Comparative study of high power Tm:YLF and Tm:LLF slab lasers in continuous wave regime

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Abstract: We report on Tm:YLF and Tm:LLF slab lasers (1.5 x 11 x 20 mm$^3$) end pumped from one end with a high-brightness 792 nm laser diode stack. These two lasers are compared under identical pump conditions in continuous-wave regime. A stronger negative thermal lens in Tm:LLF than in Tm:YLF is highlighted, making it more difficult to operate the Tm:LLF laser under stable lasing conditions. In a configuration where the high reflectivity cavity mirror has a radius of curvature of $r = 150$ mm, the Tm:YLF (Tm:LLF) laser produces a maximum output power of 150 W (143 W) for 428 W of incident pump power (respectively). For a second cavity configuration where the high reflectivity cavity mirror has a radius of curvature of $r = 500$ mm, the Tm:YLF laser produces a maximum output power of 164 W for 412 W of incident pump power and a 57% slope efficiency with respect to the absorbed pump power. The emitted wavelength of these two lasers are measured as a function of the output coupler reflectivity and it shows that Tm:LLF laser emits at a longer wavelength than Tm:YLF.

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1. Introduction

High-power and high-energy lasers at 2 µm can be used for processing of materials that are transparent at 1 µm and are thus difficult to process with established industrial laser systems. They are also useful for remote sensing, medical laser applications and for pumping optical parametric oscillators to reach longer wavelengths [1].

Due to its small footprint potential, a Tm-doped slab laser design is a good alternative to high power Tm:fiber lasers, and can be used directly for modulated continuous-wave output, or for pumping Ho-doped lasers and amplifiers. Different power scaling strategies of Tm\(^{3+}\):YLiF\(_4\) (Tm:YLF), as a particularly attractive host crystal, have been presented over the last decade. In 2006, an output power of 70 W from a Tm:YLF slab laser end-pumped with a 300 W diode stack was reported by So et al. [2], the slope efficiency was 44% with respect to the absorbed pump power. In 2009, Schellhorn et al demonstrated a dual-end-pumped Tm\(^{3+}\):YLF slab laser producing 148 W output at 1912 nm with a slope efficiency of 41% with respect to absorbed pump power [3]. An improved version of this laser later recorded 192.5 W output power at 1908 nm [4]. A modified version later produced 187 W at 1890 nm with a total pump power of 550 W and a slope efficiency of 38% [5]. In 2013, using an Innoslab pump architecture, a Tm:YLF laser with 200 W of output at 1908 nm and a slope efficiency of 52% with respect to the absorbed pump power, was reported by Li et al. [6]. In this study we wanted to analyze the potential, for high average operation, of another material, Tm\(^{3+}\):LiLuF\(_4\) (Tm:LLF), which has similar spectroscopic values than Tm:YLF [7–13].

The first Tm:LLF laser has been reported by Coluccelli et al in 2007 [14], an average output power of 1.1 W was achieved. Comparative studies of Tm\(^{3+}\):LiLnF\(_4\) (Ln = Y, Gd, and Lu) crystals properties have been reported [7,8] and recently highly-efficient microchip lasers at ~2 µm using those crystals have been presented [12]. The performance of Tm:LLF in a thin disk laser configuration has been reported by Stoeppli et al in 2009 [15]. Moreover, Q-switched operation has been reported by Cheng et al in 2009 [16]. In this work we directly compare Tm:YLF and Tm:LLF host materials, in an otherwise identical configuration, to evaluate the power scalability of these two related materials, since high power operation of Tm:LLF has never been reported so far. We also analyze the wavelength behavior of these two crystals as a function of output coupler reflectivity, at maximum output power, to find the best match for pumping holmium doped materials.

2. Experimental setup

For this study, we use a crystal (Tm:YLF or Tm:LLF) with a slab geometry: 11 mm wide (c-axis), 1.5 mm thick (a-axis) and 20 mm long (a-axis) from AC Materials. The thulium concentration is 2.5 at.%. Both end faces (11 mm by 1.5 mm) of the slab are antireflection coated (from TwinStar Optics) for the laser wavelengths in the range 1.9–2.0 µm and the diode wavelength around 790 nm. The slab is sandwiched between indium foils using two
microchannel coolers (Micro Cooling Concepts, SA-2 cooler) connected to two water-cooled copper heat sinks. Unless otherwise specified, the cooling water temperature is kept constant at 20°C using a chiller.

The crystal is end-pumped from one side by a laser diode stack (Lasertel T6 Water Cooled Laser Diode). The diode stack consists of 6 water-cooled diode bars stacked with a pitch of 1.2 mm. Each bar is composed of 24 emitters for a total width of 10 mm. They are collimated in the fast axes with micro-lenses. An additional optic is integrated onto the stack. This optic is a monolithic array of cylindrical lenses for slow axis collimation with additional smile error correction (PowerPhotonic, SmileSAC). For a driving current of 75 A, the diode stack emits an average power of 460 W. The diode stack is cooled with water (deionized water is not needed for this type of diode) adjusted between 14 and 20°C using a chiller.

![Fig. 1. Top view of the laser setup (\(\lambda/2\): Half-wave plate, Lens: 80 mm focal length, OC: output coupler, HR mirror: high reflectivity at laser wavelength and 500 mm or 150 mm radius of curvature, Crystal: Tm:YLF or Tm:LLF).](image1)

![Fig. 2. Diode stack normalized intensity as a function of the wavelength for seven different output powers and for a water cooling temperature of 20°C.](image2)

The experimental setup is detailed on Fig. 1 The footprint of the laser is approximately 90 x 190 mm² which makes it a compact source. A plano-convex GRADIUM lens (LightPath Technologies GPX-30-80-BB2), with a focal length of 80 mm, is used to focus the beam of the diode stack. In the y-axis it was designed to focus the beam to a waist of \(\omega_p \sim 480\) µm (1/e² radius of intensity). The pump waist is positioned inside the slab crystal at approximately 1/3 of its length. In the x-axis the optical setup was designed to image the laser diode stack full width onto the entrance width of the slab. For a diode cooling water temperature of 20°C, the peak wavelength of the pump light is measured to be 789 nm at diode lasing threshold and increased to 795 nm at an output power of 433 W (Fig. 2). The spectral width is ~3 nm at full width half maximum (FWHM). The pump light of the diode stacks is 97% TM polarized (perpendicular to the bars). In our setup the pump light is polarized perpendicular to the c-axis of the crystal (\(\sigma\)-polarized) with a maximum incident pump power of 428 W. A halfwave
plate can be inserted to rotate the polarization parallel to the c-axis of the crystal ($\pi$-polarized) with a maximum incident pump power of 412 W due to slight losses.

The expected wavelength of the laser beam is in the 1.91 $\mu$m spectral region which corresponds to strong water absorption (see Figs. 12 and 13). The consequence is that the laser output power tends to show amplitude instabilities (unstable spiking behavior) which can damage the anti-reflection coating of the crystals and intra-cavity optics at high power operation. Therefore, the setup was enclosed in a sealed box flushed with dry air, assuring a relative humidity below 5%. The folded resonator consists of a concave high reflectivity mirror (R > 99.8% in the wavelength range 1.9 - 2.2 $\mu$m) with a 150 mm (or 500 mm) radius of curvature, two flat 45° dichroic mirrors with high reflectivity (R > 99.9% in the wavelength range 1.8 - 2.1 $\mu$m) and high transmission at the pump wavelength (T > 95% in the wavelength range 750 - 850 nm) and a flat output coupler with various reflectivities (between 60% and 90%) at 1908 nm. The physical resonator length is approximately 90 mm.

3. Results

3.1 Small cavity mode configuration

The first experiment is carried out using a 150 mm radius of curvature (ROC) high reflectivity (HR) cavity mirror and an 81% reflectivity output coupler. The laser cavity mode size can be evaluated considering an effective thin lens placed in the middle of the crystal to simulate the thermal lens in the crystal due to the high pump intensity. With Tm:YLF and Tm:LLF crystals, we are expecting a negative thermal lens [12]. The radius of the cavity mode size in the middle of the crystal is approximately 250 $\mu$m for a thermal lens focal length longer than −200 mm (see Fig. 3). The cavity becomes unstable for focal length approaching −150 mm.

![Fig. 3. Simulation of the cavity mode radius in the middle of the crystal as a function of the thermal lens focal length. The high reflectivity cavity mirror has a radius of curvature of 150 mm.](image)

By experimentally implementing this cavity configuration, the output power of the Tm:YLF laser and Tm:LLF laser are recorded as a function of the incident pump power (see Fig. 4 (left)) for a pump beam polarization perpendicular to the c-axis of the crystal ($\sigma$-polarized). The percentage of the pump beam which is transmitted through the crystal, while the laser is operated, is plotted as a function of the incident pump power (see Fig. 4 (right)). As expected [7], the Tm:LLF crystal has a slightly higher absorption than the Tm:YLF crystal, leading to a lower lasing threshold. Despite a lower pump absorption, the Tm:YLF laser exhibits a slightly better slope efficiency and maximum output power than the Tm:LLF laser. The two laser beam profiles, measured on a Pyrocam I camera in the far field, are quite similar, showing a highly multimode content in the c-axis direction along the width of the crystal. The laser beam polarization is linear, and it is polarized perpendicular to the c-axis of the crystal.
Using a half wave plate in front of the diode stack, we rotated the pump beam polarization by 90°. The output power of the Tm:YLF laser and Tm:LLF laser are recorded as a function of the incident pump power (see Fig. 5 (left)) for a pump beam polarization parallel to the c-axis of the crystal (π-polarized). The percentage of the pump beam which is transmitted through the crystal, while the laser is operated, is plotted as a function of the incident pump power (see Fig. 5 (right)). The Tm:YLF laser maximum output power is higher than that of the Tm:LLF laser. For this pump polarization and for the two crystals, the percentage of pump transmission changes by nearly a factor of two as a function of the incident pump power. This higher fluctuation, as compared to the σ-polarized case, is due to a narrower (and stronger) absorption peak as a function of the wavelength for the π-polarization [7]. A consequence of this evolution in the absorption is that the curve representing the output power as a function of the incident pump power is not as straight as it is for the σ-polarized case. On the other hand, it is possible to shift the maximum of the absorption toward higher pump power by reducing the temperature of the diode cooling water. This would result in a higher laser maximum output power.

In Fig. 6 (left) is plotted, on the same graph, the laser output power as a function of the incident pump power for the two crystals and for the two polarizations. If we plot the laser output power as a function of the absorbed pump power, we can see that the data points from the Tm:YLF laser follow a straight line independent of the pump polarization (see Fig. 6
The same remark stands for the Tm:LLF laser, but with a lower slope efficiency. For the Tm:YLF laser, a maximum output power of 150 W (149 W) is obtained at an absorbed pump power level of 339 W (336 W) with a pump polarization perpendicular (parallel) to the c-axis. The slope efficiency with respect to the absorbed pump power is approximately 52%. For the Tm:LLF laser a maximum output power of 143 W (137 W) is obtained at an absorbed pump power level of 346 W (338 W) with a pump polarization perpendicular (parallel) to the c-axis. The slope efficiency with respect to the absorbed pump power is approximately 48%.

![Fig. 6. Tm:YLF and Tm:LLF lasers output power as a function of the incident pump power (left) and absorbed pump power (right) for two pump beam polarizations and best linear fit to the data (right).](image)

We measured the beam propagation factor of the Tm:YLF and Tm:LLF lasers at 140 W output power and for two perpendicular directions (see Fig. 7). For these measurements the pump was π-polarized. We used a 75 mm focal length focusing lens and the chopper wheel method with an integrating sphere and a fast photodiode (Thorlabs PDA10D-EC) to measure the beam diameter as a function of the distance after the lens [19]. The beam propagation factors of the two lasers are the same order of magnitude. They are around $M^2 \approx 1.2$ in the direction perpendicular to the c-axis and $M^2 \approx 400$ for the direction parallel to the c-axis. The focus position of the Tm:LLF laser beam is significantly different for the two directions. This difference in focusing position is not present for the Tm:YLF laser, which we ascribed to the lower thermal lens in this crystal compared to the Tm:LLF crystal. In Fig. 8, we plotted the Tm:LLF caustic, in the direction perpendicular to the c-axis, for different laser output powers.

![Fig. 7. Tm:LLF and Tm:YLF lasers beam propagation factor measurement at 140 W output power and for a pump π-polarized. The graphs represent the laser beam radius in the direction perpendicular ($M^2_{\perp}$) and parallel ($M^2_{||}$) to the c-axis as a function of the distance after the 75 mm focal length focusing lens. Solid curves are fits to a standard Gaussian beam propagation expression.](image)
to evaluate the shift in the position of the focus. At low power (20 W), the position of the waist (103 mm) in this beam direction is almost equal to the one in other direction (90 mm). With increasing output power, the position of the waist increases to 115 mm at 81 W and 128 mm at 140 W output power.

Fig. 8. Tm:LLF laser beam radius in the direction perpendicular to the c-axis plotted as a function of the distance after the 75 mm focal length focusing lens, at different output powers. Solid curves are fits to a standard Gaussian beam propagation expression.

We measured the laser output parameters, for a pump polarization perpendicular the c-axis, for five different output coupler reflectivities. In Fig. 9, we plotted the Tm:LLF laser output power as a function of the incident pump power and absorbed pump power for different output coupler reflectivities. The maximum output power (145 W) is obtained with a reflectivity of 90%, whereas the maximum slope efficiency with respect to the absorbed pump power (47.2%) is obtained with a reflectivity of 81%. In Fig. 10, we plotted the Tm:YLF laser output power as a function of the incident pump power and absorbed pump power for different output coupler reflectivities. The maximum output power (151 W) is obtained with a reflectivity of 85%, whereas the maximum slope efficiency with respect to the absorbed pump power (52.4%) is obtained with a reflectivity of 70%. For every output coupler the Tm:YLF laser shows a higher laser threshold but a higher slope efficiency leading to higher maximum output power than the Tm:LLF laser.

In Fig. 11 we plotted the inverse of the slope efficiency multiplied by the ratio of pump and laser wavelength versus the inverse of the output coupler transmission, also known as a Caird plot [17]. We found a value of 3.8% (1.3%) for the resonator losses and an intrinsic slope efficiency of 53.9% (47.9%) for the Tm:YLF laser (Tm:LLF respectively).

Fig. 9. Tm:LLF laser output powers as a function of the incident pump power (left) and as a function of the absorbed pump power (right) for five output coupler reflectivities. The slope efficiencies are given with respect to absorbed pump power as result of linear fits to the experimental data (right).
Fig. 10. Tm:YLF laser output powers as a function of the incident pump power (left) and as a function of the absorbed pump power (right) for five output coupler reflectivities. The slope efficiencies are given with respect to absorbed pump power as result of linear fits to the experimental data (right).

Fig. 11. Inverse of the slope efficiency multiplied by the ratio of pump and laser wavelength versus the inverse of the output coupler transmission for the Tm:LLF laser (left) and Tm:YLF laser (right).

We measured the laser wavelength with a spectrum analyzer (OSA205, Thorlabs) flushed with dry air. The Tm:LLF laser normalized power density as a function of the wavelength, for five different output coupler reflectivities and at maximum pump power, is plotted in Fig. 12. The laser wavelength shifts as a function of the output coupler reflectivity, from 1912 nm for a reflectivity of 60% to 1918 nm for a reflectivity of 90%. The Tm:YLF laser normalized power density as a function of the wavelength, for five different output coupler reflectivity and at maximum pump power, is plotted in Fig. 13. The laser central wavelength shifts as a function of the output coupler reflectivity, from 1906 nm for a reflectivity of 60% to 1912 nm for a reflectivity of 90%. The central wavelength of the Tm:LLF laser is approximately 6 nm longer than the Tm:YLF in the same cavity design conditions. For both lasers, we can see a modulation in the power density as a function of the wavelength for every output coupler due to an etalon effect. This effect is ascribed to a non-perfect antireflection coating on the back face of the plane parallel fused silica output coupler mirrors. This modulation is maximum for the output coupler with a R = 81% reflectivity. The mirror substrate has a thickness of $l_{\text{substrate}} = 6.35 \text{ mm}$ which produces equally spaced lines of $\frac{\lambda_{\text{laser}}}{n_{\text{substrate}} \times 2 \times l_{\text{substrate}}} = 200 \text{ nm}$. It is also clear that the water absorption lines, present in this part of the spectrum, play a key role in the laser spectra. Even though the laser (and the spectrum analyzer) is enclosed in a sealed box flushed with dry air (for this experiment the relative humidity was < 5%), the laser tried to avoid water absorption lines. For example, with a reflectivity of 70%, the Tm:LLF laser
wavelength is centered at 1913 nm. Due to the high atmospheric absorption at this wavelength, the power density shifts to the adjacent atmospheric transmission windows (see Fig. 12). For every output coupler and at maximum output power, the laser beam polarization is linear, and it is polarized perpendicular to the c-axis of the crystal.

![Fig. 12. Tm:LLF laser normalized power density for five output coupler reflectivities as a function of wavelength at maximum pump power. In grey: atmospheric transmission as a function of the wavelength (Pressure: 1 atm - Optical path: 2 m - USA model, mean latitude, summer, H = 0) [18].](image1)

![Fig. 13. Tm:YLF laser normalized power density for five output coupler reflectivities as a function of wavelength at maximum pump power. In grey: atmospheric transmission as a function of the wavelength (Pressure: 1 atm - Optical path: 2 m - USA model, mean latitude, summer, H = 0) [18].](image2)

The influence of crystal temperature on laser performance was studied for the Tm:LLF and Tm:YLF lasers with an output coupler reflectivity of $R = 81\%$. The crystal temperature was tuned by controlling the temperature of the cooling water between 5 and 30°C. Figures 14 and 15 show the output power performance obtained with the Tm:LLF and Tm:YLF lasers, respectively, with respect to incident pump power (left) and with respect to absorbed pump power (right) for different crystal cooling water temperatures. The Tm:LLF laser has a slightly lower threshold than the Tm:YLF laser for every temperature tested. Due to higher re-absorption losses with increasing temperature, the laser threshold is shifted to higher pump power. The slope efficiencies with respect to absorbed pump power are slightly higher for Tm:YLF than Tm:LLF and the slopes decrease with increasing temperature of the crystal cooling water.
Fig. 14. Tm:LLF laser output power as a function of the incident pump power (left) and as a function of the absorbed pump power (right) for six crystal cooling water temperatures using the output coupler with a reflectivity of $R = 81\%$. Slope efficiencies are given as result of linear fits to the experimental data (right).

Fig. 15. Tm:YLF laser output power as a function of the incident pump power (left) and as a function of the absorbed pump power (right) for six crystal cooling water temperatures using the output coupler with a reflectivity of $R = 81\%$. Slope efficiencies are given as result of linear fits to the experimental data (right).

Fig. 16. Left graph: Tm:LLF (right graph: Tm:YLF) laser output power as a function of crystal cooling water temperature at three pump power levels using the output coupler with a reflectivity of $R = 81\%$. Solid lines are best linear fits to the data.

Figure 16 shows the output power as a function of crystal cooling water temperature between 5 and 30°C for three pump powers. For pump powers of 88 W, 265 W and 428 W the slopes were $-181 \text{ mW/K}$, $-391 \text{ mW/K}$ and $-396 \text{ mW/K}$ for the Tm:LLF, and $-177 \text{ mW/K}$ for the Tm:YLF.
mW/K, \(-351\) mW/K and \(-408\) mW/K for the Tm:YLF. These results show that the influence of crystal temperature on laser output power is very similar for both materials.

3.2 Large cavity mode configuration

For the second experiment, we use a 500 mm radius of curvature high reflectivity cavity mirror. The radius of the cavity mode size in the middle of the crystal is approximately 400 µm for a thermal lens focal length longer than \(-700\) mm. For stronger thermal lens the mode size increases rapidly, and the cavity becomes unstable for a focal length shorter than \(-500\) mm (see Fig. 17). In this configuration, the cavity mode size, with a half-height of approximately 400 µm, has a better overlap with the pump compared to the previous cavity mode size with a half-height of approximately 250 µm. The pump beam half-height is approximately 480 µm in the crystal.

![HR mirror with 500 mm ROC](image)

Fig. 17. Simulation of the cavity mode radius in the middle of the crystal as a function of the thermal lens focal length. The high reflectivity cavity mirror has a radius of curvature of 500 mm.

In the Fig. 18 we can see a roll-off in the Tm:LLF laser output power which we do not observe for the Tm:YLF laser. We attribute this difference to the thermal lens in the Tm:LLF crystal to be stronger than in the Tm:YLF crystal. We can estimate that, for this pump power level, the thermal lens focal length in the Tm:LLF crystal is shorter than \(-500\) mm because of the mode instability observed in the second cavity configuration, but longer than \(-150\) mm because we did not observe any mode instability in the first cavity configuration. The beam starts to become unstable in the Tm:LLF laser for an incident pump power of 200 W. Due to roll-off and instability, we limited the pump power to 300 W to avoid damaging optical components. We can estimate that the thermal lens focal length in the Tm:YLF crystal is longer than \(-500\) mm because we did not observe any mode instability in the second cavity configuration. The output power was observed to be higher for Tm:YLF laser in this second cavity configuration (see Fig. 19). The transmitted pump power, for the Tm:YLF laser, exhibit a relatively similar behavior in the two cavity configurations. We observe a higher absorption at low pump power in the first cavity configuration and a higher absorption at higher pump power in the second cavity configuration. The laser mode in the crystal is smaller in the first configuration than in the second, therefore the laser threshold is achieved at a lower pump power: 66 W compared to 83 W. The maximum output power is 159 W in the second experiment compared to 150 W in the first for the same crystal (20°C) and diode (16°C) water cooling temperature.
For the Tm:YLF laser, with a crystal (20°C) and diode (16°C) water cooling temperature, a maximum output power of 159 W (157 W) was obtained for 342 W (338 W) of absorbed pump power for a pump polarization perpendicular (parallel) to the c-axis (see Fig. 20). The slope efficiency with respect to the absorbed pump power of approximately 57% is higher
than the published value of 52% of Li et al. [6]. The Tm:YLF laser does not show any roll-off at maximum output power.

As we mentioned before, it is possible to increase to maximum output power of the laser by adjusting the temperature of the cooling water of the diode and of the crystal. Reducing the diode cooling water temperature has two implications. It increases the diode output power and more importantly it changes the emitting wavelength. Therefore, it is possible to match the diode emitted wavelength, at the maximum output power, to the peak of the absorption in the crystal. The Fig. 2 shows the evolution of the diode spectrum as we increase the output power. In Fig. 21, we plotted the laser output power (left) and the percentage of transmitted power (right) as a function of the incident pump power for different diode and crystal water cooling temperatures for a pump π-polarized. As expected, the lower the transmitted pump power is (meaning higher pump absorption) the higher is the laser output power. To some extent, the influence of the crystal temperature (see Fig. 16 for more details) is not as important as the diode temperature. The diode wavelength shift from a water cooling temperature of 20°C to 14°C makes a significant impact on the crystal absorption and therefore on the output power especially for a pump π-polarized. The maximum output power increases by more than 30 W, from 132 W to 164 W.

We measured the beam propagation factor of the Tm:YLF laser for different output powers and for two perpendicular directions (see Fig. 22). For these measurements the pump was π-polarized. We used a 150 mm focal length focusing lens and the chopper wheel method. In the direction perpendicular to the c-axis, the beam propagation factor doesn’t depend on the output power. It has an $M^2 \sim 3$ at all power levels. In the direction parallel to the c-axis the beam propagation factor strongly depends on the output power. The beam propagation factor increases from $M^2 \sim 190$ at 15 W to $M^2 \sim 300$ at full output power. The beam profile at full output power, taken with an infrared Pyrocam I camera, is display on the inset of Fig. 22 (left).
4. Conclusion

We presented a comparative study on high power Tm:YLF and Tm:LLF slab lasers single end-pumped by a high-brightness laser diode stack. The presence of a stronger negative thermal lens in Tm:LLF crystal than in Tm:YLF crystal has been highlighted for the first time at this power level. The thermal lens focal length of the Tm:YLF laser was estimated to be longer than $-500 \text{ mm}$ while in the Tm:LLF laser it has been estimated to be shorter than $-500 \text{ mm}$ but longer than $-150 \text{ mm}$. In a stable cavity configuration, these two crystals produce approximately the same output power, with a small advantage to Tm:YLF. The emitted wavelength of these two lasers are slightly different and depend on the output coupler. For the same output coupler reflectivity the Tm:LLF laser wavelength is 6 nm longer than the Tm:YLF. For the same output power (140 W), the beam propagation factor of the two laser beams are similar with $M^2 \sim 400$ in the direction parallel to the c-axis and $M^2 \sim 1.2$ in the direction perpendicular. The laser beam is linearly polarized. The Tm:YLF laser produces a maximum output power of 164 W with slope efficiency with respect to the absorbed pump power of 57%. The Tm:YLF laser wavelength is centered at 1908 nm for a $R = 81\%$ output coupler. This wavelength is matching the absorption peak of Ho:YAG crystal, making the compact (190 x 90 mm$^2$ footprint) slab Tm:YLF laser an excellent candidate for a pump source. The longer emitting wavelength of the Tm:LLF laser could be advantageous for pumping Ho:YLF or Ho:LLF lasers.

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