High-power intracavity upconversion pumped Tm:YLF laser emitting at 2.3 µm

Hippolyte Dupont[1,*], *Timothée* Lenfant[2], *Lauren* Guillemot[2], *Xavier* Delen[1], *Pavel* Loiko[2], *Alain* Braud[2], *Pascal* Loiseau[3], *Bruno* Viana[3], *Thierry* Georges[4], *Patrick* Georges[1], *Patrice* Camy[2], and *Frédéric* Druon[1]

[1]Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France
[2]Centre de Recherche sur les Ions, les Matériaux et la Photonique, UMR 6252 CEA-CNRS-ENSICAEN, Université de Caen, 6 Boulevard Maréchal Juin, 14050 Caen Cedex 4, France
[3]Chimie ParisTech, PSL University, CNRS, Institut de Recherche de Chimie Paris, 11 rue Pierre et Marie Curie, 75005 Paris, France
[4]Oxxius S.A, 4 rue Louis de Broglie, 22300 Lannion, France

Abstract. A Tm:LiYF$_4$ laser operating on the $^3H_4 \rightarrow {}^3H_5$ transition is integrated into a high-power diode-pumped Nd:ASL laser for intracavity upconversion pumping at 1.05 µm. This architecture leads to a record-high output power at 2.3 µm ever extracted from any upconversion pumped Thulium laser. The continuous-wave Tm-laser yields 1.81 W at 2.3 µm at 32 W of laser-diode pump power at 0.8 µm, rivalling direct diode pumping. The intracavity pumping mitigates weak absorption inherent to the upconversion pumping scheme and disperses the deposited heat over two laser crystals. This laser design minimizes heating of the Tm-crystal and enhances the tolerance to Tm^{3+} excited-state absorption, being promising for high-power 2.3-µm solid-state lasers based on thulium ions.

1 Introduction

Lasers emitting around 2.3 µm represent a promising area of research for various applications such as atmospheric gas sensing, glucose blood testing, combustion studies and mid-infrared fiber gas photonics. Various 2.3 µm laser sources have been developed so far, including non-linear frequency converters such as OPO/OPA, semiconductor lasers and solid-state lasers based on Cr^{2+}-doped zinc chalcogenides (ZnS and ZnSe) as gain media. Another way to access this wavelength range is to employ the $^3H_4 \rightarrow {}^3H_5$ transition of thulium ions (Tm^{3+}). In this case, different pump configurations are available. So far, direct pumping from the ground state ($^3H_6$) to the upper laser level ($^3H_4$) allowed for accessing both high laser slope efficiencies exceeding the Stokes limit when using high-brightness Ti:sapphire laser pumping [1], as well as multi-Watt laser output when using commercial high-power spatially multimode fiber coupled AlGaAs diode laser modules [2].

Although its potential still needs to be revealed, the recently proposed upconversion (UC) pumping slightly above 1 µm is quite promising, as it gives access to very mature Yb and Nd fiber and solid-state laser technologies for pump sources. As shown in Fig. 1(a), this pumping scheme involves a non-resonant ground state absorption $^3H_6 \rightarrow {}^3H_5$ to populate the intermediate $^3F_4$ metastable level (lifetime: 11 ms for Tm:LiYF$_4$) after a non-radiative (NR) relaxation step. The resonant $^3F_4 \rightarrow {}^3F_{2,3}$ excited-state absorption followed by another NR relaxation step subsequently populates the upper laser level. Moreover, an efficient cross-relaxation process can also play a positive role in the UC pumping as it drives a photon avalanche mechanism, Fig. 1(a). UC pumping has been successfully applied in Tm fiber [3] and crystalline [4] lasers. However, this pumping scheme suffers from the need for high pump intensities driving the photon avalanche which is often hard to observe in bulk lasers especially under low-brightness pumping. It is thus often difficult to reach sufficiently high pump absorption efficiency, so a modified approach relying on dual-wavelength pumping has been proposed to resolve this issue but with a relatively modest improvement in terms of the output power [5].

Another innovative idea we are proposing here consists of using an intracavity upconversion pumping scheme relying on the well-developed technology of diode-pumped Nd solid-state lasers to benefit from high-brightness pumping.

2 Laser setup

As a gain material for the proof-of-principle, we have selected the Tm:LiYF$_4$ (Tm:YLF) laser crystal. It exhibits a strong excited-state absorption at 1050 nm [5], Fig. 1(c). A Nd^{3+}-activated strontium lanthanum aluminate crystal $Sr_{1-x}Nd_yLa_{x-y}Mg_xAl_{12-x}O_{19}$ (Nd:ASL) has been chosen to address this pump wavelength. This crystal was pumped using a high-power spatially multimode fiber-coupled (numerical aperture: 0.22, fiber core diameter: 106 µm) AlGaAs laser diode emitting up to 35 W at 785 nm. A V-shaped cavity was developed to evaluate the performance of this Nd-laser. An optimal output power of 6 W was

---

[*] Corresponding author: frédéric.druon@institutoptique.fr

obtained using 20% output coupling. The cavity was further extended to obtain a second beam waist of 45 µm where a 2.5 at.% Tm^{3+}-doped 8 mm-thick Tm:YLF crystal was inserted, as shown in Fig. 1(b). For the 2.3-µm laser, again a V-shaped cavity was designed containing two dichroic mirrors (both coated for HT at 1.05 µm and HR at 2.3 µm), namely a plane one and a concave one (radius of curvature, RoC = -200 mm) and a plane 3% output coupler. The curved dichroic mirror acted as a plano-concave lens in the Nd-laser cavity. Both laser crystals were AR coated and mounted in Cu holders cooled down to 18 °C. To demonstrate the advantage of intracavity pumping, we first demonstrated, as a reference, a "classical" extra-cavity pumping using the Nd:ASL laser. An output power of 170 mW at 2.3 µm was obtained for 6 W of pump power at 1.05 µm. The performance is good compared to the state-of-the-art, but the pump absorption is limited to 26%.

3 Intracavity pumped Thulium laser

The output performances obtained with intracavity upconversion pumping are presented in Fig. 1(e). In this original setup, 1.59 W of output power at 2.3 µm are demonstrated for an intracavity pump power of 19.2 W (this value was determined by measuring the leakage through the HR end mirror), for a laser diode power of 35 W.

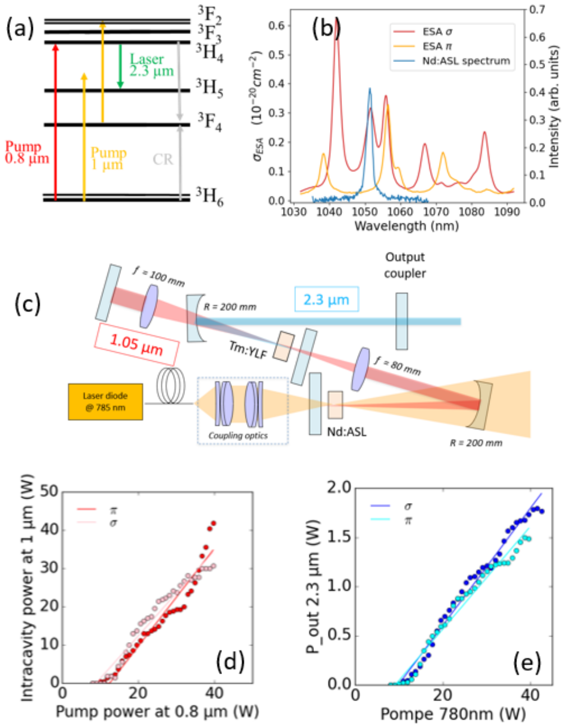

Fig. 1. Continuous-wave 2.3-µm Tm:YLF laser with intracavity upconversion pumping by a 1.05-µm Nd:ASL laser: (a) Energy-level scheme of Tm^{3+} ions; (b) excited-state absorption, σ_{ESA}, cross-sections of Tm^{3+} ions in YLF for the $^3F_4 \rightarrow {}^3F_{2,3}$ transition for σ and π polarizations. The Nd:ASL laser spectrum is given for comparison; (c) laser set-up; (d) intracavity pump power at 1.05 µm after the Tm-crystal vs. the pump power at 0.8 µm; (e) output performance of the 2.3 µm laser when the Tm-crystal is pumped into σ and π polarizations.

The 1.05 µm pump absorption in the Tm-crystal is estimated to be 27%. The heating of the Tm:YLF crystal is not an issue even at this high pump level. Indeed, the maximum temperature rise reaches 73 °C with a gradient of 20 °C. The thermal lenses of both crystals are considered for the design and adjustment of the cavity.

For intracavity pumping, a strong interplay may occur between the Tm^{3+} absorption and the 1.05-µm intracavity power, since the former effect can be seen as an intracavity loss for the Nd-laser. This can be easily verified using the fact that the ESA cross-sections for Tm^{3+} ions in $LiYF_4$ are different for σ and *π* polarizations. Indeed, we turned the Tm-crystal to access one polarization or the other. When the crystal is oriented for pumping into π polarization, the absorption at 1.05 µm decreases and so does the intracavity loss for the Nd-laser. The intracavity power increases to 26.4 W (for 35 W of laser diode power). The single-pass absorption of the 1.05 µm pump radiation is measured to be only 8%. The output power at 2.3 µm decreases to 1.15 W.

4 Conclusion

The obtained results highlight the adaptability of the intracavity pumping scheme to absorption of Tm-crystals. As the 1.05 µm pump absorption decreases, the intracavity power at this wavelength tends to increase, so that both effects compensate for each other leading to high output power at 2.3 µm. This is a key advantage of the intracavity pumping architecture, as extracavity UC pumping is very sensitive to pump intensity variations and doping concentration. The output power obtained in the present work proposed for the sake of demonstration is already competitive with previously reported diode-pumped Tm:YLF lasers emitting at 2.3 µm. Compared to the direct diode pumping, the heating of the Tm:YLF crystal is relatively weak, opening a new paradigm promising for high-power solid-state lasers at 2.3 µm based on thulium ions.

References

1. P. Loiko, R. Soulard, L. Guillemot, G. Brasse, J.-L. Doualan, A. Braud, A. Tyazhev, A. Hideur, F. Druon, P. Camy. IEEE J. Quantum Electron. **55**, 1700212 (2019)
2. E. Kifle, P. Loiko, L. Guillemot, J.-L. Doualan, F. Starecki, A. Braud, T. Georges, J. Rouvillain, P. Camy, Appl. Opt. **59**, 7530-7539 (2020)
3. A. Tyazhev, F. Starecki, S. Cozic, P. Loiko, L. Guillemot, A. Braud, F. Joulain, M. Tang, T. Godin, A. Hideur, P. Camy, Opt. Lett. **45**, 5788-5791 (2020)
4. L. Guillemot, P. Loiko, R. Soulard, A. Braud, J.-L. Doualan, A. Hideur, R. Moncorgé, P. Camy, Opt. Lett. **44**, 4071-4074 (2019)
5. H. Dupont, L. Guillemot, P. Loiko, A. Braud, J.-L. Doualan, P. Camy, P. Georges, F. Druon, Opt. Express **30**, 32141-32150 (2022)