Intra-Cavity Side-Pumped Ho:YAG Laser

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Abstract: We present a novel, compact and power scalable Ho:YAG laser based on intracavity side-pumping by a high-power Tm:YLF slab laser. 14W of continuous wave output power is obtained at 2.09μm in the current experiments, with the clear prospect of reaching the 100W regime in a power scaled version.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state

1. Introduction

2μm holmium lasers have important medical, military, and remote sensing applications. Holmium's emission is in the eye-safe wavelength regime and, when doped into a YAG host, its operating wavelength of ~2.1μm coincides with an atmospheric transparency window. It also has a long upper state lifetime of ~8ms, dependent upon the laser host, [1], making it attractive for energy storage. This is combined with a large emission cross-section and hence a low saturation fluence of ~6J/cm^2 in Ho:YAG, allowing efficient extraction of the stored energy in the form of short Q-switched pulses. These characteristics make Ho:YAG very attractive for applications such as coherent Doppler LIDAR, [2], and as a pulsed pump-source for mid-infrared optical parametric oscillators, [3].

However, holmium does not have strong absorption bands at wavelengths corresponding to commonly available high-power diode lasers, although direct diode-pumping has been demonstrated with 1.9μm GaInAsSb and InGaAsP diodes, [4]. Fortunately, 2.1μm holmium lasers can be in-band-pumped efficiently by 1.9μm thulium lasers, which in turn can be diode-pumped efficiently at ~790nm, due to a two-for-one cross-relaxation process, whereby one pump photon can lead to the excitation of two thulium ions into the upper laser level. Co-doping of the same crystal with thulium and holmium is a compact solution, [5,6], but it can lead to severe co-operative upconversion reducing the energy storage capacity, [7], particularly in a YAG host. Alternatively one can use separate thulium and holmium doped crystals within a common laser cavity, as first demonstrated by Stoneman and Esterowitz, [8]. However, there is limited scope for brightness-scaling the Holmium output in such an intracavity-pumped configuration, as the thermal loads in the respective crystals ultimately degrade the performance of the collinearly-coupled cavities. A common approach is therefore to pump the holmium laser with a separate diode-pumped thulium laser, which also has the power-scaling advantage of separating the thermal loads. Furthermore, the separation of the thulium and holmium lasers allows individual optimization of the respective hosts and their doping levels. An example of which is the use of Tm-doped silica fibers for pumping Ho:YAG, [9,10], exploiting the recent dramatic progress in power scaling of fiber lasers, [11]. However, it is not as yet clear how well the requirements for both higher output power and high overall efficiency in a power-scalable geometry (e.g. by exploiting the two-for-one cross-relaxation process and/or by using novel pumping schemes [12]), can be met simultaneously in cladding-pumped thulium fiber lasers.

In this paper we utilize a Tm:YLF laser to pump Ho:YAG, due to the strong overlap of emission characteristics of the former with the absorption characteristics of the latter, [13].

However, power scaling single Tm:YLF rod lasers beyond 20W average power is problematic due to the host's relatively low stress-fracture limit, [14]. Therefore, we exploit a power-scalable, multimode, Tm:YLF slab laser architecture, [14], which has already delivered average powers of ~70W, from a single gain element, using a 250W diode pump laser, and which should be scalable to well beyond the 100W level. This is combined with a novel and compact, intracavity side-pumping arrangement for the Ho:YAG laser. This pumping scheme capitalizes on the high intracavity intensity of the thulium laser, whilst allowing the holmium laser to be spatially decoupled from it. Furthermore, the pumping configuration defines a relatively uniform thermal load in the holmium doped crystal, aided by the multimode nature of the Tm:YLF laser, and thus does not introduce significant thermal lens aberrations that could degrade beam quality and reduce efficiency at high power levels. An important advantage of this approach is that there is essentially no need for good beam quality from the Tm:YLF laser. This greatly simplifies the design of the Tm:YLF laser, since emphasis can be placed on obtaining high output power and a high overall efficiency with very simple pump beam delivery optics and with few constraints on the cavity design, in stark contrast to the situation where TEM_{oo} operation is needed.

2. Power Scaling Strategy

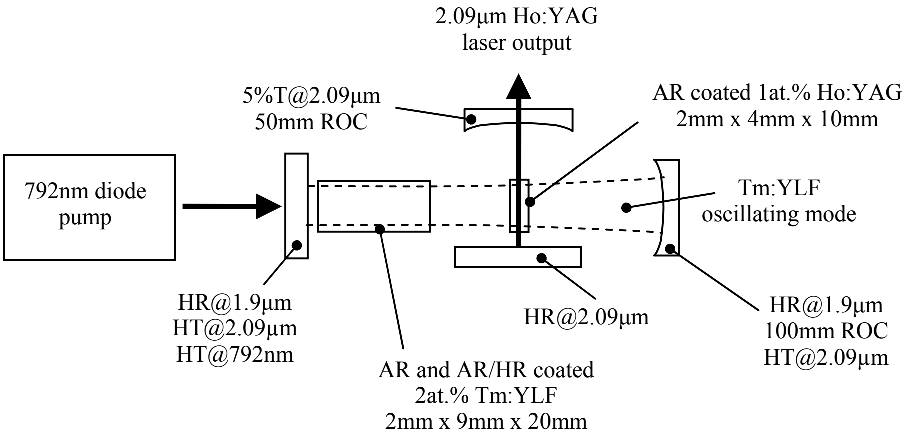


Fig. 1 Schematic diagram of the Ho:YAG intracavity side-pumped laser

Figure 1 shows a schematic diagram of the intracavity side-pumped Ho:YAG laser. The underlying principle of operation is that the absorption of the Tm:YLF laser intracavity power by the Ho:YAG (i.e. the effective output coupling loss) should dominate over any other losses in the Tm:YLF cavity, and hence lead to very efficient pumping. Also, as the optimum output coupling of the continuous-wave Tm:YLF laser is ~10-20%, we need only have ~5-10% absorption per pass in the Ho:YAG crystal, allowing a relatively uniform excitation that is beneficial for power scaling. This also allows the use of relatively low holmium doping levels to reduce Ho:Ho upconversion, [15]. Although pumping of a holmium laser by placing it inside the cavity of a thulium laser has been demonstrated by several authors, [8,16,17], if the crystals share a common cavity, [8,16], the thermal lensing in both crystals can seriously affect the beam quality of the Ho:YAG output. To tackle this problem, Schellhorn et al, [17], introduced a novel configuration whereby the Ho:YAG laser cavity was partly decoupled from the Tm:YLF cavity by polarization. In our design the two cavities are fully decoupled through the use of side-pumping, which has the further advantage of much less stringent requirements on the beam quality for the thulium pump laser. In fact, an asymmetric, multimode, relatively flat-top beam profile is advantageous in creating a uniform pumping distribution, and hence to the power scaling of the Ho:YAG laser. Consequently, we are able to utilize a very simple slab pump laser that can be scaled to much higher powers than those available from an end-pumped rod laser, [18].

3. The Tm:YLF Pump Laser

We have recently developed a high-power Tm:YLF slab laser that meets the requirements of an intracavity side-pumped Ho:YAG laser very well, [14]. The 9mm-wide (c-axis) by 1.5mm-thick, 20mm-long YLF slab had a thulium doping level, optimized for the highest output power before fracture, of 2at.%. The slab was pumped by a 6-bar low-fill-factor diode-stack at 792nm. Each bar was collimated in both fast and slow-axes with micro-lenses and the overall, TM-polarized, diode stack beam-quality was measured to be $M_{slow}^2 \approx 450$ by $M_{fast}^2 \approx 45$. The Tm:YLF laser had a compact 5cm-long cavity, consisting of a plane high-reflectivity input coupling mirror, the Tm:YLF slab, and a 20cm radius of curvature, 87% reflectivity, output coupler. The pump optics delivered a beam which was collimated and approximately filled the slab aperture in the plane of the slab (the horizontal axis). In the vertical axis, the pump beam size was selected for roughly confocal focusing over a double pass of the slab ($1/e^2$ waist diameter of 0.74mm), due to the use of a dual HR/AR coating on the end face of the slab to allow double-pass pumping. The combined transverse modes of the Tm:YLF laser were found to nearly fill the slab aperture with an overall super-Gaussian-like profile in the plane of the slab and with an approximately Gaussian profile in the vertical direction. Figure 2 shows the Tm:YLF laser performance, delivering 68W of σ-polarized output at 1.9µm, with a slope efficiency of 44%. The mode profile, relay-imaged from the high-reflectivity plane mirror, is shown inset and the M^2 values were measured to be 3.5 (vertical) by 350 (horizontal).

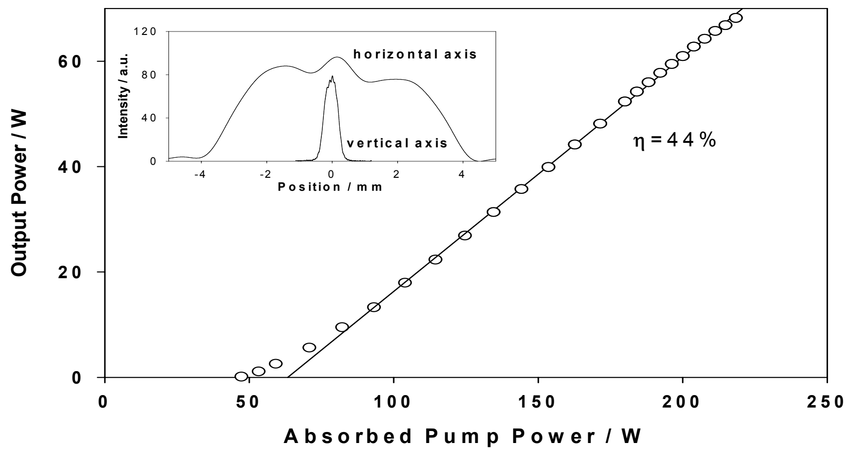
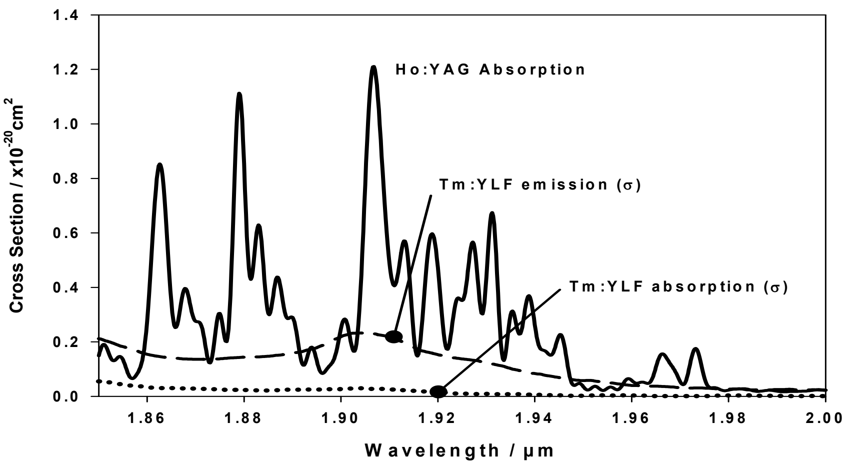


Fig. 2 Output power against absorbed pump power for the Tm:YLF laser. The multimode laser mode profile is inset.

4. Intracavity Pumping Experimental Design

For the results discussed in this section we were forced to use a Tm:YLF slab of dimensions 9mm wide by 20mm long and 2mm thick, instead of the 1.5mm-thick slab discussed in the previous section. This was due to the fact that the AR/HR coating of the thinner Tm:YLF slab was damaged by high intensity spikes in the thulium-holmium cavity, when the pump power was high and the holmium cavity was not lasing due to misalignment. In general, intensity spikes were observed from the Tm:YLF laser when the holmium cavity was below threshold, due to the holmium acting as saturable absorber for the thulium laser. However, pulsing behavior was not observed when the holmium was lasing and the spike intensity below the holmium threshold never became high enough to cause damage. The use of a thicker crystal, which was the only one available, limited the pump power that we could use in pumping the Tm:YLF, as we were guided by the experimental fracture point of a previous crystal with the same dimensions (~200W absorbed power), [14].

The Ho:YAG slab was 4mm wide (pumping direction), 10mm long (lasing direction) and 2mm thick, with a doping concentration of 1at.%. The doping concentration and width of the slab were chosen to give a small-signal absorption of ~17% round-trip, assuming a Tm:YLF operating wavelength of 1.92µm. Such a strong absorption, even when partially saturated, should dominate any other losses in the thulium cavity and hence allow efficient pumping of the Ho:YAG slab. Previous reports of intracavity pumping have shown that the thulium wavelength can shift to avoid the strong holmium absorption, and in the only other previous report of Tm:YLF intracavity pumping Ho:YAG, [17], the Tm:YLF laser shifted to ~1.95µm, see figure 3. In order to control this effect, and attempt to push operation to the stronger holmium absorption minimum around 1.92µm, we employed high-pass edge mirrors to form the thulium laser cavity. The edge mirrors were HR from 1.6µm to 1.92µm, rising to ~2% transmission at 1.95µm, and several tens of percent at 2.09µm (there was some mirror-to-



mirror variation in the exact position of the fast-rising transmission edge). The use of these mirrors was also beneficial in preventing the possibility of the holmium lasing in the direction of the thulium cavity axis, where the latter has some residual gain at the holmium wavelength.

Fig.3 σ-polarized Tm:YLF emission and absorption cross-sections (data extracted from ref.[19]), and Ho:YAG absorption cross-section (data calculated from the measured absorption spectrum of an uncoated slab and the known doping level).

Figure 1 shows the setup of the thulium-holmium cavity and the various coatings employed. Both the thulium and holmium resonators are formed by simple two-mirror cavities. The thulium cavity length was increased to 67mm in order to accommodate the mirrors of the holmium cavity, and consisted of a plane HR mirror and a 10cm radius of curvature HR mirror, both of which were edge mirrors. The holmium cavity was 23mm long, with a broadband plane HR and a 5cm radius of curvature output coupler of 95%R at 2.09µm.

The diode pump and its focusing were the same as that mentioned in the previous section, but the absorbed diode power was not increased beyond 190W for fear of damaging the thicker Tm:YLF slab.

5. Intracavity Pumping Experimental Results

With the Ho:YAG crystal in the Tm:YLF cavity it was found that the edge mirror coatings had indeed prevented the Tm:YLF lasing wavelength from shifting to 1.95µm, and the holmium from lasing in the Tm:YLF cavity. However, rather than lasing at the target thulium wavelength of 1.92µm, we in fact observed lasing at 1.897µm. While this wavelength has a significantly stronger absorption in the Ho:YAG than 1.95µm, it is roughly half of that at 1.92µm, see figure 3. Combining this lower than expected absorption with the fact that the AR coatings (especially the dual HR/AR coating) are not as low loss at 1.897µm as they are at 1.92µm, led to a situation in which the absorption did not fully dominate the Tm:YLF cavity losses. Nevertheless, lasing was observed in the Ho:YAG cavity with the performance shown in figure 4. We observed up to 14W output from the Ho:YAG laser with a 16% slope efficiency with respect to diode pump power absorbed in the Tm:YLF crystal. If the absorption in the Ho:YAG had dominated the losses in the Tm:YLF cavity, and we neglect any concerns with spatial overlap, we would have expected slope efficiencies approaching

40%. As well as the unexpected operating wavelength, we also found that the lasing mode of the Tm:YLF became significantly smaller in the vertical axis when the Ho:YAG crystal was in its cavity. This surprising result would lead to a worse spatial overlap between the diode pump and the Tm:YLF lasing mode, decreasing its efficiency. The reason for the mode size reduction is not yet clear, although hard aperturing by the Ho:YAG crystal has been eliminated as a possible cause. Soft aperturing due to saturation of the Ho:YAG absorption may be playing a role in this unexpected result. Future work will investigate the causes of the low efficiency further, and will implement wavelength selection in the Tm:YLF cavity to enforce operation at a wavelength with stronger Holmium absorption.

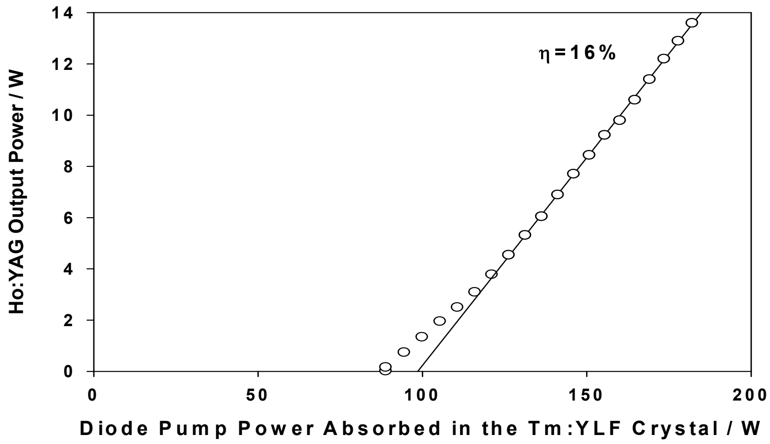


Fig.4 Intracavity side-pumped Ho:YAG output power against absorbed diode-pump power in the Tm:YLF crystal.

Thus the intracavity side-pumped Ho:YAG laser has delivered 14W of continuous-wave output power in a very compact arrangement with good prospects for further power scaling. Indeed, it is predicted that a 1.5mm by 20mm by 20mm Tm:YLF slab could absorb ~600W pump power before fracture occurred, [14], and even without improving the current efficiency this would allow ~80W output from a similar Ho:YAG cavity. Further power scaling from this point should also be possible by increasing the Tm:YLF slab length (or using several slabs) and pumping from the sides.

6. Summary

We have demonstrated a novel, compact and power scalable, intracavity side-pumped Ho:YAG laser. Based on a power scalable Tm:YLF slab laser, we are currently able to demonstrate 14W output power at 2.09μm with a 16% slope efficiency with respect to the diode pump power absorbed in the Tm:YLF crystal. It is expected that efficiencies nearer to 40% would be achievable if the losses in the Tm:YLF laser cavity could be minimized and/or wavelength selection was used in the cavity to drive the Tm:YLF laser to work at 1.92μm rather than the current 1.897μm. Power scaling predictions for a 1.5mm by 20mm by 20mm Tm:YLF slab pump laser, would suggest that ~80W of Ho:YAG output should be possible even without improving the efficiency.

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