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," Proc. SPIE 10518, Laser Resonators, Microresonators, and Beam Control XX, 1051816 (16 February 2018); doi: 10.1117/12.2290596

Event: SPIE LASE, 2018, San Francisco, California, United States

Intracavity diode-side-pumped Raman laser at 1147 nm and 1163 nm

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ABSTRACT

Wavelengths in the yellow-orange range are of significant interest due to their application potential in the medical and biomedical areas, as well as for applications in laser displays and in remote sensing. These wavelengths can be obtained by frequency-doubling or sum-frequency generation of lasers with near-IR emission like VCSELS, fiber lasers, and OPOs. However, all these alternatives have several limitations that justify the development of alternative methods. As a possible solution for these limitations, a configuration of an intracavity converted Raman laser may be developed to obtain two wavelengths, 1163 nm, and 1147 nm, with high efficiency and good beam quality. This paper presents a configuration of a side-pumped intracavity converted Raman laser to achieve these objectives. A Nd:$YLiF_4$ crystal was used as fundamental wavelength gain crystal. The side-pumped configuration guarantees practicability and cost reduction while allowing good efficiency and fundamental mode laser beam. The intracavity conversion configuration allows high fundamental wavelength power at the Stokes crystal in order to facilitate the obtention of the Stokes wavelengths and enables optimization of its efficiency. As a result an output power at 1163 nm of 3.8 W in the multimode regime was obtained, corresponding to a pump to Stokes efficiency of 9.6%. The TEM_{00} diode to Stokes efficiency was 7%. For the emission at 1147 nm, 1.5W of output power with a diode to Stokes efficiency of 3.7% was achieved. The side-pumped Nd:YLF/KGW intracavity Raman laser configuration is reported for the first time, to our knowledge.

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

1. INTRODUCTION

Lasers emitting in the yellow-orange wavelength range are of interest due to their large number of applications such as sodium guide star, medical and biomedical applications, display technology and quantum computation. One important application is the treatment of ophthalmologic diseases of the retina where the orange-yellow radiation presents good clinical results with minimal collateral effects[1]. The application of photocauterization of small blood vessels is a highlight of that wavelength, because water does have little absorption in the orange-yellow range whereas both, blood and melanin, have a considerable absorption in this spectral range[2]. The orange-yellow laser has applications in confocal microscopy too. Fluorescence microscopy uses light of 588 nm because some fluorophores have their absorption peak[3] at this wavelength. This range of wavelengths has also potential application in flow cytometry, a technique that is in demand of wavelengths between 561 nm and 640 nm with power stability, low noise, and Gaussian mode beam quality [4, 5].

The first laser operating in this range, based on a Raman laser, was reported in 2007, using a Nd:$GdVO_4$ crystal for the fundamental laser and a KGW crystal for Stokes conversion to the 1170 nm range. In this work, 704 mW of output power at 588 nm was achieved with 5,1% optical efficiency[6]. With the same laser crystal and a $BaWO_4$ Raman crystal, 2,9 W of output power at 590 nm was achieved with 11% of optical efficiency[7]. The same group reported a self-Raman laser with 8,4% of optical efficiency and output power of 320 mW using Nd:YVO_4 [8]. The highest output power of 4,3 W obtained at 590 nm and optical efficiency of 17% was with a self-Raman laser with a Nd:$GdVO_4$ crystal [9].

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Laser Resonators, Microresonators, and Beam Control XX, edited by Alexis V. Kudryashov, Alan H. Paxton, Vladimir S. Ilchenko, Proc. of SPIE Vol. 10518, 1051816 · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2290596

Another work achieved 3,5 W output power and 13,3% optical efficiency with a $Nd:LuVO_4$ self-Raman laser [10]. Kores et al.[11] reported a diode-side-pumped $Nd:YVO_4$ self-Raman laser operating at 1176 nm with an optical conversion efficiency of 11,5% and 8 W multimode or 3,7 W TEM_{00} mode output power, having an optical conversion efficiency of 5,4% in quasi-CW operation.

Savitski et al.[12] used a Nd:YLF laser module operating at 1047 nm to pump a diamond crystal, obtaining 5,1 W at 1217 nm (M^2~1.1). Using this same system they also pumped a KGW crystal, obtaining 6.1 W at 1139 nm (M^2~5.5), corresponding to a diode to Stokes conversion efficiency of 4%. Bu et al.[13] operated a Nd:YLF-based laser at 1047 nm that was Stokes shifted using a $SrWO_4$ crystal and then frequency doubled the wavelength in LBO to generate a laser source at 579 nm with 889 mW output power corresponding to a diode to yellow conversion efficiency of 5.8%. The most recent work was reported by Neto et al.[14], which consisted of a Nd:YLF/KGW Raman laser pumped in a longitudinal configuration in continous-wave (CW) operation. They achieved results for quasi-CW operation at near IR, yellow and lime-green wavelengths of 1.2 W output power and M^2~1.44 at 1147 nm with 6% of conversion efficiency, 1.56 W output power at 1163 nm with M^2 of 1.49 and conversion efficiency of 7.4% and 14% conversion efficiency at 552 nm, respectively.

The benefits of using $Nd^{3+}:LiYF_4$ (Nd:YLF) as the fundamental laser crystal in intracavity Raman lasers are that it provides a naturally polarized emission and a weak thermal lens[15] when compared with isotropic crystals such as YAG. It has π and σ polarized emissions at different wavelengths, 1047 nm, and 1053 nm, respectively, shorter than the traditional 1064 nm, thus providing an unusual range of Stokes wavelengths and corresponding visible wavelengths. The desired polarization (π or σ) can be selected by the Brewster angle. In our case, the crystal was c-cut and the σ polarization selected by the Brewster angle (~55.4º) had wavelength of 1053 nm.

One of the benefits of the diode-side-pumped cavity set-up is power scaling, which is difficult in a diode-end-pumped configuration because of two principals challenges: the coupling of high-power pump beams to the laser resonator and the heat-management of the strong thermal lensing caused by the concentrated pump radiation. 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. Also, fiber-coupled pump sources are generally not polarized which, in connection with birefringent gain media, may cause further overall efficiency loss. This makes the pump source an item of disproportional cost within the otherwise economical Raman laser device. An alternative, cost-effective approach is to use a side-pumping scheme with Brewster angle incidence geometry, as cited before.

A KGW crystal was chosen as the Raman-active crystal because it has a high Raman gain of ~4.5cm/GW, similar to the vanadates[16]. An advantage of KGW is the fact that it has two strong Raman lines at 768 cm^{-1} and at 901 cm^{-1}, with similar gain, that can be accessed separately, just by the orientation of the KGW. Given that, it is possible to obtain two different Stokes wavelengths with this system, 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 we can achieve, through SHG and SFG, the wavelengths 549 nm, 552 nm, 573 nm and 581 nm.

Using a further refinement of the diode-side-pumped resonator[17,18], called the double-beam-mode-controlling (DBMC) technology[19,20], the modal behavior inside the cavity can be controlled by changing the distance between the two beams inside the fundamental gain crystal. By creating a good overlap between these two laser beams and the pumped region, higher modes are prevented from oscillating, which allows for the generation of efficient, stable, and high-quality TEM_{00} laser operation[21,22]. It has been demonstrated that this side-pumped technology can be much more efficient than longitudinal pumping, achieving 63% optical efficiency in Nd:YLF[23,24]. Given the high efficiency of DBMC and the cost-effectiveness of side-pumping, it is therefore of interest to investigate if this technology can be applied advantageously to intracavity-converted, solid-state Raman lasers.

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

As pump source a 40W diode laser emitting at 792 nm was used. The chosen operational regime was quasi-CW and the diode power supply operated at the frequency of 71 Hz and pulse width of 500 µs (FWHM). These values were chosen to guarantee good population inversion inside the laser crystal without the risks of damage to the coatings and to the crystals. The pump wavelength of 792 nm was chosen to access the highest absorption peak of Nd:YLF in the π polarization (Figure 1).

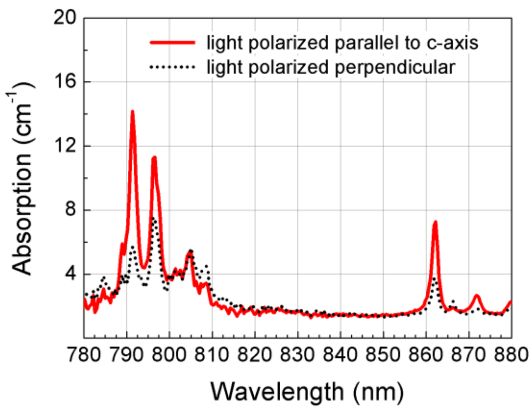


Figure 1: Absorption Spectrum in π polarization of a Nd:YLF crystal with 1% doping.

The selection of the emitting wavelength of the diode laser was done through adjustment of the diode temperature. A Peltier element was used for temperature scanning. However, the diode emission is dependent on its current too and for each current there is an ideal temperature (Figure 2).

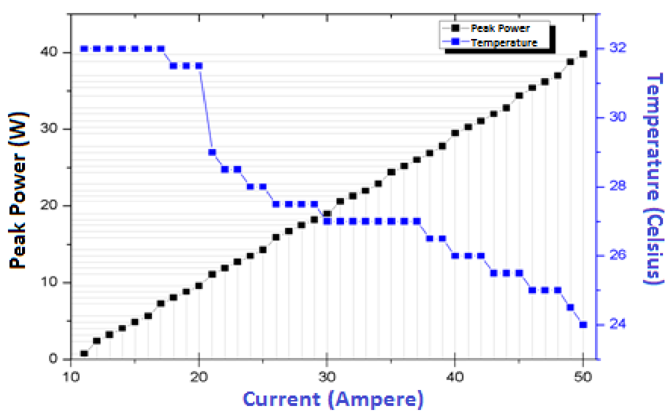
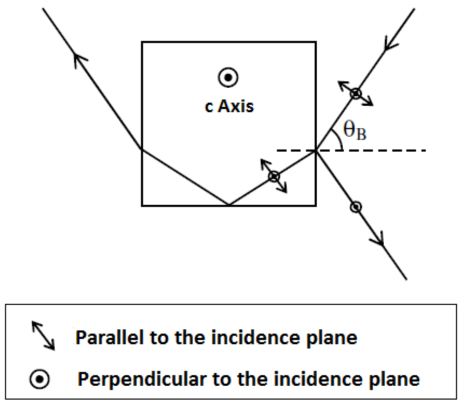


Figure 2: Graphics of the temperature adjustments of the pump diode at each diode current in order to maintain the diode emission at 792 mm.

The Nd:YLiF$_4$ laser with 1% doping, c-cut and with dimensions of 13x13x3 mm^3 (Crystech Inc.) was without anti-reflective coatings because the incidence angle of the resonant beam at the crystal facets was chosen to be Brewster angle, thus selecting the σ polarization responsible for the 1053 nm emission (see Figure 3).

The length of the cavity was determined by simulations using LasCad^R software. During the first test, there was no Raman crystal inside the cavity in order to optimize only the fundamental beam. A curved mirror with a radius of 3 meters and highly reflective (HR) coating at 1053 nm (M1) and a plane output coupler with transmission of 15% for the fundamental beam were used. In the front of the diode, a half-wave-plate was positioned to adjust the polarization of the pump beam so that it matches the π polarization that is absorbed in the Nd:YLF crystal. After the half-wave plate a f = 20 cm lens was positioned to focus the diode laser beam. The dimensions of the pump beam were chosen in order to optimize the gain inside the Nd:YLF crystal and to maintain a good overlap between the pump beam and the resonant mode. Basically, the pump beam generates a light sheet inside the crystal that is screened by the fundamental beam which undergoes a total internal reflection at the pump surface as shown in Figure 3.



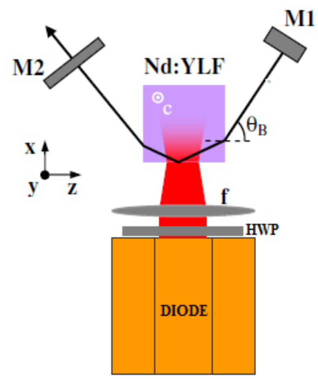


Figure 3: The left figure illustrates how the selection of the laser beam polarization was made through the Brewster angle. The right figure shows how the Nd:YLF crystal was positioned with respect to the pump diode in order to select the pump polarization which is highly absorbed along the crystal's π polarization direction.

A KGW crystal was used with dimensions of 5x5x10 mm^3 and with HR coating for 1053 nm, 1147 nm and 1163 nm at the entrance and exit facets. For an efficient Stokes conversion, the beam waist of the resonant fundamental beam inside the Raman crystal should produce a depth of focus equal to the crystal length. This is necessary because the Raman conversion efficiency depends on the fundamental beam intensity. For this new cavity configuration, a curved mirror with a radius of 75 mm that has HR coating for 1053 nm, 1147 nm, and 1163 nm substituted the former curved mirror. A plane mirror was used as output coupler with HR coatings for 1053 nm and slightly transmitting coatings at the two Raman wavelengths of ~0,4 % transmission at 1163 nm ~1% at 1147 nm. For the cavity of about 7 cm length (close to the stability limit), a spot size in the KGW of about 100 μm radius was achieved. Smaller beam waists generated damage to the crystal's coatings. The KGW was introduced close to the output coupler because the cavity's beam waist was at the output mirror (Figure 4).

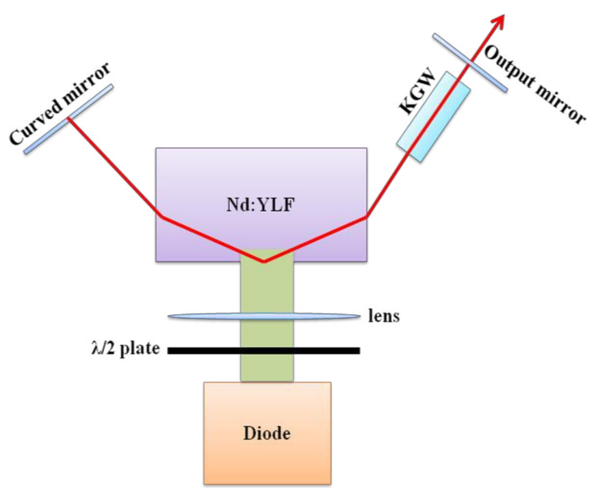


Figure 4: The optical cavity configuration. The KGW crystal was positioned in one of the arms of the resonator for the intracavity Stokes conversion. The KGW was positioned close to the output mirror because the beam waist was smallest there.

3. RESULTS

As was discussed in the previous section, the development of the laser cavity was made in two steps. The first step was the optimization of the fundamental laser at 1053 nm. In this first configuration an optical efficiency of 47% and a slope efficiency of 49% (Figure 5) were achieved using a mirror with 15% transmission.

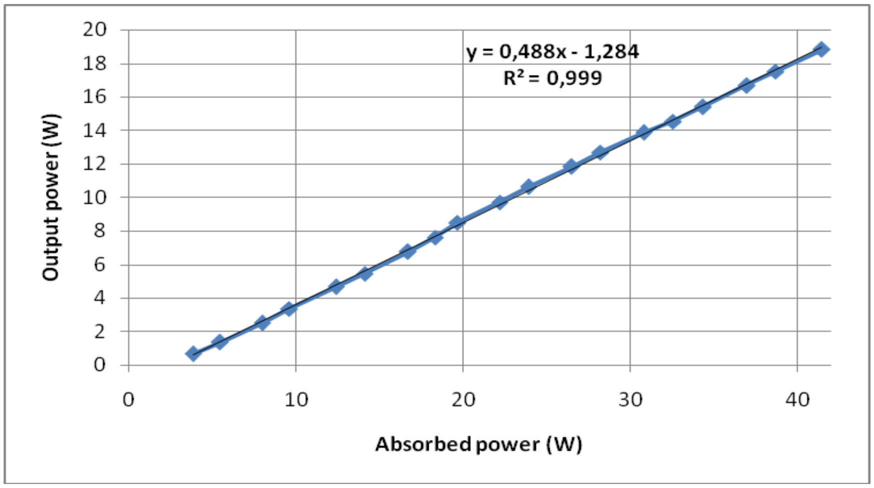


Figure 5: Input-output curve of the fundamental laser emission. A Slope efficiency of 49% was achieved and an optical efficiency of 47%.

The KGW crystal was positioned inside the cavity with its optical axis adjusted to select the 901 cm^{-1} Stokes shift. For this purpose, the fundamental and Stokes polarization must be parallel to the N_m refractive index axis of the KGW, producing as a result a Stokes emission at 1163 nm. By means of alignment, it was possible to achieve two beam quality results for this wavelength; the first was achieved in order to provide the best conversion efficiency with multimode beam quality. Using a mirror of 0.4% transmission at 1163nm, the laser achieved a slope efficiency of 10% and a conversion efficiency of 9.6%. The maximum output power was 3.8 W (Figure 6).

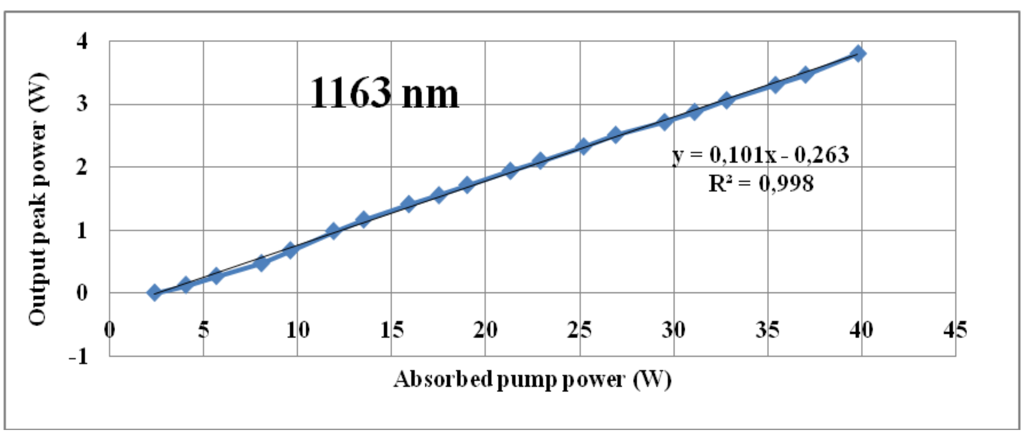


Figure 6: Stokes conversion at 1163 nm as a function of the absorbed pump power. Emission is in multimode beam quality. A slope efficiency of 10% and an optical efficiency of 9.6% were achieved. The maximum output power was 3.8 W.

The second alignment was used to provide the best beam quality, that is, emission in TEM_{00} mode. The results achieved were a slope efficiency of 6% and an optical efficiency of 7% with maximum output power of 2.4 W (Figure 7).

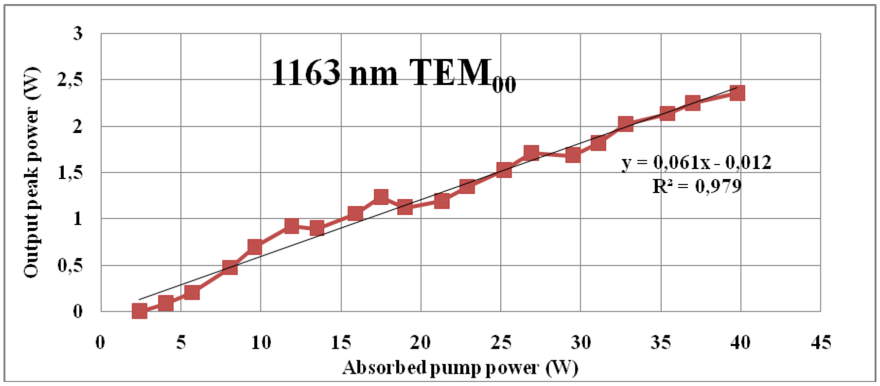


Figure 7: diode to Stokes (1163 nm) conversion curve. Emission is in fundamental (TEM_{00}) beam quality. Slope efficiency of 6% and a conversion efficiency of 7% were achieved and the maximum output power was 2.4 W

For a selection of the TEM_{00} mode by means of alignment, the laser beam mode was monitored through a CCD camera. Making small alterations in the alignment it was possible to get images of some modes, that make it possible to show how the beam quality evolves by means of alignment (Figure 8).

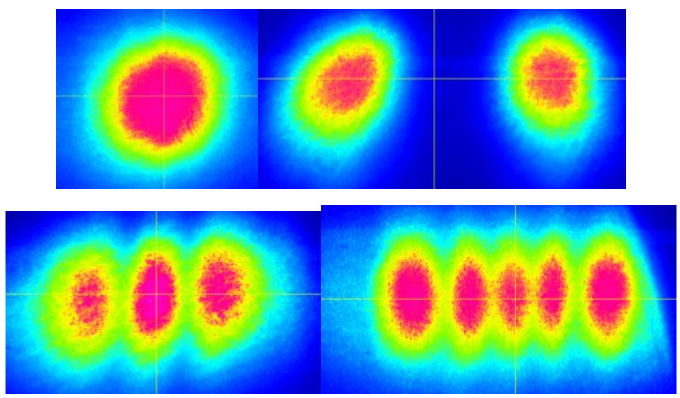


Figure 8: Mode images of the Stokes beam; the modes were obtained by alignment.

After the selection of the TEM_{00} mode, the knife edge technique was applied in order to make M^2 measurements of the Raman beam output (Figure 9).

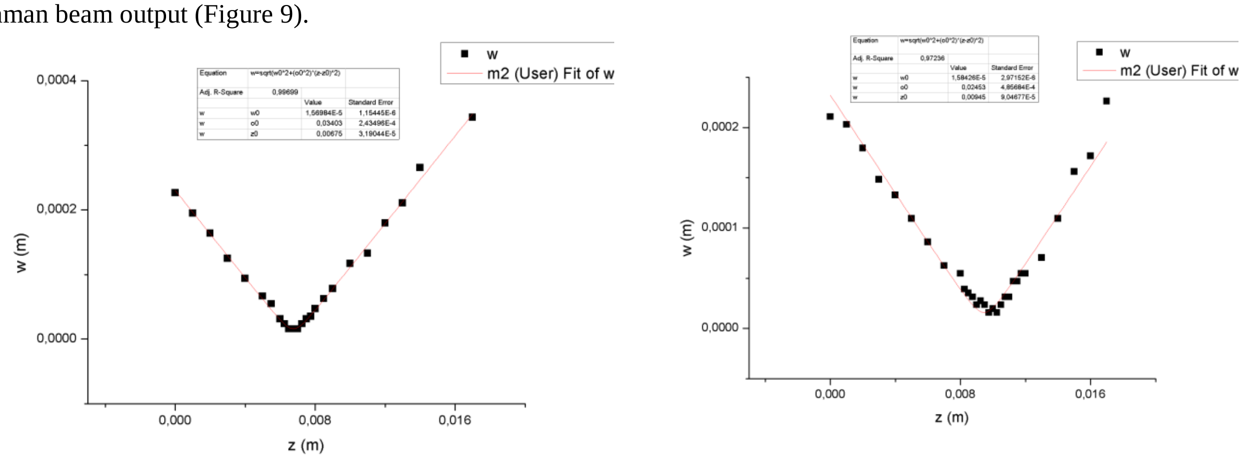


Figure 9: Measurements of M^2: vertical 1.44, horizontal 1.05 (TEM_{00} beam quality).

The KGW crystal was rotated by 90º to access the 783 cm^{-1} Stokes shift, where the fundamental and Stokes polarization are parallel to the N_g refractive index axis of the KGW, emitting at 1147 nm. For this wavelength, a slope efficiency of 5.5% and an optical conversion of 3.7% were achieved with output power of 1.5 W (Figure 10). The lower results and the much higher laser threshold can be in part attributed to the much higher transmission of the output mirror of 1% at this wavelength.

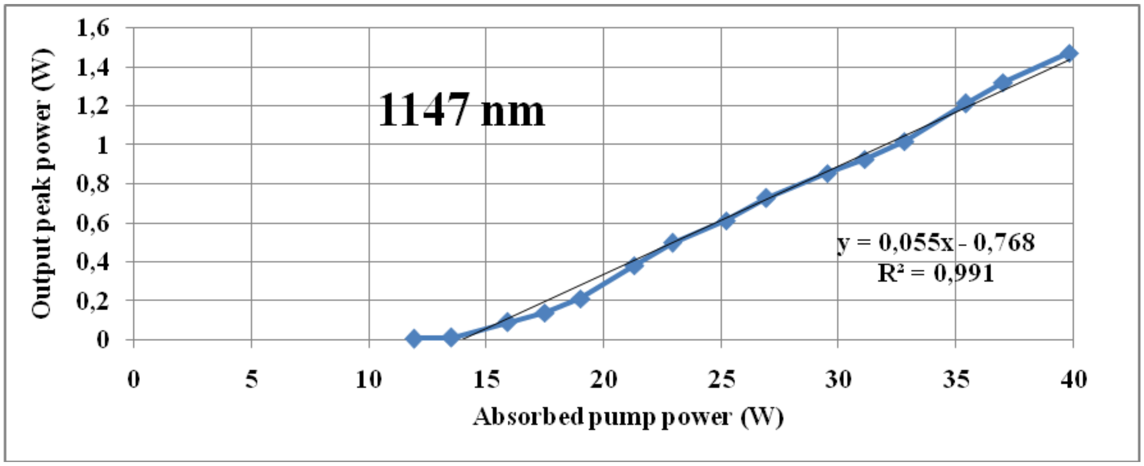


Figure 10: diode to Stokes conversion curve of the 1147 nm emission. Emission was in multimode beam quality. The slope efficiency was 5.5% and the optical efficiency was 3.7%. The maximum output power was 1.5 W

4. DISCUSSION

The results achieved in this work can be directly compared with the results in the work of Neto et al.[14], obtained for 1163 nm and 1147 nm, which used a Nd:YLF in a longitudinal pump configuration and also a KGW crystal for the Stokes conversion. Superior values in terms of output powers have been achieved in the present work at both wavelengths due to the fact that the lateral pumping configuration permits higher pump powers compared to the longitudinal pumping configuration. The results for the TEM_{00} beam characteristics at 1163 nm are similar in both works: here, a conversion efficiency of 7% and M^2 of 1.4 were achieved, they achieved M^2 of 1.49 and a conversion efficiency of 7.4%. Comparing the results at 1147 nm, the results presented here are higher output power but lower conversion efficiency.

A similar comparison can be made with the work of Kores et al.[11], with some exceptions, because in that work a Nd:YVO was utilized as self-Raman laser configuration. Self-Raman lasers are more efficient because the number of interfaces is much smaller, so the introduced losses are small in that type of cavity. However, that work utilized a laser cavity configuration very similar to ours and they also showed an evolution with the application of the DBMC technique. In that work, results were achieved at the 1176 nm emission, including a conversion efficiency of 11.5% with a multimode output power of 8 W (3.7 W in TEM_{00} mode). The multimode results compare well with our results at 1163 nm, however, in TEM_{00} mode operation our results show higher efficiency (7%). This reinforces the applicability of the side-pumped Nd:YLF configuration as a efficient intracavity Raman cavity.

5. CONCLUSION

The usefulness of the Nd:YLF/KGW laser in a side-pumped configuration as a generator of Raman wavelength at 1163 nm and 1147 nm has been demonstrated. The side-pumped configuration permits costs reduction and fundamental beam quality with good efficiency. The results were compared with results already existing in the literature for the same or similar wavelengths.

As a natural evolution of this work, we envision the application of the DBMC technique in this cavity. This should allow even higher conversion efficiency for the TEM_{00} mode and, consequently, a higher output power. This is because in the current cavity we achieve the TEM_{00} mode by introducing losses into the cavity through missalignment. With DBMC these losses are not necessary and the output power should be higher.

The last step of this work would be the obtaining of wavelengths in green and in the orange-yellow range. For this it is necessary make a conversion of the Raman wavelengths through SHG and SFG, which should allow to achieve wavelengths at 526 nm, 549 nm, 552 nm, 573 nm, and 581 nm.

ACKNOWLEDGEMENTS

We acknowledge financial support from CAPES, CNPq and FAPESP (grant 2012 11437-8).

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