Optimization of a 2.3 μm Yb:Tm:YLF laser, pumped at 685 nm and 960 nm simultaneously

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Abstract

For the first time, a unique pumping scheme for the thulium 2.3 micrometer transition is proposed that is capable of enhancing the output power by almost a factor three when compared to the traditional pumping scheme at 960 nm. The best relation between 685 nm pump power and 960 nm pump power is shown. The achieved output power of 620 mW is the highest reported so far.

Introduction

Tunable lasers emitting around 2.3 μm region are important in many application areas. They are especially of interest in gas detection [1,2] systems, because of the presence of strong absorption lines of atmospheric pollutants in the spectral region around 2.3 μm such as CO, CH_4 and HF. The 2.3 μm laser is used for sensing carbon monoxide and hydrocarbon gases in combustion experiments and LIDAR applications [3], in part because of its relatively weak water vapor absorption. Lasers in the region 2.0-2.5 μm play also an important role in noninvasive blood glucose measurements [4].

Thulium has a large emission spectra around 2.3 μm with demonstrated tuning range of 2.2-2.45 μm using the YLF host [5]. Tm:YLF has strong absorption lines at 685 and 780 nm that are accessible with diode lasers. The absorption at 685 nm is three times larger than that at 780 nm [6]. With the commercial availability of high power (up to 5 W) diode lasers emitting at 685 nm, this pumping wavelength is of interest because it permits much more effective pump arrangements due to the higher absorption coefficient. Due to a highly concentration dependent cross-relaxation process that leads to a reduction of the 2.3 micron emission from the upper laser level, the thulium concentration should be kept below 2 mol % [5]. For efficient pump absorption, a high concentration sensitizer like ytterbium can be used. Yb can be diode-pumped at 960 nm where high-power diodes are available.

In the 960 nm Yb:Tm pumping scheme occur three energy transfer up-conversion processes (ETU) as illustrated in Figure 1. After pump excitation from the $^2F_{7/2}$ level to the $^2F_{5/2}$ level, the ytterbium transfers its energy to the $^3H_5$ Tm level, followed by a fast multi-phonon relaxation down to the metastable $^3F_4$ level. A second ETU process to the $^3F_2$ energy level of Tm^{3+} followed by a rapid relaxation populates the upper laser level ($^3H_4$). The next ETU causes losses to the system because it transfers population from the upper laser level into the $^1G_4$ level of Tm. Other processes deplete the upper laser level: the non-radiative transfer via cross-relaxation originating from the $^3H_4$ and $^3H_6$ levels to the $^3F_4$ level and the back-transfer from the $^3H_4$ thulium level to $^2F_{5/2}$ ytterbium level.

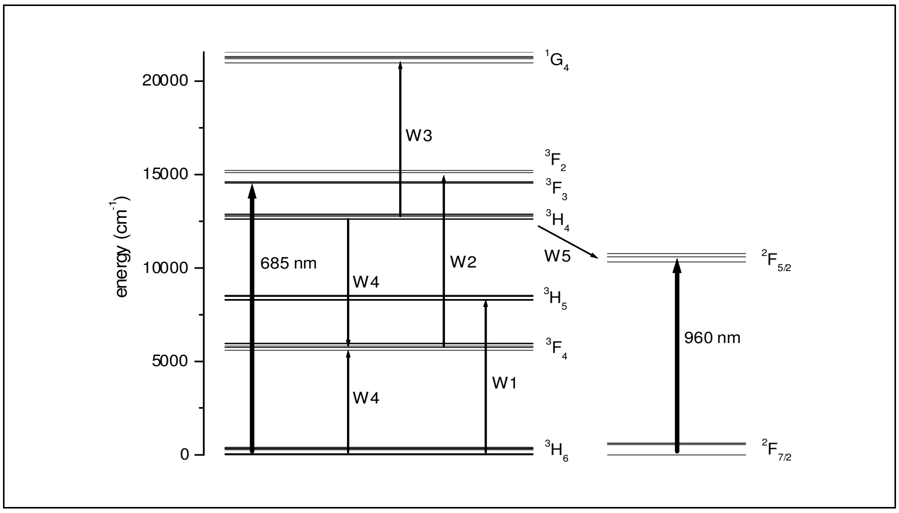

Figure 1: Energy-level scheme of Yb:Tm:YLF. W1, W2, W3 represent energy transfer upconversions; W4 is a cross-relaxation and W5 a back-transfer.

Laser action at 2.3 micron in Tm is based on the $^3H_4$-$^3H_5$ transition. In the 685 nm pumping scheme, Tm is pumped from the $^3H_6$ ground state into $^3F_3$ manifold followed by a fast multi-phonon relaxation to the upper laser lavel $^3H_4$. There exists also excited state absorption from $^3F_3$ into $^1D_2$ followed by a blue emission at 450 nm. This works studies the Yb:Tm system pumped at 685 nm and 960 nm simultaneously.

Experimental Setup

The Yb:Tm:YLF crystals were grown at our in-home crystal growth facility with a concentration of 9.5 mol % ytterbium and 1.2 mol% thulium. These concentrations allow for maximum efficiency of the 2.3 μm emission [7]. The Brewster crystal was mounted on a water-cooled copper heat-sink. Its length was 4.6 mm and it absorbed 96% of the 960 nm pump radiation. The laser cavity length was 2.3 cm using a 10 cm radius-of-curvature high-reflectivity input mirror and a flat output coupler. The crystal was first end-pumped by a 20 W diode bar at 960 nm and later both, end-pumped and side-pumped, by a 5 W diode bar at 685 nm as show in Figure 2. For the end-pumping setup, a series of lenses and a two-mirror beamshaper were used to reconfigure the diode emission into a more circular beam with approximately equal M^2 factors in the x- and y-direction [8]. A pump intensity of 19 kW/cm^2 and a M^2 quality factor of 42x29 (horizontal x vertical) were achieved at the crystal position as measured with a calibrated power meter and a CCD, using the second moment method to calculate the beam spot sizes. Pump spot size was 310 x 230 μm^2. Due to losses in the beamshaper and the input mirror, the maximum pump power was 11 W.

For the 685 nm, side-pumped set-up, we used a half-wave-plate to rotate the diode's emission parallel to the crystal's c-axis in order to access its high absorption coefficient of 4.3 cm^{-1} (1 mol% doping). The pump beam was incident on the top surface of the crystal. A 3 cm spherical lens and mirror at 45 degrees matched the pump beam to the laser mode size inside the crystal. Due to losses, the maximum pump power was 4.5 W. An indium foil between the crystal and the heat-sink reflected the 685 nm pump beam back into to the laser mode. We estimated a total absorbed pump power of 600 mW in this double-pass, side-pumped configuration. In order to allow the 685 nm pump beam to access the crystal from the top we could not remove the generated heat from the crystal's top face and had to use qcw operation.

In order to establish which fraction of 685 nm pump power achieves the highest output power, we used a numerical, time resolved simulation which included all energy-levels of Figure 1. The system of eight differential, non-linear equations is solved using a second order Fehlberg algorithm. Also, it is assumed that the crystal is longitudinally pumped from both sides with the same pump parameters as described above, except for a maximum pump power of 25 W for both 685 nm and 960 nm radiation.

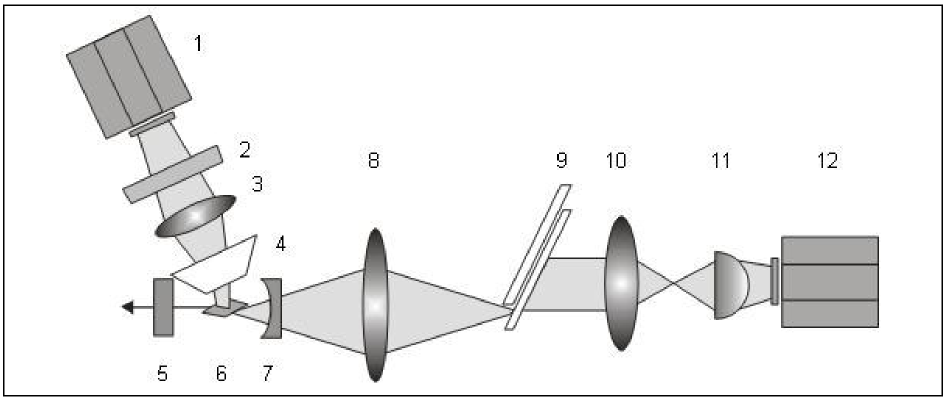

Figure 2: Pumping scheme: (1) 685 nm diode laser; (2) λ/2 waveplate; (3) spherical lens; (4) folding mirror; (5) output coupler; (6) Brewster cut Yb:Tm:YLF crystal; (7) input mirror; (8) spherical lens; (9) two-mirror beam-shaper; (10) spherical lens; (11) cylindrical lens; (12) 960 nm diode laser.

Results and Discussions

The highest output power, achieved in the first experiment that used only the end-pumped configuration, was 620 mW with a slope efficiency of 8%.

The laser performance of the second experiment that used both pump configurations is illustrated in Figure 3 for an output coupler reflectance of 98,8%. Slope efficiencies of 7,3±0.15% and 7,9±0.15% were obtained for single and double pumping, respectively. For the double pumping scheme, the 685 nm diode is fixed at 5 W output power and only the 960 nm pump is varied. The x-axis shows the total absorbed pump power. The threshold pump power reduced from 3.0 W to 2.6 W for dual pumping, although care must be taking with this information, because a large error margin is involved in the estimate of the absorbed 685 nm pump power.

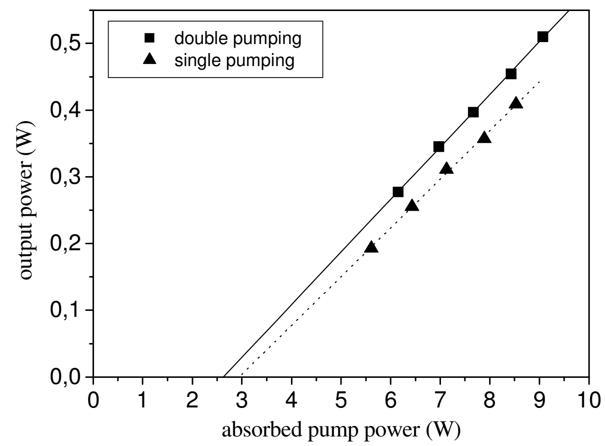

Figure 3: Measured input-output curves at the same total absorbed pump power for 960 nm pump only (triangles) and the double pumping scheme (squares) with approximately 600 mW of 685 nm pump.

Another interesting characteristic of the double pumping scheme is that the laser turn-on time reduces from 1.0 ms in the single pumping scheme to 0.82 ms in the double pumping scheme. Because resonator losses are the same in both cases, this demonstrates a higher small signal gain when using 685 nm.

Using an output coupler reflectivity of 98,1%, the numerical simulations showed a clear maximum at about 40% of 685 nm pump power (Figure 4). An increase in output power of almost 300% is obtained when compared to the traditional 960 nm pump. It should be remarked that the optimum fraction of 685 nm pump power is a function of pump absorption efficiency and therefore depends on pump parameters as well as crystal doping and geometry. The simulation also demonstrates clearly that pure 685 nm pumping is inefficient due to the bottleneck effect of the $^3F_4$ energy level.

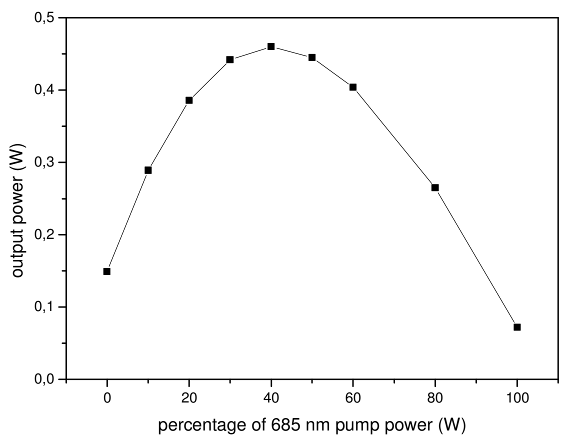

Figure 4: Numerical simulation of the output power as a function of the percentage of 685 nm pump power maintaining a total input power of 25 watt.

Conclusions

Yb:Tm:YLF laser operation at 2.3 µm, achieved by pumping simultaneously at 685 nm and 960 nm, is demonstrated. The output power of 620 mW is, to our knowledge, the highest reported so far. Higher slope efficiency is achieved for double pumping with 685 nm. The numerical simulation showed an increase in output power of approximately a factor 3 if a total pump power fraction of 40% of 685 nm pump radiation is used.

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