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Highly efficient InGaN-LD-pumped bulk Pr:YLF orange laser at 607 nm

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We report continuous-wave orange laser operation at 607.5 nm of a 8 mm long 0.2at% Pr:$LiYF_4$ single crystal with an improved laser slope efficiency. Using a single InGaN laser diode emitting at ~444 nm as a pump source, an output power of ~200 mW was achieved with a threshold absorbed pump power of ~150 mW and a laser slope efficiency of nearly 42%. M^2 factors of 1.40 and 1.28 were measured in the x and y directions, respectively, attesting to the good quality of the output laser beam.

1. Introduction

Yellow–orange laser sources (from 570 to 620 nm) are particularly useful for a number of applications in the fields of astronomy, environment, biomedicine and display. However, at present, there is still a lack of efficient, stable and continuous-wave yellow–orange laser sources around 600 nm. There are laser diodes emitting at several visible wavelengths in the blue and the red spectral regions, but none of them are really available at ~600 nm. Nonlinear frequency conversion is an important method for generating visible lasers; especially in the last 10 years, many Nd^{3+} based laser systems associated with nonlinear frequency converters such $LiNbO_3$, KTP, LBO, BBO, BiBO and others provide laser radiations in the whole visible domain. The overall efficiency, however, especially in the case of continuous-wave laser operation in the yellow–orange spectral range is rather low, and the systems are rather complex. Diode pumped frequency doubled Optically Pumped Semiconductor lasers (OPS), which are an effective source in the visible region, have power scalability, wavelength flexibility, excellent beam parameters, power stability and reliability. Frequency doubled InGaAs OPS lasers have addressed spectral range from 350 nm to 600 nm [1], e.g. 8.5 W at 575 nm and 1.61 W at 460 nm [2]. However, at present, no effective frequency doubled OPS lasers can extend to the longer wavelength of more than 600 nm.

For these reasons, Pr^{3+}-doped materials directly pumped by blue semiconductor laser diode (LD) have motivated so much interest in the recent years, which may be a cogent alternative laser source in visible compared with the above mentioned measures. Among these materials, there are fluoride glasses and crystals like Pr:ZBLAN [3,4], Pr:YLF ($LiYF_4$) [5–7], Pr:KY_3F_{10} [6,8], Pr:BYF (BaY_2F_8) [9] and Pr:LLF ($LiLuF_4$) [10] as well as two oxides Pr^{3+},Mg^{2+}:$SrAl_{12}O_{19}$ [11] and Pr:YAP ($YAlO_3$) [12]. Clearly, the direct pumping of the Pr^{3+} ion, in which a blue photon is converted into a green, orange or red photon, is indeed a very attractive solution, since it is together a very compact, efficient and simple solution. However, it is worthwhile to mention that the reabsorption into the $^1D_2$ energy level at orange emission in the Pr:YLF laser crystal is a special challenge for achieving efficient laser output.

In this paper, we focus on the specific σ-polarized 607 nm orange laser emission. By weakening the non-negligible reabsorption effect with a lowly doped Pr:YLF crystal, we report on the improved room-temperature continuous-wave operation of a diode-pumped Pr:YLF bulk crystal at the orange laser wavelength of 607 nm with currently highest laser slope efficiency of 42%, to the best of our knowledge.

2. Experimental conditions

A schematic of the experimental setup is shown in Fig. 1. A commercially available InGaN LD with a maximum output power of 850 mW was used as pump source. A lens is integrated just at the output end of the InGaN LD for collimating the pump beam. This pump source emits a linearly polarized light at a wavelength of about 443.8 nm with a line-width of 1.7 nm (FWHM). The pump beam was found to be strongly elliptical,

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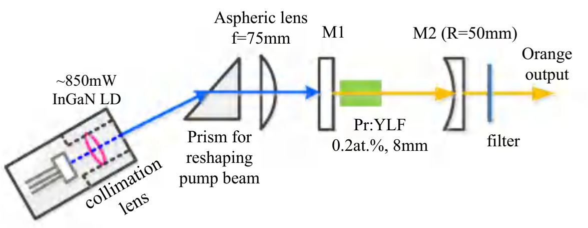

Fig. 1. Schematic experimental setup of blue laser-diode pumped Pr:YLF orange laser with a single prism for reshaping the pump beam.

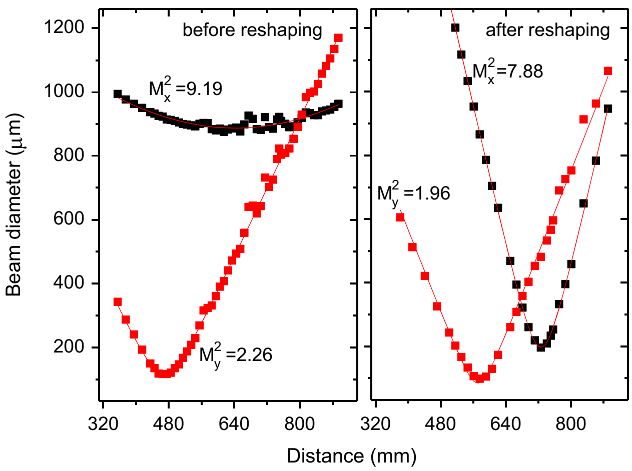

Fig. 2. *X* and *Y* pump beam diameters measured before and after reshaping with a prism.

which indicates that it is necessary to reshape the pump beam. Several publications demonstrated different pump beam reshapers, e.g. cylindrical lens pair [13] and anamorphic prism pair [14]. However, a simpler device, like a single prism with careful design and placement with matching incident angle, can realize a similar function as that of a beam reshaper. In our experiment, an isosceles right-angle prism with high transmission coatings at the pump wavelength was employed. A Spiricon M2-200 measurer registered the pump beam evolution before and after the reshaping in Fig. 2, which also gave beam propagation quality factors of $M_x^2 = 9.19$ and $M_y^2 = 2.26$ before the reshaping as well as $M_x^2 = 7.88$ and $M_y^2 = 1.96$ after the reshaping. It should be pointed out that the beam propagation quality factor of $M_x^2 = 9.19$ in *x* direction may not be accurate since no relevant far field diameter has been measured due to the limited measurement range of the measurer. However, from Fig. 2, one still can see that the beam *x*-size was narrowed down to that of the *y*-one, which is beneficial not only to decrease the laser threshold but also to improve the overlap between the pump and laser modes inside the laser crystal. An aspheric lens with a focal length of 75 mm was used to focus the laser beam inside the crystal. With this coupling lens, the measured pump beam focus sizes were about 77 and 92 μm in the *x* and *y* orientations, respectively. Moreover, the two pump beams in *x* and *y* orientations were focused to different locations with distance of about 5.8 mm along *z* axis.

The 8 mm long 0.2 at% Pr:YLF bulk laser crystal had uncoated, flat, parallel and polished end faces and was mounted only on a copper plate without any additional cooling device. No special effort was made on the optimization of the doping concentration, but we considered that a weakly doped Pr:YLF crystal should be more favorable to achieve orange laser operation around 604–607 nm, since laser emission in this wavelength domain can be

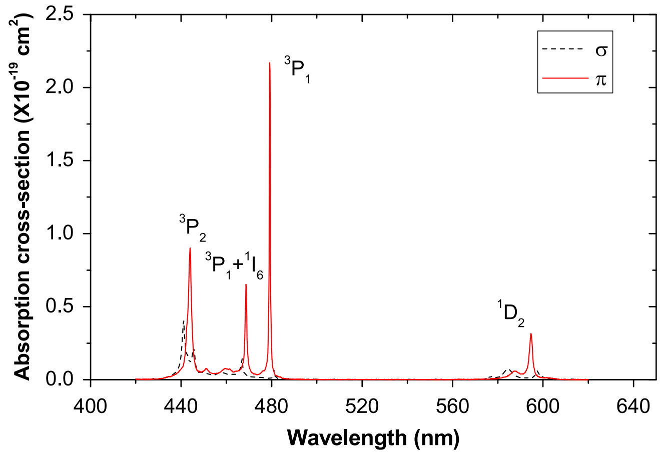

Fig. 3. Absorption spectrum of the 8-mm-long 0.2 at%Pr:YLF laser crystal. The red line stands for π polarization and the black line represents σ polarization.

subject to a non-negligible reabsorption (see Fig. 3) into the $^1D_2$ energy level. In these conditions, the crystal absorbed around 75.2% of the pump power, thus up to about 639 mW.

The laser cavity was a simple plano-concave cavity with an optimized physical length of around 47 mm. The flat dichroic input mirror M1 has a maximum transmission at the 444 nm pump wavelength and is highly reflective (>99.7%) for the orange emission. With respect to the 640 nm wavelength, the transmission of M1 is 56.8% for suppressing the $^3P_0 \rightarrow {}^3F_2$ transition, which has higher emission cross section of 2.2×10^{-19} cm^2 than the investigated 607 nm orange laser one of 1.4×10^{-19} cm^2 [7]. Two curved output mirrors (M2) were utilized, both with the radius of curvature of 50 mm and different transmissions of 3.5% and 2.3% at 607 nm as well as 3.8% and 2.6% at 604 nm (π polarization). The emission cross section of 604 nm orange laser is 1.0×10^{-19} cm^2, i.e. lower than that of 607 nm. On the other hand, the absorption spectra in Fig. 3 indicate a slightly higher reabsorption loss at 604 nm. Therefore, finally, the laser cavity leads to laser operation only at σ-polarized 607 nm emission.

3. Results and discussion

Due to the different focus positions of the pump beams in *x* and *y* directions, it is necessary to move the Pr:YLF crystal along the *z* axis in order to optimize the laser performance during the experiment. Finally, an optimized laser result at 607 nm is shown in Fig. 4. A maximum output power of about 200 mW was achieved by using a 3.5% output coupling transmission. With a threshold absorbed pump power of about 152 mW it corresponds to a laser slope efficiency of about 42% with respect to the absorbed pump power. By using a 2.3% output coupling, the maximum output power of the orange laser emission was reduced to 178 mW with a threshold of 115 mW and a slope efficiency of 33%. The laser experiment without prism was also carried out with the same laser cavity and the experimental result is shown in Fig. 5. In this case, the maximum output power of the 607 nm laser was obtained from 2.3% transmission mirror with power of 139 mW instead of from 3.5% mirror with power of 136 mW. The better laser performance after the pump beam reshaping by using a prism is most likely due to a higher gain resulting from smaller pump spots. Moreover, the far higher thresholds of 196 and 262 mW from the 2.3% and 3.5% mirrors respectively could be a proof of relatively lower gain in the case of no prism, which needs higher pump power to reach threshold level.

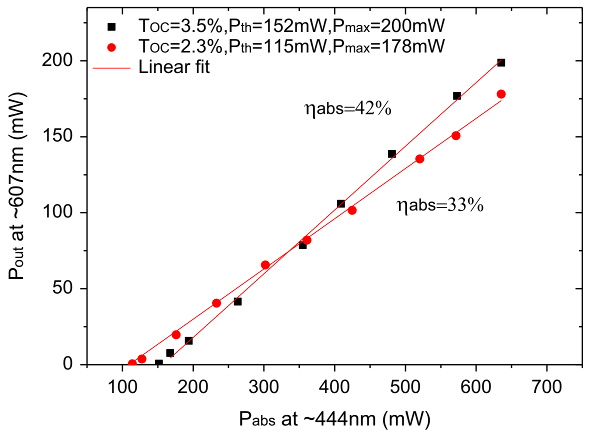

Fig. 4. Laser output vs. absorbed pump power curves of the σ-polarized 607.2 nm orange laser emission for two output couplers with prism for pump beam reshaping.

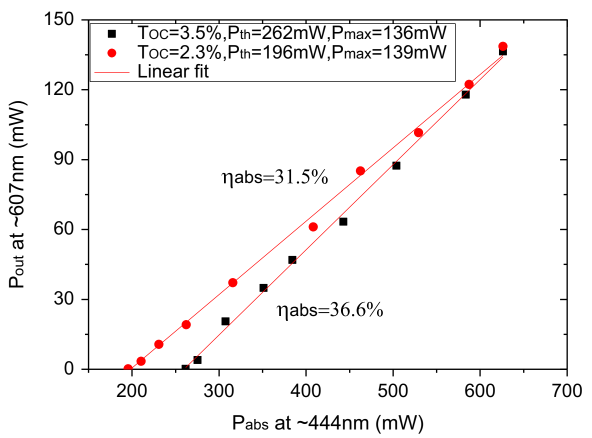

Fig. 5. Laser output vs. absorbed pump power curves of the σ-polarized 607.2 nm orange laser emission for two output couplers without prism.

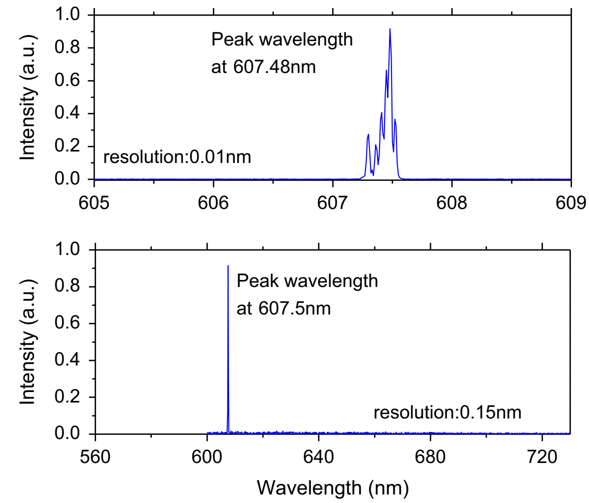

Fig. 6. Emission spectra of the ~607 nm orange laser under resolution of 0.01 nm and 0.15 nm, respectively.

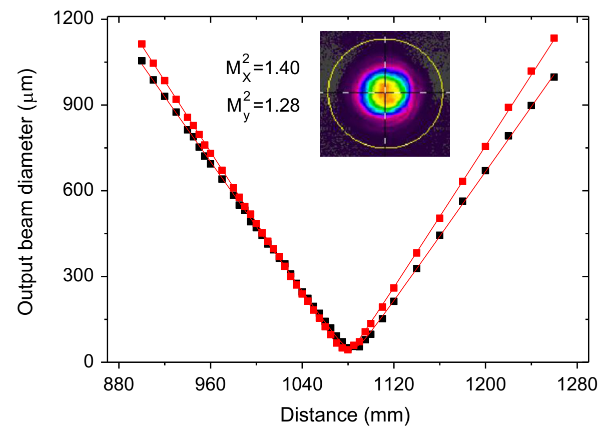

Fig. 7. *X* and *Y* output beam diameters of the 607.2 nm orange laser beam and the inset is the original image of the output beam captured by Spiricon M2-200.

It is worth noting here that similar laser experiments were already reported in the recent years. In 2008, Cornacchia et al. [15] reported a maximum output power of 42 mW and a slope efficiency of 14% for a 3.4% transmission output coupler, by using a 0.65 at% Pr:YLF laser crystal. Then, in 2011, by using 0.5 at% Pr: YLF crystal, Gün et al. [7] improved the 607 nm orange laser performance with a laser threshold of 125 mW obtained for a 3.38% output coupler, but with a maximum output power of 418 mW for an absorbed pump power of 1.5 W, thus with a laser slope efficiency of 32%. Compared with these results concerning the specific orange laser emission, we here in this work present the highest slope efficiency of 42%. This should be explained by using the weakly doped Pr:YLF laser crystal, which is favorable for diminishing the reabsorption losses. In addition, the higher laser threshold (152 mW vs. 125 mW) in this work is likely due to a higher output coupler (3.5% vs. 3.38%).

Fig. 6 shows emission spectra of the ~607 nm orange laser under resolution of 0.01 nm and 0.15 nm (Advantest Q8384 optical spectrum analyzer). The spectrum with 0.01 nm resolution shows clearly multi-peak emissions. The highest peak wavelength locates at 607.48 nm and the bandwidth is about 0.16 nm (FWHM). The spectrum with 0.15 nm resolution gives a full display of the possible emission in the visible above 600 nm (the shortest measurable wavelength of the optical spectrum analyzer) in Pr: YLF crystal, which offers an obviously pure 607 nm lasing, and no simultaneous emission at 604 or/and 640 nm was observed.

To characterize the quality of the orange laser beam, its diameter was finally measured in the *x* and *y* directions (see Fig. 7). The fits of these data then lead to the *x* and *y* M^2 factors $M_x^2 = 1.40$ and $M_y^2 = 1.28$, which clearly indicate a good beam quality. The laser mode waist diameter $2w_0$ inside the laser medium can be deduced by using the following formula:

$$w_z = w_0\sqrt{1 + \left(\frac{\lambda M^2 z}{\pi w_0^2}\right)^2}$$

where M^2 is the output beam propagation factor, w_z the measured output beam size, and z the distance between the measurement location and the laser medium. The measured and calculation-obtained laser mode waist diameter were about 78 and 81 μm in *x* and *y* directions, respectively.

4. Conclusion

In this paper, orange laser emission at 607.5 nm has been achieved with improved laser performance. To suppress the well-known reabsorption effect in the orange band, a 0.2 at% Pr weakly doped YLF laser crystal with sufficient length of 8 mm in order to absorb enough pump power was employed as the laser gain medium. A maximum output power of 200 mW is obtained with a laser slope efficiency of 42% with respect to the absorbed pump power by using a 3.5% output coupling transmission.

Compared with previous works regarding the specific laser emission, the current highest slope efficiency at this emission in this work verifies that using a lowly doped laser material is helpful in suppressing the reabsorption losses, and resultingly leads to improved laser performance. In this experiment, a different method was used for pump beam reshaping by using a simple isosceles right-angle prism, which makes the laser system more compact and less costly. The laser results in the two conditions, namely with and without prism, proved that it is very helpful in scaling the laser output power with the aid of the prism. Finally, the beam quality has been attested by measuring transverse beam quality factors $M_x^2 = 1.40$ and $M_y^2 = 1.28$.

Based on this work, a further power scaling at 607 nm lasing has now been expected by using optimized Pr:YLF crystal with optimized parameters, e.g., doping concentration and crystal length. Moreover, a comparable study of the reabsorption losses by using differently doped Pr:YLF crystal is also interesting for us. Both of them will be our next investigations.

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