High-power slab-based Tm:YLF laser for in-band pumping of Ho:YAG

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ABSTRACT

Several remote sensing applications require pulsed sources in the mid-infrared spectral regime with high average powers and good beam quality. Ho:YAG lasers have a number of attractive features for high power generation at 2.1microns, either for direct applications or as a pump source for parametric conversion to longer infra-red wavelengths. Unfortunately, direct diode pumping of Ho:YAG is not practical, so a two-step process is generally employed in which one or more diode-pumped thulium-doped lasers are used to directly pump (in-band) the Ho:YAG laser. In response, we have investigated a slab-based architecture for scaling the output power of a Tm:YLF laser to the 100W power regime at 1.91microns, corresponding to a strong Ho:YAG absorption line. Multiple slab lasers with moderate beam quality in the plane of the slab can be combined to efficiently end-pump a low-doping concentration Ho:YAG rod in a pump-guided configuration. In a preliminary demonstration, two 2at.% doped Tm:YLF slab lasers with a spatially multiplexed output of 74W were employed to end-pump a 1.5mm diameter, 80mm long, 0.25at.% Ho:YAG barrel-polished rod. A two-mirror plano-concave cavity, with 11% output coupling transmission, produced a CW output of 38W with a slope efficiency of 60% with respect to the incident power. Q-switched operation at a repetition rate of 20Hz with two intra-cavity Brewster plate polarizers and a 60% transmitting output coupler produced 14mJ pulses with a pulse duration (FWHM) of 18ns. This architecture offers an attractive route for future high-power 2micron lasers.

Keywords: Diode-pumped; End-pumped; Solid-state lasers; Tm:YLF; Ho:YAG

1. INTRODUCTION

There are two spectroscopic properties of trivalent Holmium ions that make them an important for laser sources; a long upper laser level lifetime, and an operational wavelength that lies in the “eye-safe” wavelength regime and has a high transmission through the atmosphere. Moreover, its lasing wavelength is typically longer than that obtained from more commonly available Thulium based lasers, and which is of greater interest for mid-infrared (IR) Optical Parametric Oscillators (OPO’s) that utilize non-linear crystals like ZGP due to lower absorption. This application demands high peak power as well as average output power in order to efficiently generate the required power levels in the mid-IR.

The lack of suitable holmium absorption bands at commonly available laser diode wavelengths makes it a difficult laser source to be efficiently power-scaled. Thus, typical approaches for obtaining high-average-power holmium lasers involve a two-step process, e.g. excitation through energy transfer via co-doping with thulium, or pumping in-band with a second shorter-wavelength thulium laser that can be efficiently diode pumped. Co-doping with thulium has been found to reduce the lifetime of the upper holmium laser level through Energy-Transfer Upconversion (ETU) processes, increasing the threshold requirements and reducing the system efficiency, particularly in Q-switched mode. Therefore, at present the most effective route reported for optimizing the energy storage of the holmium ions is to utilize separate host media for Tm^{3+} and Ho^{3+}. Holmium-doped Yttrium Aluminum Garnet (YAG) is the material of choice for most 2.1micron applications due to its well-known excellent thermo-mechanical properties and hence suitability for power scaling. Similarly Tm:YAG lasers have also been demonstrated to have high efficiency and power, however, their lasing wavelength is not well matched to absorption lines of Ho:YAG. Intra-cavity pumping configurations have been explored as a means to enhance the pump absorption efficiency in the holmium-doped crystal. However, this requires a complicated cavity design with additional wavelength discrimination (e.g. by using a birefringent filter) to prevent the Tm:YAG laser operating at a wavelength for which the loss (i.e. absorption) in the Ho:YAG is minimized.

Another candidate for the holmium pump source is the Tm:fiber laser. Tm:fiber lasers benefit from a geometry that allows simple thermal management and offer excellent beam quality and flexibility in operating wavelength from 1725 – 2090 nm[1]. Moreover, recent work has demonstrated Tm:fiber lasers with output powers well in excess of 100 W[2]. However, fiber-based sources generally suffer from the drawback that relatively high-brightness diode pump sources are needed adding extra complexity and cost to the overall system. An alternative approach is to use a Tm:YLF laser. Tm:YLF has excellent spectroscopic properties which allow relatively low brightness diode pump sources to be used and has an emission spectrum that overlaps the main absorption lines of interest in Ho:YAG. Unfortunately, YLF has rather poor thermo-mechanical properties that greatly hinder power-scaling in a conventional rod-based laser architecture. The situation is further exacerbated by the requirement for a relatively high Tm doping level for efficient two-for-one cross-relaxation [3] and by ETU, which increase the thermal loading density. In previous work we have demonstrated that an end-pumped Tm:YLF laser with a single-crystal rod gain element is limited in output power to ~20W due to its thermal loading limitations. However, we have also shown that this problem can be remedied by using a slab-based geometry with careful selection of the Tm doping level to maximize the fracture limit. This approach combines the advantages of relatively low-brightness pumping with a power-scalable architecture.

Here we report on the use of two spatially-multiplexed Tm:YLF slab lasers, pumped by a diode-stack-based pump module, for efficient pumping of a Ho:YAG rod laser in cw and Q-switched modes of operation. We also report on a power scalable end-pumped multimode Tm:YLF slab laser design and its operation up to power levels of 100W from a single oscillator at a wavelength of 1.91 µm, coinciding with the strongest Ho:YAG absorption peak.

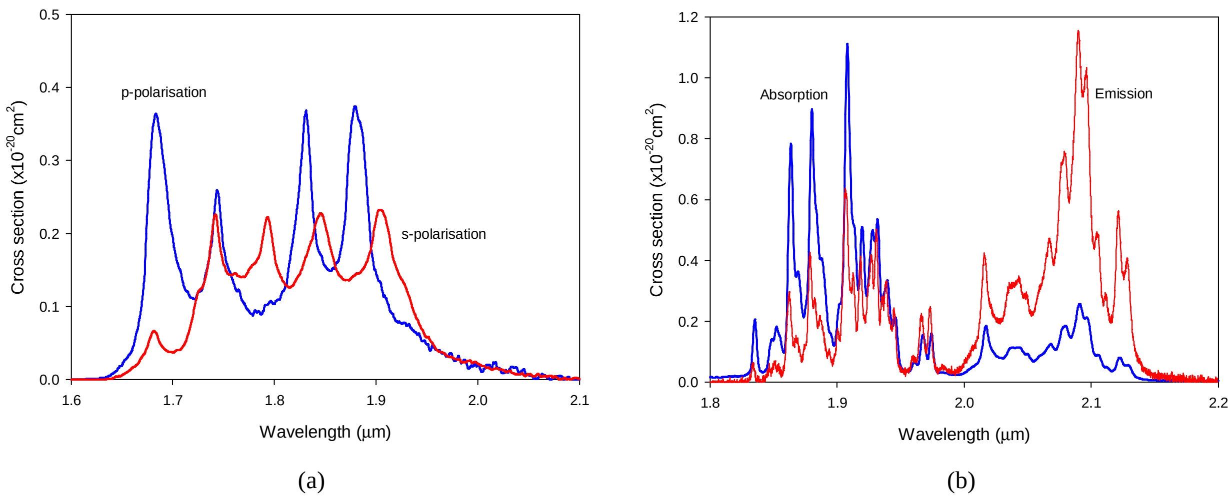
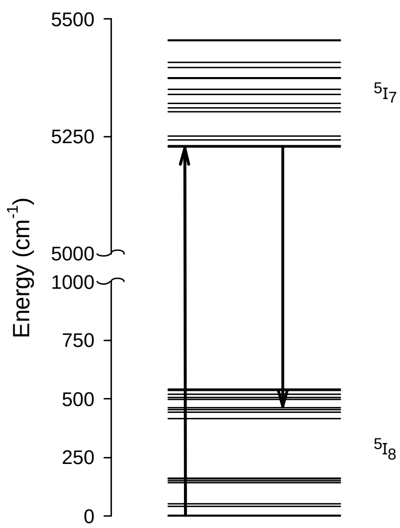


Fig. 1. (a) Room temperature Tm:YLF polarized emission cross-section versus wavelength after [4], (b) Room-temperature Ho:YAG measured absorption cross-section and calculated emission cross section via the reciprocity method[4].

2. METHODOLOGY

The terminal level for the 2.1-micron laser transition of Ho^{3+} lies in the $^5I_8$ ground state manifold and therefore suffers re-absorption at the lasing wavelength due to its finite population, nominally ~1.5% at room temperature. The upper laser level, in the first excited state $^5I_7$ manifold, can be directly populated from the $^5I_8$ manifold, i.e. in-band pumped, for pump wavelengths around 1.9 µm, as shown in Fig. 2, due to a strong splitting of the Stark levels in the ground state into two distinct groups.



(a)

Fig. 2. (a) Ho:YAG energy level diagram for the in-band pumped 2.1micron transition[5].

As is the case for Yb^{3+} in the 1-micron regime, the in-band pumped Ho^{3+} system has a small quantum defect of only ~9%. Like all quasi-three-level laser transitions, for efficient extraction efficiency from the holmium laser it is necessary to provide a pump-intensity several times that of the saturation intensity, which can often imply stringent requirements on the radiance of the pump source. Fortunately, Ho:YAG, due to its long lifetime, τ_f~8ms, and modest cross section ~$1x10^{-20}$ cm^2, has a low saturation intensity for the strongest absorption line at 1.91microns, on the order of $1kWcm^{-2}$. Moreover, the typical threshold-intensity for a holmium laser with a relatively low loss resonator is on the same order-of-magnitude, however, this is strongly dependent upon the holmium doping concentration and resulting ETU processes [6]. Consequently, a certain degree of ground-state bleaching is necessary to operate the holmium laser in an efficient power extraction regime. For low repetition-rate Q-switched (QS) systems that have a significant population inversion, bleaching of the ground state can have significant implications on the absorption and therefore overall efficiency.

2.1 Tm:YLF power scaling strategy

To increase the output power from Tm:YLF, requires knowledge of the underlying effects that generate heat and therefore stress within the crystal, such as the quantum defect and ETU processes. Armed with this knowledge it is possible to optimize the laser crystal dimensions, geometry, and doping concentration to minimize the thermal loading density and induced stress in the active material. The results reported in [5] provide an estimate for the heat power contribution from ETU and the quantum defect (dependent upon the cross relaxation 2-for-1 process when pumping with a wavelength of ~800nm into the $^3H_4$ manifold), according to the Tm^{3+} doping concentration. The better thermal management characteristics of the planar geometry in comparison to that of the cylindrical rod, enables output powers significantly greater than the ~20W limit for a standard rod configuration. It is well known that the stress-fracture limit in terms of power absorbed per unit length, P_{abs}/l, or more importantly the thermal load per unit length, for a uniformly pumped slab, is dependent upon the width-to-thickness ratio of the gain medium, along with other material properties [7]. Therefore, for the same media, in order to increase the thermal fracture pump power limit it is necessary to increase the aspect ratio of the pump beam. In the case of an end-pumped configuration, as investigated here, the absorption is not uniform but follows a Beer's law distribution along the crystal length; therefore, the absorption coefficient is an alternate parameter usually open to optimizing the thermal load per unit length. Unfortunately, for thulium-doped materials, the 2-for-1 cross relaxation dependence upon the doping concentration increases the quantum yield for increasing Tm^{3+}concentration; however at the expense of decreasing the absorption length. In addition, the heating power within the active crystal generated through ETU increases with the density of thulium ions. These counter dependent parameters lead to an optimum doping concentration for the end-pumped configuration that minimizes the thermal load per unit length in correspondence with extracting the maximum thulium laser power. We demonstrated that in an end-pumped configuration a 2at.% doping concentration is the optimum in terms of distributing the heat power along the pump propagation axis to obtain the maximum laser performance possible from the Tm:YLF crystal.

2.2 Experiment set-up

Two low-fill-factor six-bar diode stacks, with fast and slow axis collimating lenses and spatial-multiplexing in the fast-axis, were used to excite the Tm:YLF slab gain media as shown in Fig. 3. This set-up provided a total pump power of 430W at a wavelength of 790nm, with a combined beam quality of M^2 ~ 40 and 360 for the fast and slow directions respectively. A portion of the diode-stack's output was reflected with a high reflectance mirror at 45º so that two separate Tm:YLF slabs could be pumped simultaneously. A cylindrical lens telescope was used to de-magnify the x-axis (slow axis) beam size, with the respective focal lengths f_{x1}=100mm and f_{x2}=80mm, producing a pump spot diameter of ~8mm in the slabs. The individual emitters of the constituent diode-bars were re-imaged at a plane slightly before the input face of the slabs, thus avoiding localized hot-spots inside the YLF crystal. Another cylindrical lens f_y=250mm was used to focus the y-axis (fast axis) beam to a pump waist diameter of 0.74mm, positioned at the far end of each slab.

Each Tm:YLF laser comprised a plane input coupler, which was highly reflective at the laser wavelength and highly transmissive for the 790nm pump; a plane output coupler with 88% reflectivity; and an intra-cavity f=150mm spherical lens. The cavity length was 135mm and the lens was positioned 80mm from the output coupler. An intra-cavity lens was used instead of a curved output coupler mirror as we did not have the appropriate mirrors at the time. For this cavity configuration, the calculated fundamental mode size was ~300µm in the gain medium, well-matched to the vertical pump dimension.

Two 2at.% Tm-doped YLF slabs of dimensions 9mm-wide (c-axis) and 20mm-long were used in this experiment, with thicknesses of 1.5mm and 2.0mm. The TM polarized diodes were therefore σ-polarized with respect to the crystallographic axes of the slabs (E_{pump}⊥c-axis), for which, this slab length corresponds to ~2 absorption lengths. Both the input and output faces (9mm by 1.5 or 2.0 mm) had been polished to a laser optical quality, while the others were finished with a fine grind lap to prevent parasitic lasing paths. The input face of the respective slabs was anti-reflection (AR) coated at the pump and laser wavelengths, while the output face was coated for AR in the region 1925+/-25nm and >95% reflectance at the pump wavelength, effectively providing a double-pass of the pump beam. These slabs were sandwiched between two water-cooled copper heat-sinks with the large surfaces (9mm x 20mm) conductively-cooled through a thin indium foil thermal interface layer. The heat sinks were cooled with flowing water maintained at a temperature of 16ºC.

The Ho:YAG laser comprised a low concentration, 0.25at.%, barrel-polished Ho:YAG rod, which was directly water cooled also providing a low index interface and high numerical aperture (NA) for efficient pump guiding along the rod length. The diameter of the pump-guiding rod effectively defines the threshold pump-power requirement, therefore, for the CW laser configuration the smallest possible rod aperture of 1.5mm (at limit of the fabrication process) was selected for the 80mm crystal length. Both end faces were AR coated for the pump and lasing wavelengths. The rod, fixed only at the very extremes of its length, ~1mm, in a copper block, to ensure that the surrounding flowing water was in contact with practically its entire length. Un-doped end caps were not used for these experiments, although they have been shown to be very effective for this type of laser configuration [8]. The benefit of a pump-guiding configuration is two-fold in the case of Ho:YAG; firstly, it allows the use of a very long rod lengths and thus a low doping concentration and, secondly, the absorbed power per unit length can be kept low, thus increasing the power handling limit. At the low doping level used in our experiments, ETU is effectively negligible, where it has been observed that above 1at% Ho:YAG the upconversion rate starts to have a significant impact on the laser performance [6], which is especially important when operating in the Q-switched regime at low-repetition-rates and high inversion densities.

The output of the two thulium slab lasers was collimated and spatially multiplexed before being coupled into the Ho:YAG rod as shown in Fig. 3. The spatially combined thulium pump beam was focused into the Ho:YAG rod using two lenses of focal lengths f=40m and f=50mm. This combination provided an x-axis pump spot size at the entrance face to the rod, small enough that the transmitted beam avoided hitting the contact surface area between the rod and the mount, where it might have damaged the seal.

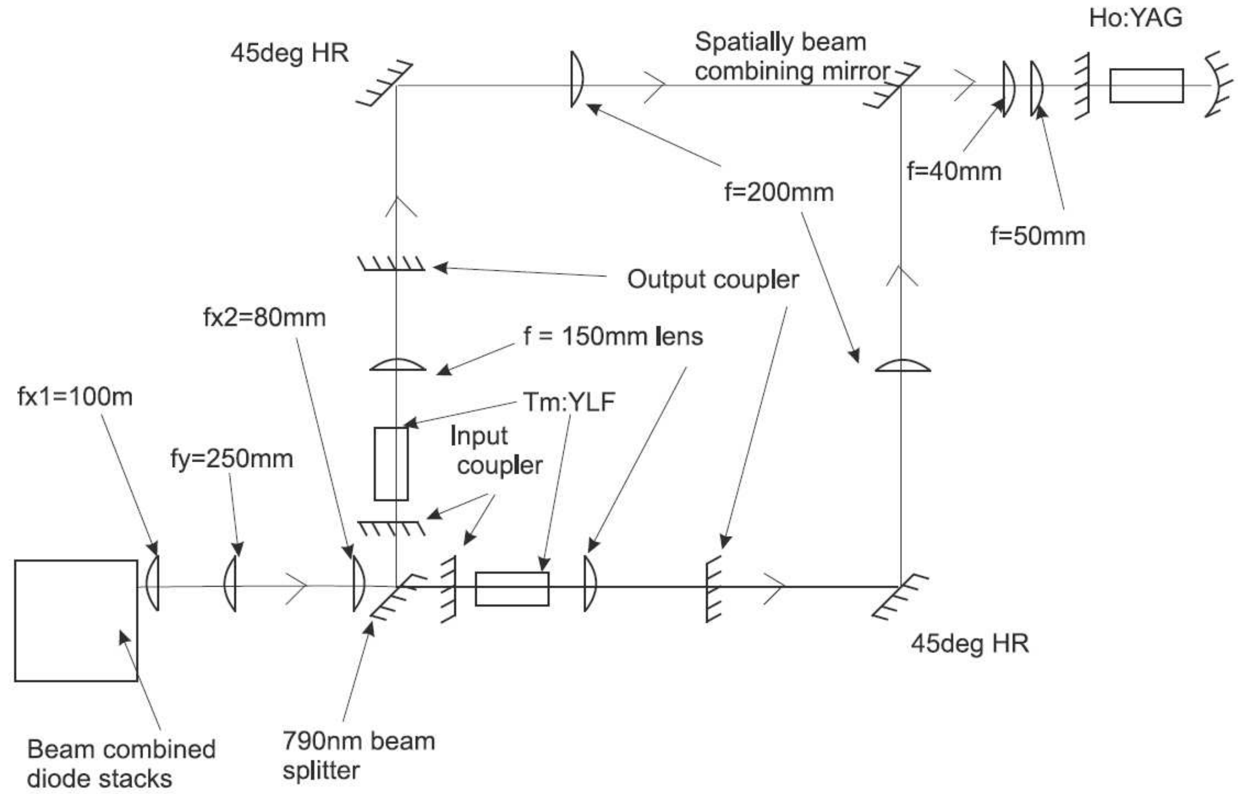


Fig. 3. Experiment layout for the diode-pumped Tm:YLF slab lasers, spatially multiplexed to end-pump a Ho:YAG rod laser, in the CW configuration. Note for the QS configuration two YAG Brewster plates and an RTP Pockels cell were inserted into the cavity between the output coupler and the Ho:YAG rod.

For CW mode of operation, we employed a simple plano-concave cavity with a 100mm cavity length. The plane input coupler had been coated for high-transmission at 1.9μm on both sides and high-reflectivity at 2.1μm, while the 100mm radius of curvature broadband output coupler had a reflectance of 89% at the holmium lasing wavelength. Although the output coupler was also reflective at the thulium laser wavelength, with >90%R, the reflected beam was much larger than the Ho:YAG rod, thus the thulium pump was not double-passed. Notwithstanding, at threshold, typically <20% of the incident thulium power exited the rear face of the rod.

For QS operation we employed the experimental layout shown in Fig. 3, however, the resonator was changed to allow for two uncoated YAG ~1mm thick Brewster plates, which provided polarization selection, between the Ho:YAG rod and the output coupler, along with a Rhubidium Titanyl Phosphate (RTP) Pockels cell. A longer cavity length was required in order to fit in the additional optics for the Q-switching configuration, in addition it was necessary to use a higher output coupling, with respect to the CW configuration, to prevent coating damage by to the high intensity Q-switched pulses. As such with the same plane input coupler and the cavity length extended to 220mm, the output coupler was changed to a 500mm radius of curvature concave mirror with 40% reflectivity at the lasing wavelength.

3. RESULTS

3.1 Tm:YLF pump laser results

The best thulium laser performance was obtained with the thinner of the two slabs; a 40% slope efficiency was measured with respect to the incident pump power, with a maximum output power of 47W for 183W of diode-pump and a threshold power of 53W. In contrast, the 2mm slab operated with only 25% slope efficiency, much lower than expected and attributed to poorer thermal contact between the slab and heat sinks, and higher cavity losses associated with minor damage to the end-face coatings sustained during previous experiments. The maximum output power was 29W for an incident pump power of 167W, with a threshold power of 49W. The slightly lower threshold with respect to the 1.5mm slab was due to a smaller pump size corresponding to an asymmetric splitting of the diode-pump beam. The thulium lasing wavelengths were at 1.91µm, with measured beam quality factors, in the plane and perpendicular to the plane of the slabs, found to be M^2 ~ 175 by 1.2 and M^2 ~ 187 by 1.3 for the 1.5mm and 2mm slabs, respectively. The resulting beam quality of the spatially-multiplexed outputs of the two lasers was M^2 ~ 193 x 11 with a pump beam-waist radius of 0.4 by 0.05mm at the input face of the holmium-doped rod. The total transmission of the optical train from the respective output couplers to Ho:YAG crystal was ~96%, initially giving a total incident thulium pump power of 73W for 350W of diode power. It should be noted that if two 1.5mm-thick Tm:YLF slabs had been available, then ~100W of thulium pump power would have been attainable.

3.2 HoYAG laser results

3.2.1 CW results

Fig. 4 shows the CW laser performance of the pump-guided Ho:YAG laser, which operated with a slope efficiency of 61% with respect to the incident thulium pump power with a threshold of 4.3W. A maximum holmium laser output-power of 38W was achieved for 73W of thulium power, with a lasing wavelength of 2090nm. The single-pass absorption was measured to be 83% at threshold pump power, indicating a 73% slope efficiency with respect to absorbed pump power. The measured output beam quality was M^2 ~ 18.3 by 3.3, without any means taken to try to improve it. A more symmetric beam was obtained by altering the y-axis launch conditions with an additional cylindrical lens, such that the incident beam filled the height of the rod more effectively. With such a configuration the beam quality in both axes was close to M^2 = 18, with a slightly higher threshold power of 5.7W and the same slope efficiency as shown in Fig. 4. Improved beam quality is expected for an optimized cavity configuration, providing larger cavity modes or by utilizing graded reflectivity mirrors with an unstable resonator.

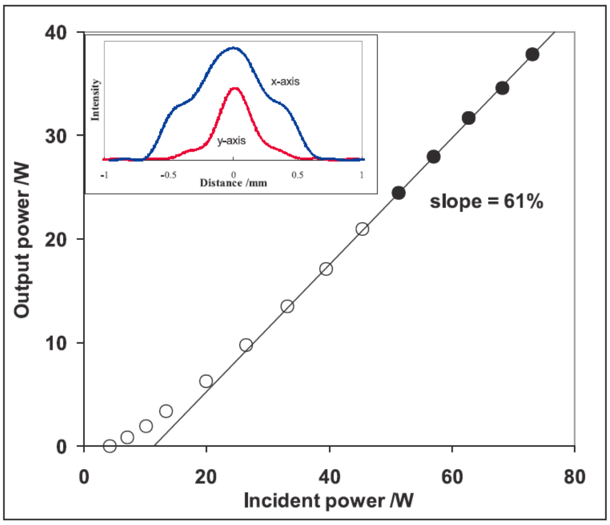


Fig. 4. Ho:YAG rod laser performance pumped by two spatially-multiplexed diode-pumped Tm:YLF slab lasers. Insert represents the mode profile in the laser rod.

3.2.2 Pulsed results

In the pulsed configuration, a larger aperture rod, 2.5mm diameter, was used to reduce the intra-cavity fluence at the optical coatings on the rod end faces. Therefore, the threshold power was expected to increase by ~2.8 times. A comparative measure with the same cavity used for the CW regime gave a threshold power of 14W, i.e. ~3.3 times the aforementioned, in reasonable agreement noting that a slightly different pump focusing set-up in the vertical axis.

The cavity described for the QS configuration characterized under CW operation gave a threshold power of 40W, with all the additional components in the cavity. The most significant loss elements were the Brewster plates, highlighting that stress-induced depolarization was present. Inserting a quarter-waveplate between the HR input coupler and the Ho:YAG rod did reduce the depolarization loss, as observed by an ~85% decrease in the power ejected from the cavity by the Brewster plates, however, there was only a marginal overall improvement in the efficiency and therefore the waveplate was not used during later pulsed operation experiments. The laser was observed to operate at two wavelengths with similar intensity that is 2090nm and 2097nm.

Performance of the QS laser is shown in Fig. 5 where the output pulse energy and pulse width were measured while operating at a repetition rate of 20Hz.. The pulse energy was calculated from the repetition rate and the measured average power, and it was confirmed that there was no CW lasing occurring between pulses. The pulse energy increases linearly with pump power, and reached a pulse-energy of 14mJ for a thulium pump power of 68W. This was the maximum pump power available at the time. The pulse-width started from ~50ns just above threshold decreasing for higher powers toward a limiting value of ~17ns. The effective threshold was 45W in good agreement with the threshold for CW operation, a slight increase is expected due to greater ground state bleaching at the higher pump intensity between pulses.

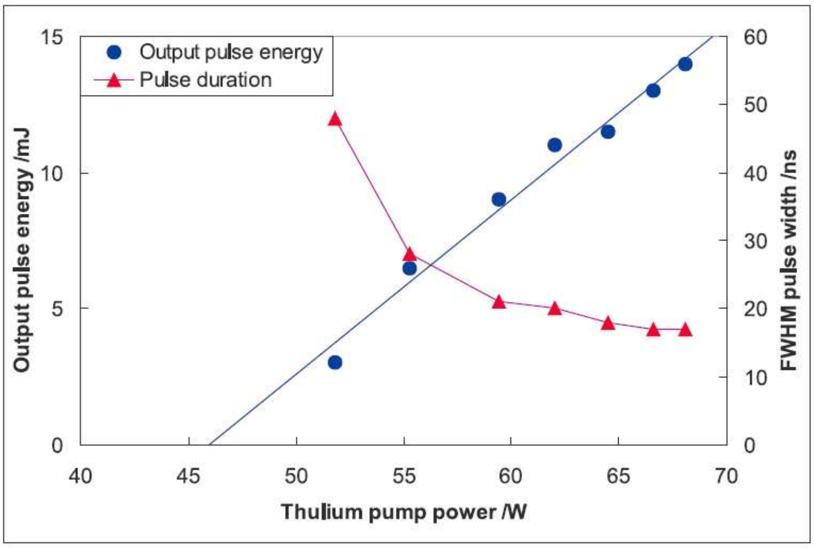


Fig. 5. Ho:YAG QS laser performance at a 20Hz repetition-rate.

The maximum pulse energy achievable at a thulium pump power of 68W as a function of the repetition rate is shown in Fig. 6. It can be seen that in terms of the energy storage capacity of the Holmium ions, the output energy is more or less constant until ~100Hz, which corresponds to a storage lifetime on the order of 10ms, in good agreement with the reported value of $\tau_f \sim 8.4$ms [9]. This supports the earlier assumption that for the low holmium-doping concentration in this crystal, ETU losses are negligible.

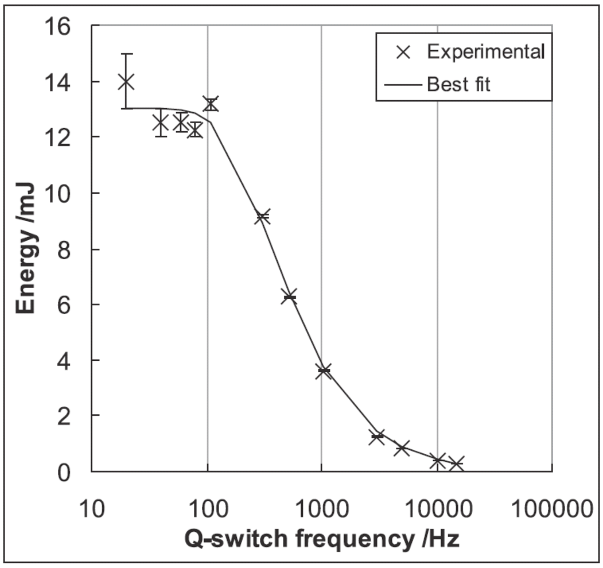


Fig. 6. Ho:YAG pulse energy as a function of repetition rate at the maximum available thulium-laser pump power of 68W.

3.3 Tm:YLF 100W laser

In order to scale the Tm:YLF output power safely into 100W regime, a higher aspect ratio pump distribution was required than could be obtained with our pump source and limited single slab dimensions. To increase the aspect ratio further we used two slabs, similar to that described above, although the 20mmx1.5mm faces were polished and coated as the end faces instead. With two slabs one after the other, as illustrated in the inset of Fig. 7, we were able to effectively make a gain element with an overall area cross section of 20mm x 1.5mm and 18mm in length. Using the same two diode-stack pump source described in section 2.2 and different pump conditioning optics, which produced a beam width of ~13mm full width in the gain block, the same cavity configuration produced an output power of 100W for ~400W of incident diode power, as shown in Fig. 7. The roll-over at the highest pump power is actually related to the diode stacks operating at two different wavelengths and straddling the now π-polarised Tm:YLF absorption peak at 792nm.

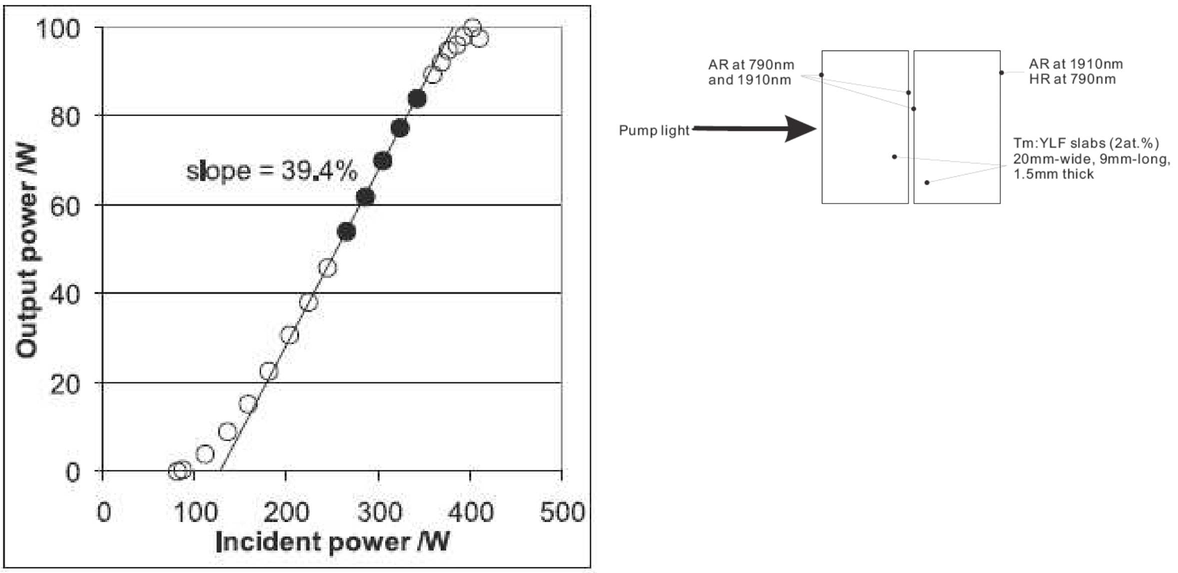


Fig. 7. Laser performance with the Tm:YLF dual slab gain block, illustrated in the inset.

4. DISCUSSION

A limiting factor for the power scaling of the Holmium laser in this experiment was the relatively poor performance of the 2mm thick Tm:YLF slab laser in comparison to that obtained with the thinner crystal. Notwithstanding, these initial results are extremely encouraging in terms of the potential for this configuration. The low saturation intensity of Ho:YAG at 1.9-microns enables in-band pumping with high efficiency, while also having a modest threshold intensity. As demonstrated at in the 1micron regime with the Yb:YAG guided-rod architecture, for a low quantum defect system this configuration can be scaled to the kilo-Watt regime[10]. Moreover, other laser architectures such as zig-zag slabs similar to those developed at Northrop Gruman[11] offer similar advantages, and are also well disposed to multiplexed thulium-slab pump lasers.

As shown in Section 3.3 the output power from a single Tm:YLF slab laser can reach the 100W level, albeit in a multi-mode configuration. Efficient extraction of this power in a near diffraction limited beam quality is conceivable with a multi-pass configuration as developed by Q-peak Ltd. [12] or with stable-unstable resonators utilised by EdgeWave Gmbh [13]. For the application described here, good beam quality in both axes is not necessary, due to the guiding structure of the holmium gain element. To achieve efficient spatial multiplexing however, it is beneficial to have good beam quality in at least one axis as demonstrated here. An end-pumped configuration has been reported here, which could easily be replaced with a side-pumped Tm:YLF slab, with even greater power scaling potential for the Tm:YLF oscillator units.

As shown an efficient Ho:YAG CW oscillator has been demonstrated, where the low holmium-doping concentration enabled a long rod length and hence distributed thermal load, with moderate thermal effects for which there are already solutions reported in the literature. The low concentration also alleviates ETU losses that generate more heat in the laser crystal and effectively reduce the energy storage capacity of the active ions. This latter characteristic is a prerequisite for the low-repetition rate QS regime where the output pulse energy is dependent upon a long storage lifetime of the Ho^{3+}. As evidenced by the fact that the output pulse energy from the CW pumped holmium laser remained relatively constant up to a Q-switch repetition rate of ~100Hz. In the experiment described here the laser was not operated in its optimum regime, i.e. at least three times laser threshold. Where the damage threshold for the intra-cavity coatings in this wavelength regime was found to be inferior with respect to that achievable for the 1micron regime. It is evident that better optical coatings are required if Joule level pulses are to be reached via this approach.

5. CONCLUSIONS

We have demonstrated CW and pulsed Ho:YAG lasers and a pump-guiding configuration excited by spatially multiplexed high-power diode-pumped Tm:YLF slab lasers. The simplicity of the thulium laser sources offsets the lack of beam quality in one direction and provides a suitable pump source for the holmium laser. A power scaling strategy has been utilized with the Tm:YLF slab design that has enabled 100W output powers from a single oscillator and gain block. In-band pumping of Ho:YAG is once again shown to be very efficient for the CW regime, and offers good advantages for QS systems as well. Further scaling of 2.1micron Ho:YAG lasers can be readily achieved by increasing the number of thulium pump sources multiplexed with the potential to scale into the kilo-Watt average power regime in this wavelength band.

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