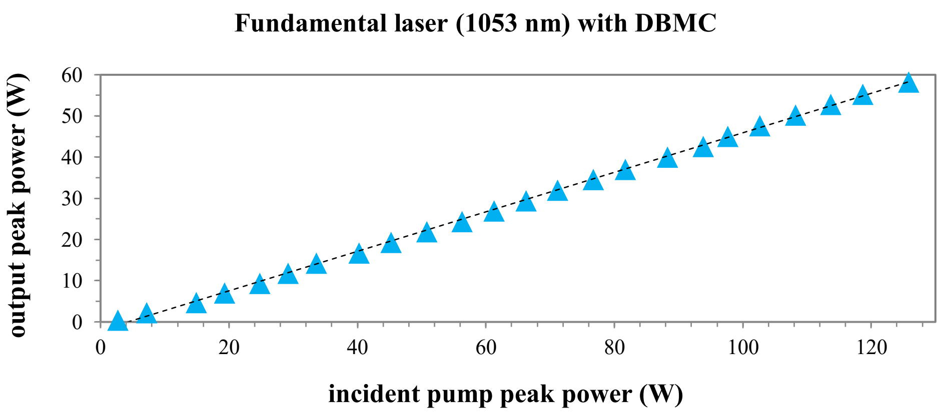

Figure 3: Input to output power conversion curve of the 1053 nm fundamental laser in DBMC configuration coupled to the z-cavity as in figure 1 but without the KGW crystal.

The slope efficiency obtained for the fundamental laser was 48% and 47% of optical efficiency. but in this case, there is a big improvement with the emission in TEM_{00} mode with horizontal M^2 of 1.57 and vertical M^2 of 1.05. The result can be directly compared to our previous work that was realized in a similar cavity but with only one single bounce of the laser mode at the pump face [12]. This previous work, which employed a diode without VBG, resulted in similar fundamental laser efficiencies but with multimode output.

Next, the Raman crystal was inserted into the cavity and the output coupler replaced. We experimented with two different KGW crystal length, 25 mm and 10 mm, and found that the 10 mm long KGW crystal operates better, probably due to smaller losses given its reduced length. The crystal was positioned such that the Stokes and fundamental polarizations were parallel to the Ng axis of the KGW. Results were initially obtained with the Stokes shifts of 768 cm^{-1} and 901 cm^{-1} obtained simultaneously, 1147 nm and 1163 nm, respectively. A total conversion efficiency of 11% and 17% slope efficiency were obtained for this simultaneous Raman wavelengths operation (figure 4).

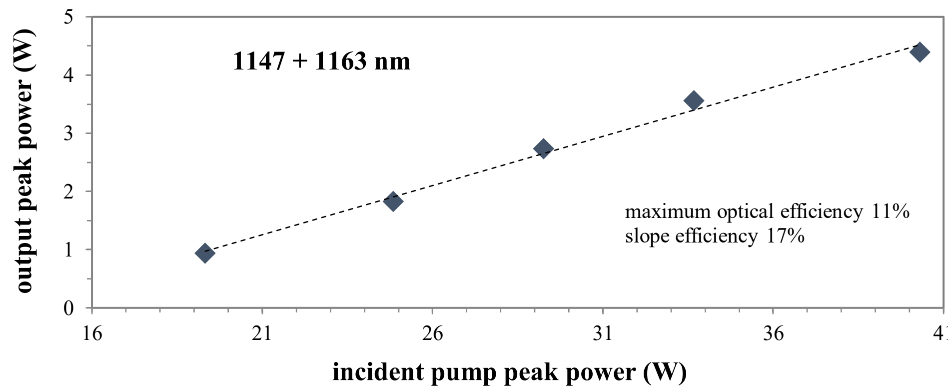

Figure 4: Diode to Raman input-output conversion curve of the DBMC + z-cavity with simultaneous Stokes shift of 768 cm^{-1} and 901 cm^{-1}.

The 1147 nm Raman laser could be obtained alone by optimizing the 1147 nm emission separately. This procedure automatically decreased the 1163 nm emission to the point of zero output power at his wavelength. The results are shown in figure 5.

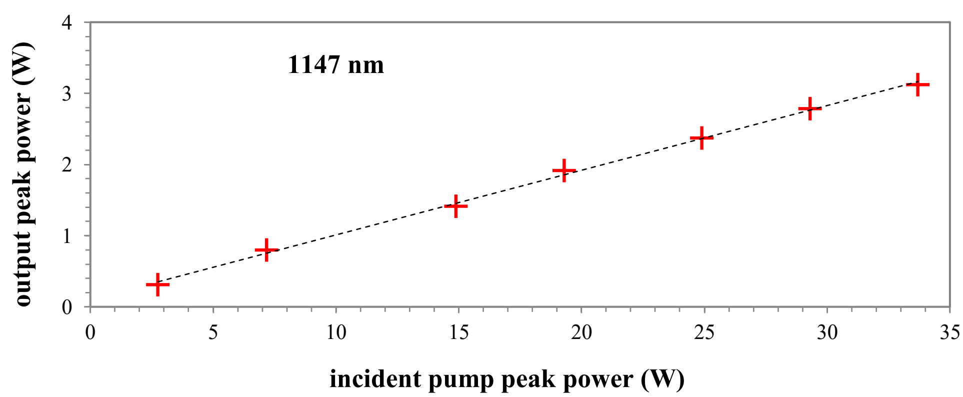

Figure 5: diode to Raman conversion curve for the 1147 nm emission.

The 1147 nm emission alone achieved a slope efficiency of 9% and an optical conversion efficiency of 11%. The output beam quality was close to TEM_{00} mode with vertical M^2 of 1.1 and horizontal M^2 of 1.9 at the maximum output power of 3.12 W. Again, comparing these results with those obtained for the single-folded, side-pumped cavity of reference 11 it can be observed that there is a visible gain in quality when the DBMC configuration is applied.

In order to achieve single emission at 1163 nm the KGW crystal was rotated 90 ° so that the 901 cm^{-1} Stokes displacement was more efficient. the result obtained can be seen in figure 6.

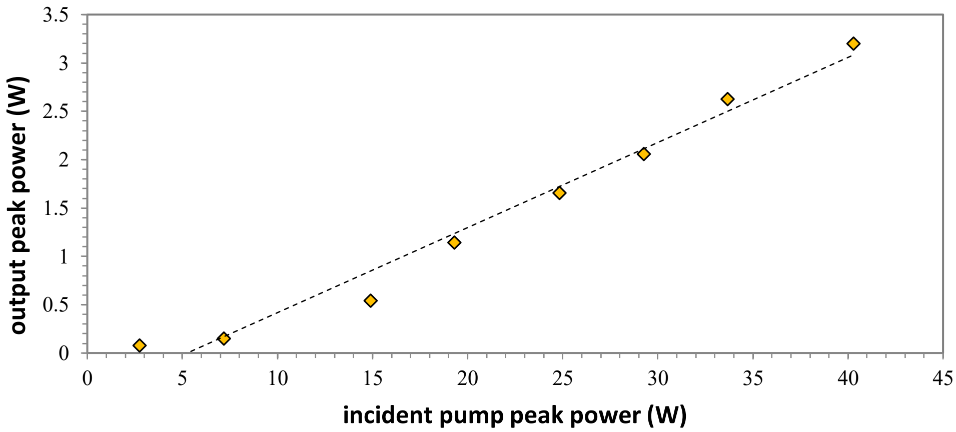

Figure 6: diode to Raman conversion curve for the 1163 nm emission.

A maximum output power of 3.2 W with an 8.8% slope efficiency and 8% diode to Raman conversion efficiency were obtained. The beam quality for this result was similar to that previously reported for the 1147 nm conversion. We expected that this Stokes shift would achieve a higher conversion efficiency compared to the laser at 1147 nm, since the 901 cm^{-1} conversion at this polarization, parallel to the N_m Crystal axis, has a greater cross-section than the 768 cm^{-1} conversion in the polarization parallel to Ng. However, this was not observed and the emission at this wavelength proved difficult to reach in this cavity configuration.

As explained before, the maximum pump power had to be decreased to below 40 W because of coating damage to the KGW. A summary of these results can be seen in the table 1.

Table 1. Raman results obtained for the DBMC cavity configuration.

Wavelength (nm)	Output Power (W)	M^2	Optical efficiency (%)
1147	3.12	Vertical 1.1	11
1163	3.2	Horizontal 1.9	8

4. CONCLUSIONS

Comparing these results with those obtained by Kores et. al. [13], which reported TEM_{00} mode emission for the 1st Stokes emission at 1176 nm with 5.4% optical efficiency and 3.7 W maximum output power in a $Nd:YVO_4$ self-Raman DBMC configuration, the results obtained in this work for both wavelengths, 1147 and 1163 nm, are significantly higher, obtaining inferior results only in terms maximum output power. Maximum pump power has been limited for safety purposes only, and increasing the beam waist at the KGW crystal should allow higher output powers without crystal coating damage.

Comparing with the results obtained by Neto et.al.[3], who achieved during quasi-CW operation 6% optical efficiency and 1.2 W maximum power at 1147 nm and 7.4% optical efficiency and 1.56 W maximum output power at 1163 nm, it can be stated that our results are higher. This direct comparison shows again that the DBMC side-pumping configuration can be advantageous compared to the longitudinal pumping configuration.

The DBMC configuration permits higher output power values, with excellent optical conversion efficiencies allowing to maintain beam quality near the diffraction limit without loss of efficiency. At 1147 nm, single-mode transverse operation was obtained with 3.12 W of maximum output power and 11% optical efficiency. At 1163 nm, also in transverse single-mode, 3.2 W of maximum power was obtained with 8% optical efficiency. In comparison with single-bounce, side-pumping[12], where TEM_{00} mode can also be achieved by introducing losses for higher order modes through cavity misalignment, the better results obtained with the DBMC cavity can be recognized by the fact that DBMC requires one to align the cavity for maximum output power in order to remain in fundamental transverse mode and, on the contrary, misalignment causes multimode operation.

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