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# Quasi-three level Nd:YLF fundamental and Raman laser operating under 872 nm and 880 nm direct diode pumping

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## ABSTRACT

Nd:YLiF<sub>4</sub> is the gain material of choice whenever outstanding beam quality or a birefringent gain material is necessary such as in certain applications for terahertz radiation or dual-frequency mode-locking. However, for high power CW applications the material is hampered by a low thermal fracture threshold. This problem can be mitigated by special 2D pump set-ups or by keeping the quantum defect to a minimum. Direct pumping into the upper laser level of Nd:YLiF<sub>4</sub> is usually performed at 880 nm. For quasi-three level laser emission at 908 nm, direct pumping at this wavelength provides a high quantum defect of 0.97, which allows for very high CW pump powers. Although the direct pumping transition to the upper laser state at 872 nm has a slightly smaller quantum defect of 0.96, its pump absorption cross section along the c-axis is 50% higher than at 880 nm, leading to a higher absorption efficiency. In this work we explore, for the first time to our knowledge, 908 nm lasing under 872 nm diode pumping and compare the results with 880 nm pumping for quasi-cw and cw operation. By inserting a KGW crystal in the cavity, Raman lines at 990 nm and 972 nm were obtained for the first time from a directly pumped 908 nm Nd:YLF fundamental laser for both quasi-cw and cw conditions.

**Keywords:** Laser resonators, Laser optics, neodymium Lasers, solid-state Lasers, pumping.

## 1. INTRODUCTION

Developing lasers in the blue wavelength range is of paramount interest to a great many applications that include biological tissue excitation, pump sources for lasers such Ti:sapphire, expansion of the RGB color gamut for projectors, TVs and displays in general, medical diagnostics and magnetic levitation. One of the many possibilities to achieve blue wavelength, such as frequency up-conversion,<sup>1,2</sup> is the intracavity frequency doubling (SHG) of neodymium doped crystals operating on quasi-three level transition lines. Neodymium solid state lasers operating on the three level transition  $4F_{3/2} \rightarrow 4I_{9/2}$  generally use the highest fundamental stark level as lower laser level to generate photons between 900 nm and 950 nm, which can be efficiently converted to the blue spectral range between 450 nm and 475 nm by intracavity frequency doubling. A maximum blue output power of 14.8 W at 456 nm was reported using Nd:GdVO<sub>4</sub>.<sup>3</sup> Whereas the most used crystal hosts for neodymium are oxide hosts, the lowest wavelength emission stemming from SHG using these hosts is around 456 nm. A deeper blue emission at 451.5 nm and 454 nm may be achieved with neodymium doped yttrium-lithium-fluoride (Nd:YLF), which is a well known birefringent laser media (and therefore naturally polarized) that shows strong emission lines at 1053 nm and 1047 nm.<sup>4,5</sup> Additionally it has another advantage for this specific application, which is its very weak thermal lensing due to the combination of a negative index lens and positive end face bulging. The wavelength of the fundamental -polarization is 908 nm and of the -polarization is 903 nm.

Recent achievements in intracavity Raman laser technology resulted in laser operation at three different lines in the wavelength region between 908 and 990 nm, opening the way for Raman lasers in the blue spectral range.<sup>6-10</sup> Before these works, intracavity sum frequency generation (SFG) and second harmonic generation (SHG) has been reported for neodymium doped hosts only for laser output in the yellow-orange-red spectral region.<sup>11-14</sup> The striking feature of these blue Raman lasers based on Nd:YLF is that after SHG and SFG up to 10 emission lines can be achieved in a wavelength interval determined by the Raman shift. This is mainly possible because of the strong separation in wavelength of the main emission peaks for the  $\sigma$  and  $\pi$  emissions in Nd:YLF, which is not the case for the oxide birefringent crystals such as Nd:GdVO and Nd:YVO. Using Nd:YLF together with a KGW Raman converter, the strong 901 cm<sup>-1</sup> and 768 cm<sup>-1</sup> Stokes shifts result in a 50 nm wide spectra composed of ten lines ranging from 451 nm to 495 nm. On the other hand, if the 89 cm<sup>-1</sup> Stokes shift is used, the spectral tuning range goes from 451 nm to 459 nm.

In our previous works, we have achieved ten lines in the blue with good output power only when using quasi-cw operation. It is our objective to expand these results to cw operation. However, because of the three-level operation,

reabsorption becomes a problem during cw operation. For this reason we must decrease the Stokes coefficient within the fundamental laser crystal by choosing longer pump wavelength. The wavelength of choice are 972 nm and 880 nm that present a Stokes coefficient of 96% and 97%. In other words, a 25% higher heat conversion is expected at 972 nm when compared to 880 nm.

## 2. LASER SET-UP

A double pump pass configuration was initially used for obtaining laser at 908 nm due to the low absorption at the pump wavelengths. Figure 1 shows the laser setup. Both mirrors were AR coated at the pump wavelengths ( $T > 93\%$ ) and HR coated ( $R = 99,968$ ) at 908 nm with high transmission ( $T > 90\%$ ) at 1047 nm and 1053 nm to prevent parasitic four-level laser oscillation and these high emission cross-section transitions. Due to the constraints imposed on the mirrors for realizing the double pump pass there were no mirrors available in the lab with more suitable transmission value for output coupling. Pump beam waist was  $110\mu\text{m}$  and resonant beam waist was  $95\mu\text{m}$  at the Nd:YLF crystal. Cavity length was approximately 44 mm. The Nd:YLF crystals (from Crystech Inc.), doped with 0.7 at.% neodymium and with  $3 \times 3 \text{mm}^2$  cross section, had lengths ranging from 3 mm to 9 mm, with both faces AR coated at pump and lasing wavelengths and also at 1047 and 1054 nm. The double pump pass increased the absorbed power in 58-72% depending on the crystal length and pump wavelength, but restricted the useful output power at fundamental wavelength. For single pump pass lasing, the  $f = 76 \text{ mm}$  collimating lens and the pump mirror were removed from the set-up of Figure 3 allowing the use of output couplers with 1.14% transmission (Figure 2a) and with 3.3% transmission (Figure 2b).

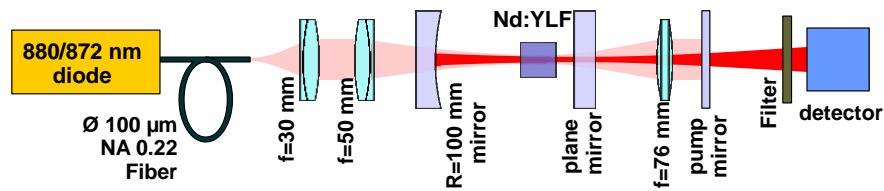


Figure 1: Laser setup for double pump pass configuration.

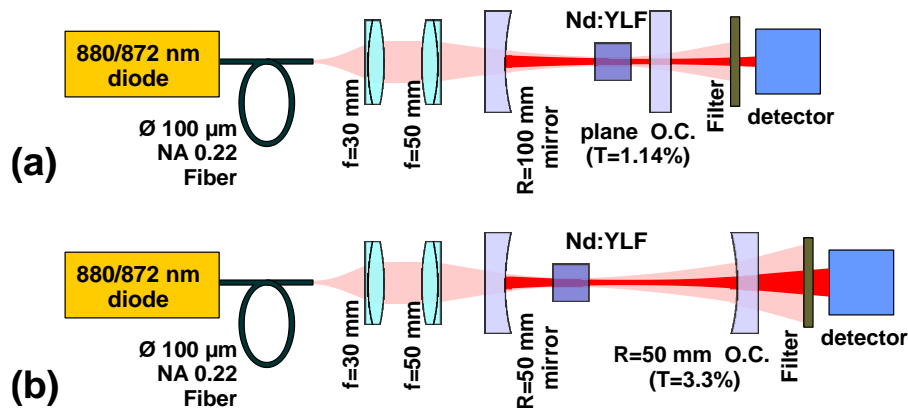


Figure 2: Laser setup for single pump pass configuration using  $T = 1.14\%$  (a) and  $T = 3.3\%$  (b) output couplers (O.C.).

Laser operation was obtained in quasi-cw mode using  $750\mu\text{s}$  pump pulses and also in cw mode. A purely  $\pi$ -polarized pump beam was also tested by inserting a polarizer beam splitter cube with 90% transmission and 1000:1 extinction ratio between the pump focusing lenses.

Raman lines at 990 nm and 976 nm were obtained by utilizing a  $3 \times 3 \times 10 \text{mm}^3$  long KGW crystal. The setup is shown in Figure 3. The beam waist in the KGW was  $70\mu\text{m}$ . The output coupler had  $R = 99.974\%$  at 908 nm, 0.28% transmission at 990 nm and 0.041% at 976 nm.

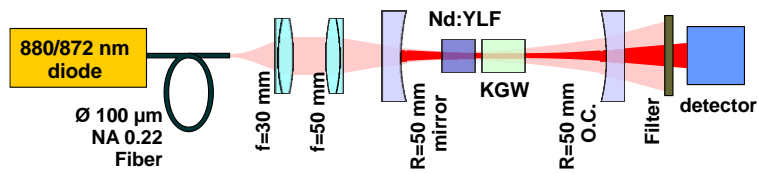


Figure 3: Setup for 990 nm and 976 nm Raman laser generation.

### 3. RESULTS

#### 3.1 Fundamental laser at 908 nm

In a first measurement we compared absorbed pump power at 872 nm and 880 nm under direct diode pumping using the same pump set-up and cavity configuration and a 5.5 mm long Nd:YLF crystal. As shown in Figure 4, absorption at 872 nm is 25% higher.

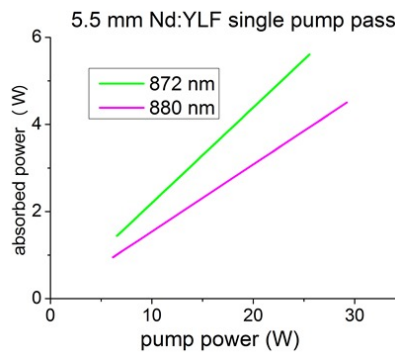


Figure 4. Absorbed pump power for the 5.5 mm long Nd:YLF crystal.

Output powers obtained for double pump pass lasing are shown in Figure 5. Output powers are higher for 880 nm in terms of absorbed pump power and higher for 872 when considering incident pump power. The 5.5 mm and 6 mm long crystals showed the best performance. Because both, pump beam waist and resonant beam waist, were kept constant, the longest crystal had the worst performance once its length is several times the Rayleigh range and the pump beam overlap worsens when compared to smaller crystals, allowing reabsorption in regions with lower pump intensity.

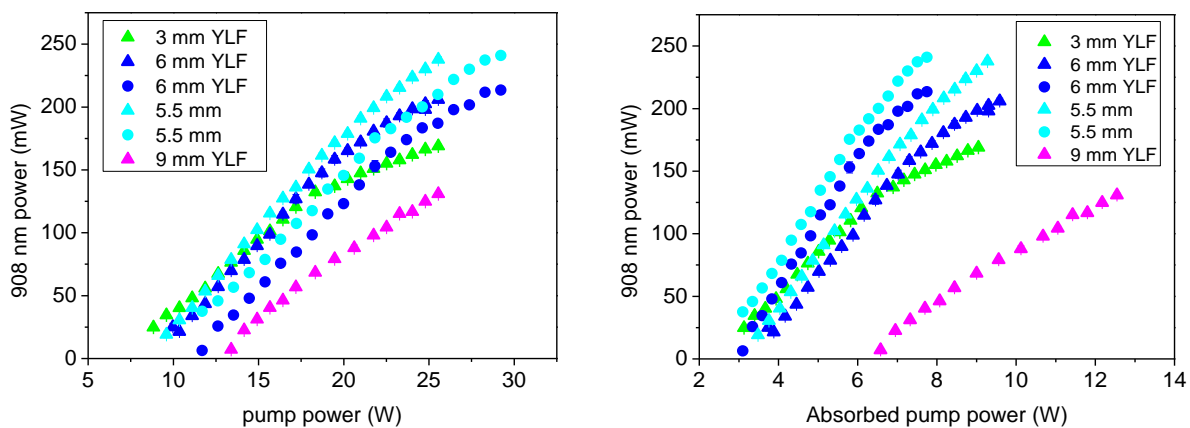


Figure 5. Output powers of the double pump pass configuration for several crystal lengths. Triangles represents 872 nm pump while circles represents 880 nm pump.

In Figure 6, output powers for single and double pump pass are compared for the best, 5.5 mm long, Nd:YLF crystal. Clearly seen is the better efficiency for double pump pass. During double pump pass operation it was observed that after power optimization two beams were leaving the resonator and there were two pump fluorescence paths in the crystal. We suppose the cavity was working as a near concentric resonator instead of a near hemispheric resonator. When forcing alignment to obtain a single laser spot and a single fluorescence path in the crystal, the power decreased.

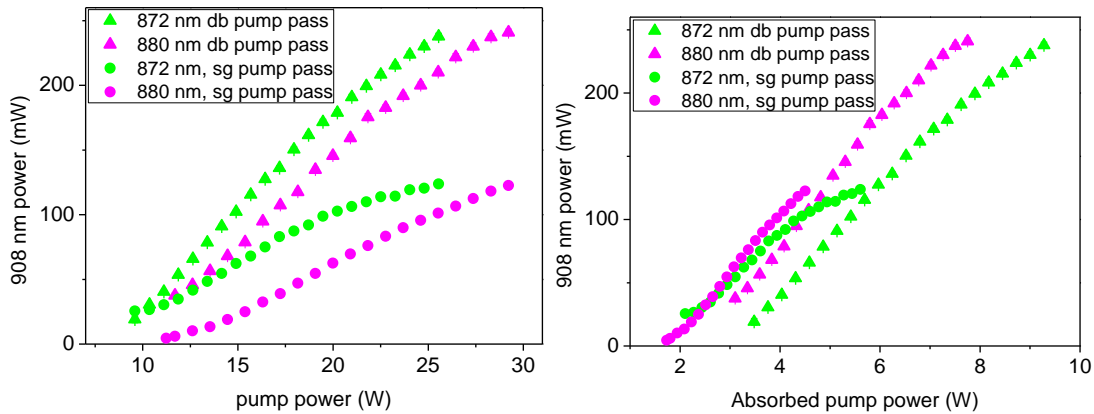


Figure 6. Output powers for double and single pump pass for the 5.5 mm long Nd:YLF crystal.

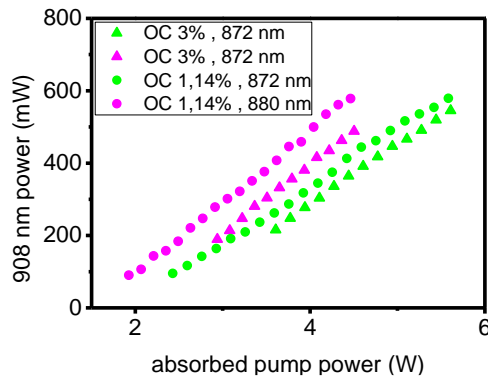


Figure 7. Comparison between 3% and 1.14% output couplers for the 5.5 mm crystal.

In Figure 7 the results for the 1.14% and 3% output couplers are shown, using the 5.5 mm crystal. In Figure 8 the  $\pi$ -polarized pump is compared to unpolarized pump for the 5.5 mm long crystal and 1.14% output coupler. As absorption is increased, higher output powers are available for the same pump power, especially for the 872 nm pump. In this test, pump powers were limited to 45% of the unpolarized pump for the reason that we had to polarize the unpolarized pump beam, but the objective is to utilize a polarized pump source.



Figure 8. Output powers for 1.14% (a) and 3.3% (b) transmission output coupler for both unpolarized and  $\pi$ -polarized pump with 5.5 mm long Nd:YLF

Figure 9 shows a comparison between vw and quasi-cw operation using both output couplers. The results demonstrate that for more than 2.5 W of absorbed pump power a strong occupation of the lower laser level occurs (reabsorption).

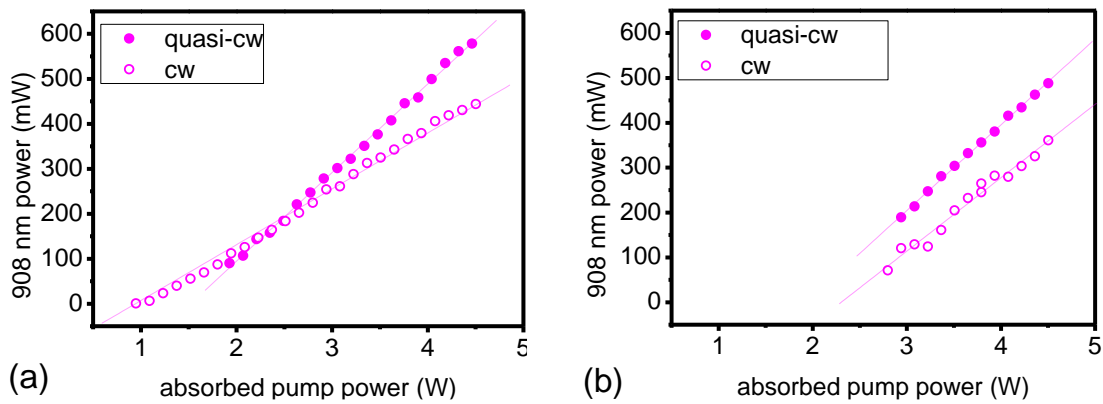


Figure 9. Output powers for 1.14% transmission (a) and 3.3% (b) output coupler for cw and quasi-cw with 5.5 mm Nd:YLF at 880 nm pump

### 3.2 Raman laser

Both, 990 nm and 976nm, Raman lines could be observed as seen on Figure 10. However, the transmission of the output coupler was too low for 976 nm and only a weak output was observed at this wavelength. The 990 nm power was characterized and Figure 10 (right) presents the output power curve and values from previous work with 797 nm pump are plotted additionally for comparison. The slope increases and the threshold decreases for shorter pump wavelengths as expected.

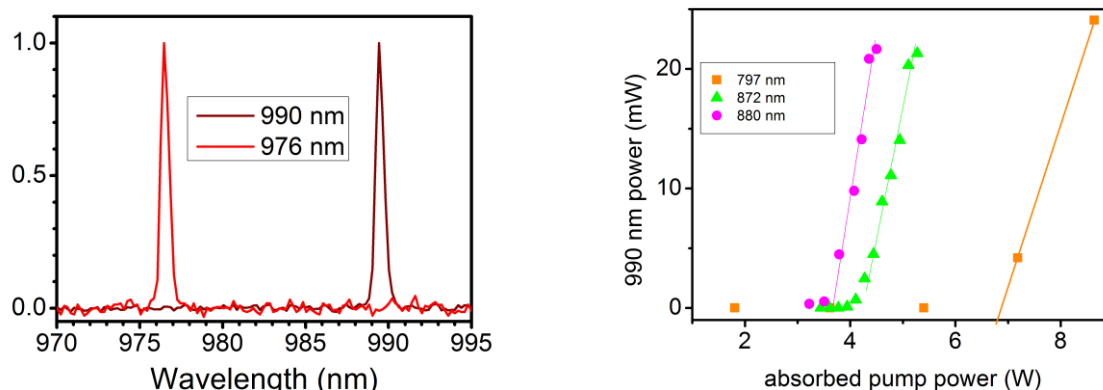


Figure 10. Left: spectrum of observed Raman lines at 990 and 976 nm. Right: 990 nm Raman power obtained for 880 and 872 nm pump and comparison with previous results with pump at 797 nm.

#### 4. CONCLUSIONS

Higher absorption at 872 nm could lead to higher output power when compared to 880 nm. The absorption is still lower than at 797 nm but quantum defect is greatly decreased. The double pump pass optics led to increased pump power absorption but there are difficulties to find adequate mirrors and crystals with special coatings since the Raman crystal should be in the middle of the cavity and the retro injection of the pump radiation is done with external cavity optics.

The 5.5 mm and 6 mm crystals showed the best performance for the fundamental laser beam power but, because the beam waist was the same for all the crystals, we could not evaluate correctly the 9 mm long Nd:YLF crystal that required a much longer Rayleigh range and therefore suffered strong reabsorption, leading to poorer performance.

At the low pump powers used in our set-up, the best results for fundamental output was obtained with the 1.14% output coupler. The 3.3% output coupler should be optimized for higher pump power, according to our previous work.

Because absorption is increased, output power increases by polarizing the pump beam. However, if the objective is cw operation, this might not be a viable option.

Continuous operation was obtained with lower slope. For the 1.14% output coupler cw-threshold was lower than for qcw operation. Operation was less stable for the 3.3% output coupler may be due to the near concentric cavity with higher sensitivity to misalignment.

Both 990 nm and 976 nm Raman lines could be observed but output at 976 nm was weak because the output coupler had too low transmission at his wavelength. The 990 nm laser showed higher slope efficiency and lower threshold as pump wavelength decreases, as expected. The maximum output power of 20 mW is still very low because of little absorbed pump power.

Next steps consist in increasing the absorbed pump power. To achieve higher output powers the following actions will be taken: increase of the Nd:YLF crystal length to 15 mm; increase of doping levels from 0.7 at. % to 1.0 at.%; use of two diode bars with 60 W output power for pumping at 880 nm and applying a beam shaping mechanism to decrease  $M^2$  of pump beam to approximately 40 and increase spatial overlap with intracavity laser beam.

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