QCW - Tm:Ho:YLF laser pumped by a 20 W diode bar using a two mirror beam shaper

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We report on a highly efficient and compact, quasi-continuous, 2.06μm Tm:Ho:YLF laser which has produced 1.7 W of peak power when operated at room temperature and pumped by a 14 W, 792nm diode laser bar, at 10% duty cycle. By lowering the crystal temperature to 6°C, this peak power is maintained up to a maximum duty cycle of 28%.

I Introduction

We are currently developing a 2-μm laser for various applications including dental caries prevention and air turbulence detection. Both applications belong to the missions adopted by our Institute, which seek to benefit society in terms of comfort and safety. Within this program we are investigating the modifications induced in dentin, the internal mineralized tissue of teeth, by laser radiation in order to increase the resistance to caries and for restorative procedures. The goal is to melt the dentin surface and, after resolidification, obtain a surface with partial closure of the dentinal tubules for increased resistance to caries, reduced sensitivity to pain and improved microhardness and roughness for better bond strength of composite resin restorations [1,2].

Also within the program of our institute and in cooperation with the secretary for the environment (SVMA) is the need to develop a Doppler LIDAR system operating at 2 μm to detect aerosol flow which will add to the data obtained by a frequency doubled Nd:YLF lidar currently under development in our group. The detection range should be up to 3 Km, which translates to a performance specification of 2 mJ pulse energy, 200 ns pulse duration and at least 10 Hz repetition rate. Using low loss, externally triggered acousto-optic modulators these specifications can be easily obtained once the laser generates more than 1.5 W of peak power in the qcw regime [3]. In a next step this system will be injection seeded for single frequency operation [4].

Both systems should be compact to allow for easy transportation.

II Pump configuration

The Tm:Ho:YLF laser emitting at 2.06 μm is a quasi-three-level system with a non-negligible thermal population of the lower laser level resulting in considerable reabsorption at room temperature [5]. Additionally, the system has upconversion processes in both thulium and holmium, which reduce the population of the upper laser level [6]. The net effect of upconversion losses is an increase in the threshold pump power whereas reabsorption losses imply in lower slope efficiencies. Both effects can be significantly decreased by cooling the crystal below -40 degrees Celsius and employing a pump distribution which spreads the absorption uniformly over the whole crystal length by pumping it from both sides [7].

Another technique that offsets these adverse effects is to use quasi cw pumping of the crystal, allowing operation at crystal temperatures above 0°C. The main advantage of this technique is a simpler architecture of the laser resonator once there is no need for a nitrogen-purged enclosure of the crystal or a double side pumping technique. Furthermore, cooling of the diode bar and the crystal can be done by air cooled Peltier elements. Besides, it has been shown [6] that Tm:Ho:YLF has relatively small upconversion losses under Q-switched operation when compared to Tm:Ho:YAG. Therefore, pumping the crystal with higher intensities should permit a higher gain, which in turn permits higher pulse energies and a shorter pulse duration [8].

The laser was pumped by a 20 W diode bar emitting at 792 nm which consists of 24 individual emitters in a linear array. It contains an anti-reflection coated collimating (cylindrical) fiber lens in the fast axis, which is factory installed in front of the array. The beam, with total emitting dimensions of $w_x = 1$ cm parallel to the bar and wy $w_y \approx 0.2$ mm perpendicular to the bar is highly elongated and as a result nearly diffraction limited in the y-direction but more than 2000 times diffraction limited in the x-direction. This renders the diode bar output extremely difficult to focus to a small circular spot.

The two mirror beam-shaping technique [9] permits effective control of the beam-quality factors in the orthogonal x and y-planes and, if desired, their equalization. Therefore, this technique, when combined with standard focusing lenses, generates a circular spot at the focus with dimensions that are much smaller than when using lenses alone. Basically, the beam shaper decomposes the highly elongated beam of the diode bar into 24 beams emitted by the individual emitters. These beams can be rearranged and stacked on top of each other [9]. In our case the beam was reconfigured into three columns of eight beams each as shown in the inset of Figure 1. The reconfigured beam had dimensions and quality factors of $w_x = 200$ μm, $M_x^2 = 130$ and $w_y = 190 \mu$m, $M_y^2 = 85$ at the focus where the crystal is placed. With the diode bar emitting 20 W of output power we had a total peak pump power incident on the crystal of 14 W due to losses in the beam shaper, lenses and the resonator input coupling mirror.

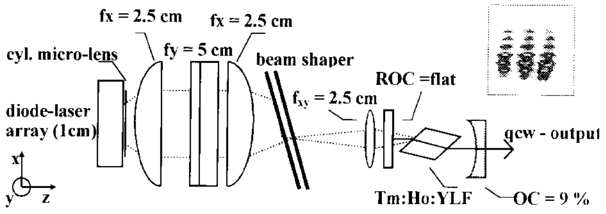

Figure 1. Setup of the Tm:Ho:YLF laser utilizing a two mirror beam shaper in the pump arrangement. The inset shows a photo of the pump distribution at the focus, taken with a CCD.

The laser resonator consisted of a flat, high reflecting mirror for 2.06 μm, which had 90% transmission for the pump beam and a curved output coupler with an optimized 9% transmission at the laser wavelength. The cavity length was held at 3 cm but remains stable up to a length of 9.5 cm (however, with additional 10% loss attributed to water absorption), which allows for future insertion of a Q-switcher. The only available output coupler's radius of curvature (ROC) of 10 cm generates a beam waist of 170 μm inside the Brewster cut crystal for the 2.06-μm fundamental transversal mode (TEM$_{00}$). This beam waist permits good overlap between the TEM$_{00}$ mode and the previously shaped pump beam, although another cavity configuration, with a slightly larger TEM$_{00}$ beam waist might show a better matching with this obtained pump beam geometry and quality.

III Results

We tested four laser crystals, with two different Ho concentrations and crystal lengths. Two crystals had 0.4-mol% Ho concentration and 3.2 mm and 5.5 mm length. Two other crystals had 1-mol% Ho concentration and 2 mm and 3.2 mm length. We have experimentally found that the 0.4-mol% Ho, 5.5-mm laser crystal presented, in our case, the best compromise between efficient pump absorption and small reabsorption losses.

Keeping the crystal heatsink at room temperature, while varying the duty cycle of the diode bar, we achieved a best result of 1.7 W of peak output power at 10% duty cycle. At higher duty cycles we verified a loss in laser efficiency. The operation at higher duty cycles rises the local crystal temperatures and the observed drop in laser efficiency points out that the main loss mechanism of this laser crystal is due to the increase in ground state population and thus reabsorption. At this condition, the increase in ground state population leads to an almost equivalent performance as the higher Ho concentration crystals under low-duty cycle pumping. We also observed the same effect (and it was particularly strong) when using the crystals with higher Ho concentration (1%).

The peak output power can be optimized by detuning the diode bar emission wavelength from 792 nm (which occurs at a diode temperature of 21°C). The pumping wavelength detuning also favors the laser efficiency due to the spread of the absorbed pump power over the whole crystal length, leading to lower local temperatures. Some results from this pumping wavelength optimization are shown in Figure 2. The 0.4-mol% Ho, 5.5-mm laser crystal presented a maximum output power at positive 2-nm detuning. For the 1-mol% Ho, 3.2-mm crystal, a four times lower maximum output power was obtained at an optimum positive 3.3-nm detuning. We observed that, in our case, this optimization is a function of the crystal heatsink temperature. At lower heatsink temperatures no significant benefits in output power were observed from detuning the diode laser wavelength from 792 nm.

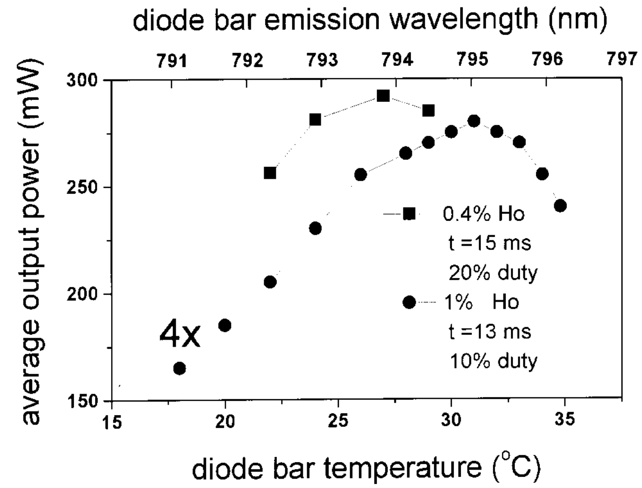

Figure 2. Measured average output power from the Tm:Ho:YLF laser as a function of diode bar emission wavelength for two different Ho concentrations, using individually optimized duty cycles. In both cases the crystal is held at room temperature. For better comparison, the values of the measured output power of the 1% Ho crystal (circles) has been multiplied by four.

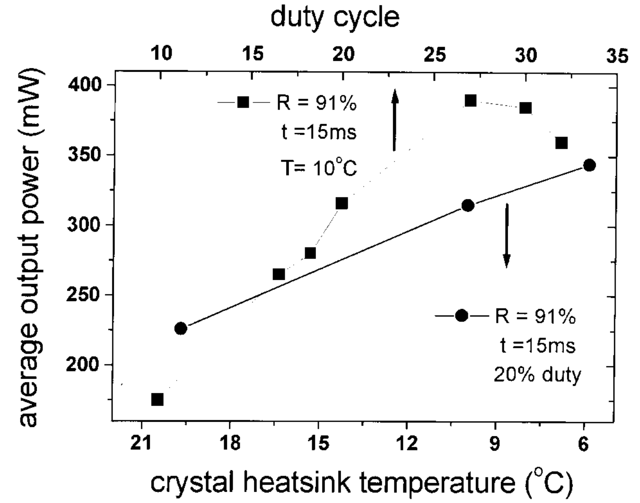

Figure 3. Average output power as a function of a) duty cycle at fixed crystal heatsink temperature (squares) and b) as a function of crystal heatsink temperature at fixed duty cycle (circles). In both cases the same crystal of 5.5 mm length and 0.4% Ho concentration was used.

Lowering the crystal temperature and keeping the diode emission wavelength at 792 nm, the laser can sustain its efficiency at duty cycles higher than 10%. Using a 20% duty cycle and cooling the crystal to the lowest obtainable temperature in our setup (6°C), a maximum average output power of 345 mW was achieved, which corresponds to 1.7 W of peak output power (Figure 3). By varying the diode bar duty cycle and maintaining the crystal at 10°C, we verified an almost linear increase in output power up to a maximum duty cycle of 28% after that thermal problems started (Figure 3). Combining the lowest obtained crystal temperature (6°C) with the maximum duty cycle of 28% we achieved the same peak output power as in the previous experiment with the crystal at room temperature and 10% duty cycle (1.7 W - not shown in the figure).

IV Conclusions

We report on a highly efficient quasi-continuous Tm:Ho:YLF laser which has produced 1.7 W of peak power when operated at room temperature and 10% duty cycle, pumped with a 14 W diode laser bar. No cooling circuit is required for this setup. By lowering the crystal temperature to 6°C, this peak power is maintained up to a maximum duty cycle of 28%. The system is compact and easily transportable. All the preliminary requirements for a Doppler LIDAR system were therefore achieved. The output power obtained from this system is also enough to initiate studies for caries prevention.

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