Q-switched Ho:YLF Laser Pumped by a Tm:$GdVO_4$ Laser

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ABSTRACT
We have, through careful analysis of spectroscopic data, designed and demonstrated a diode-end-pumped, quasi-continuous wave Tm:$GdVO_4$ laser operating at 1892 nm in order to pump a *Q*-switched Ho:YLF laser. The Ho:YLF maximum output energy was 1.9 mJ in an 18 ns pulse, at a wavelength of 2050 nm.

Type 1: Oral or Poster

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INTRODUCTION

Orthovanadates are attractive host crystals for rare-earth doped diode-pumped solid-state lasers. This is also the case when doped with Tm^{3+} or Ho^{3+}, which have been shown to exhibit certain advantages over other host crystals for Mid-IR lasers.[1,2] In particular, it has been shown that $Tm:GdVO_4$ has strong and broad absorption features at the emission wavelength of commercially available high power laser diodes at ~800 nm.[1] In addition, the broad emission peak at 1.9 µm in $Tm:GdVO_4$ can be utilised for laser operation over a wide wavelength tuning range, including wavelengths which can be used to pump Ho^{3+} and Cr^{2+}:ZnSe lasers.[3] The highest laser output power was reported by Li *et al* who achieved a maximum continuous-wave output power of 2.8 W from a diode-end-pumped $Tm:GdVO_4$ laser.[4] In addition, with the use of an intra-cavity birefringence filter, they demonstrated a tuning range of 126 nm (1820 to 1946 nm). More recently, a comparative study of the tuning ranges of $Tm:YVO_4$, $Tm:LuVO_4$ and $Tm:GdVO_4$ was conducted by Šulc *et al*, both in continuous wave (CW) and quasi-continuous wave (QCW) mode.[5] Also, we have previously demonstrated a diode-end-pumped QCW $Tm:GdVO_4$ laser operating at 1818 nm or at 1915 nm by appropriate selection of the resonator output coupling value.[6] Thus, even though significant wavelength tuning has been demonstrated for $Tm:GdVO_4$, to our knowledge, there has been no report of a $Tm:GdVO_4$ laser pumping a Ho^{3+} laser. In this paper we report on the design and operation of a diode-end-pumped QCW $Tm:GdVO_4$ laser selected to lase at 1892 nm, which was used to pump a Q-switched Ho:YLF laser.

SPECTRAL ANALYSIS

To design a high-power diode-pumped $Tm:GdVO_4$ laser for pumping a Ho:YLF laser, detailed spectroscopic studies of the laser materials are required. The absorption cross section data (σ_{abs}) of Ho:YLF for the $^5I_8 - {}^5I_7$ transition is shown in Figure 1.[7] The absorption is highly polarised and it would be preferential to pump on either of the two absorption peaks of the π-polarisation ($\boldsymbol{E}||c$), located at 1892 nm (0.72 x 10^{-20} cm^2), and at 1940 nm (0.99 x 10^{-20} cm^2).[7] When pumped at either of these two wavelengths, the Ho:YLF laser can emit at 2.05 µm, (on π-polarisation) or at 2.06 µm when forced to lase on the weaker σ-polarisation ($\boldsymbol{E}\perp c$).

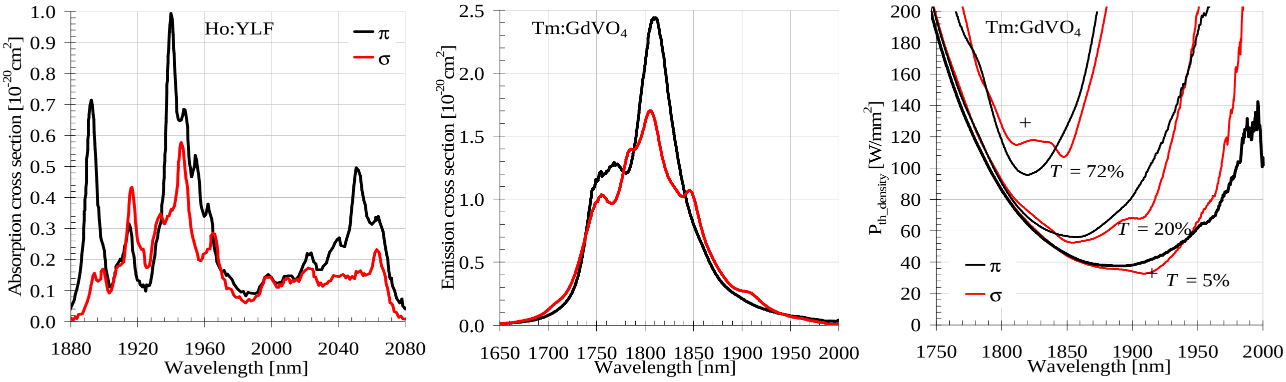

Figure 1: The absorption cross section of Ho:YLF; the emission cross section of $Tm:GdVO_4$, and the calculated threshold power density of the $Tm:GdVO_4$ laser with different transmission T output coupler mirrors.

We have previously measured the absorption cross section (σ_{abs}) of our $Tm:GdVO_4$ laser crystals at 1.9 µm to enable accurate predictions of the laser performance[8]. Based on the measurements, we calculated with the reciprocity method[9] the emission cross section (σ_{em}) of $Tm:GdVO_4$ for the $^3F_4 - {}^3H_6$ laser transition, also shown in Figure 1. From this graph it is evident that the $Tm:GdVO_4$ laser emission will be stronger at the 1892 nm pump wavelength of Ho:YLF, compared to the 1940 nm absorption line.

The wavelength of the quasi-three level $Tm:GdVO_4$ laser can be roughly selected by choosing the correct output coupling value. To determine the output coupler transmission to operate at 1892 nm, we calculated the expected threshold power and the operational wavelength of the Tm:$GdVO_4$ laser for different output coupling values *T*. The calculations were made using the expression,[10, 11]

$$P_{\mathrm{th\_density}}(\lambda) = \frac{P_{\mathrm{th}}}{\pi w^2} = \frac{h\nu_{\mathrm{p}}\left[L + T + 2Nl\sigma_{\mathrm{abs}}(\lambda)\right]}{2\tau\eta_{\mathrm{p-q}}\sigma_{\mathrm{em}}(\lambda)}$$

where *L* represents additional resonator losses, assumed to be 1%; $w_l \approx w_p \approx w$ is the laser mode and pump beam radius in the laser crystal, assumed to be equal for the end-pumped laser developed; *N* is the concentration of Tm^{3+} ions in the laser crystal (3% at. doping x 1.21×10^{22} cm^3);[12] ν_p is the frequency of the pump light; $\eta_{p\text{-}q}$ is the pump quantum efficiency, typically assumed to be 1.5 for diode-pumped Tm^{3+} lasers to incorporate the 2-for-1 pumping process; τ is the lifetime of the $^3F_4$ upper laser manifold, taken as 1.85 ms);[1] and *l* is the length of the laser crystal, which was 3 mm.

The result of the calculations for three output coupling values is shown in Figure 1. For a particular output coupling value *T*, continuous-wave laser oscillation will occur at the wavelength and polarisation for which the threshold power density is a minimum. This method of analysing a laser material for laser performance is complimentary to the "effective emission cross section" method used by other authors.[1,13] The calculation method we used provides a clear indication on what polarisation and output coupling loss to select in order to operate the Tm:$GdVO_4$ laser at 1892 nm. By selecting an output coupler transmission *T* = 5% (reflectivity 95%), and by inserting a Brewster plate inside the laser to force it to operate on π-polarisation, the Tm:$GdVO_4$ wavelength will be approximately at 1890 nm. To further fine-tune the output wavelength of the Tm:$GdVO_4$ laser onto the absorption peak of Ho:YLF at 1892 nm, we inserted an uncoated fused-silica etalon of thickness 100 µm in the Tm:$GdVO_4$ laser resonator.

EXPERIMENTAL SETUP

The 3% at. doped Tm:$GdVO_4$ crystal (2.5 x 2.5 x 3 mm^3) was end-pumped with two fibre-coupled laser diodes, as indicated in Figure 2. The laser diodes were operated in a quasi-continuous-wave (QCW) mode with the pump pulse on-time set to 20 ms at 5 Hz repetition rate (10% duty cycle). The duty cycle was limited, as well as the launched pump power (maximum 30 W from each diode), to avoid thermal fracture of the Tm:$GdVO_4$ crystal. The Tm:$GdVO_4$ resonator was based on a compact design, with a concave high-reflector (HR) end-mirror with r = 200 mm, which was also coated for high transmission (HT) at the pump wavelength (804 nm). The plane output coupler reflectivity was 95% at 1.9 µm (unspecified at 804 nm). The Tm:$GdVO_4$ resonator, containing a Brewster plate and a 100 µm etalon, had an optical length of approximately 73 mm.

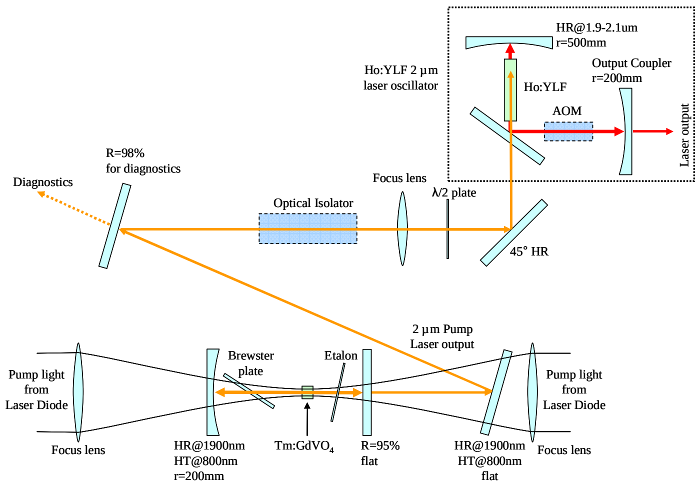

Figure 2: Experimental setup of the Tm:$GdVO_4$ pumped Ho:YLF laser.

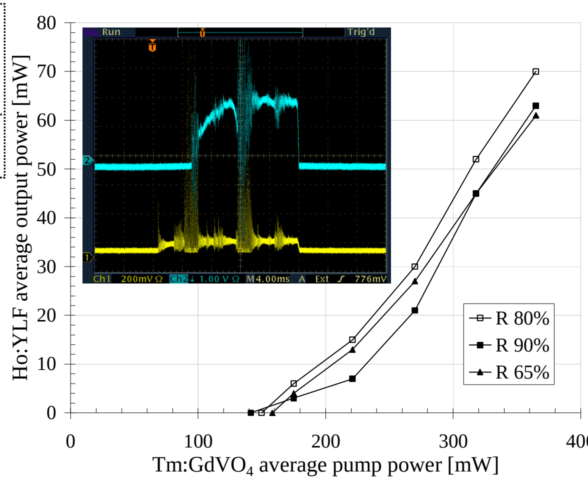

Figure 3: QCW output of the Ho:YLF laser.

The output beam of the Tm:$GdVO_4$ laser was transmitted through an optical isolator to protect the Tm:$GdVO_4$ laser from back reflections from the Ho:YLF resonator. A lens with focal length 350 mm was used to produce a spot size of 480 µm diameter inside the 40 mm long, 0.5% doped Ho:YLF crystal. The folded Ho:YLF resonator was formed between the 500 mm curved end-mirror and the 200 mm curved output coupler mirror. The fold mirror had a 25-30% loss for the p-polarisation and a high reflection for the s-polarisation at the Ho:YLF laser wavelengths, and a high transmission for the pump light at 1892 nm. Due to this fold mirror, the Ho:YLF laser could be operated on either π-polarisation (2.05 µm) or σ-polarisation (2.06 µm) by the appropriate orientation of the Ho:YLF crystal axis. The pump polarisation was controlled with the λ/2 plate at 1892 nm to ensure that the Ho:YLF crystal was pumped on the π-polarisation. The laser back mirror also reflected the pump beam to realise a double-pass pump scheme. The etalon inside the Tm:$GdVO_4$ cavity was adjusted during lasing conditions to set its wavelength to the maximum absorption in Ho:YLF. An acoustic-optical modulator (AOM) was used as *Q*-switch for the Ho:YLF laser, which was synchronised to the QCW output pulse of the Tm:$GdVO_4$ laser.

RESULTS

Three Ho:YLF output coupler mirrors with reflectivity R80%, R90% and R65% at 2 µm were used during the initial QCW experiments, the result of which is shown in Figure 3. Also shown in Figure 3 is the measured QCW pump pulse at 1892 nm (Channel 1), and the free-running Ho:YLF laser pulse (Channel 2) that followed the pump pulse after a delay of approximately 5 ms. The severe spiking behaviour of the Tm:$GdVO_4$ pulse was attributed to instabilities caused by strong atmospheric water absorption at 1892 nm. The maximum average pump power from the Tm:$GdVO_4$ laser incident on the Ho:YLF resonator was 365 mW, or 3.65 W peak power during the on-time of the 20 ms QCW pulse. With the R80% output coupler, the Ho:YLF laser produced a maximum of 70 mW average power, with pulse duration of approximately 15 ms. The Ho:YLF crystal was orientated to lase on σ-polarisation, the measured centre wavelength of which was 2064 nm. Next, the AOM was inserted in the cavity to *Q*-switch the Ho:YLF laser. The output coupler reflectivity was R65%, and the Ho:YLF crystal axis was orientated to lase on the stronger π-polarisation. The laser threshold was slightly higher with the AOM inserted, at 200 mW of average pump power. The maximum output energy of 1.9 mJ in an 18 ns pulse, as shown in Figure 4, was achieved with only 270 mW of average pump power. Increasing the pump power beyond this point resulted in the *Q*-switched Ho:YLF laser to have unstable output and pre-lasing, since the AOM could not hold-off lasing with such high gain inside the resonator. The wavelength output of the *Q*-switched Ho:YLF laser was centred at 2050 nm.

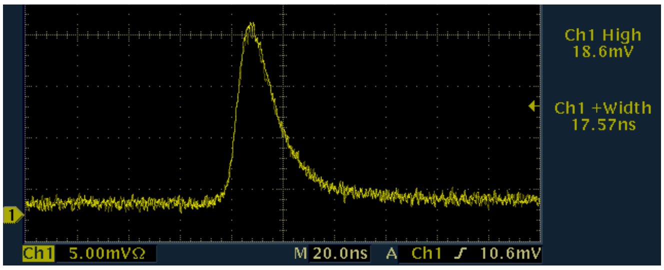

Figure 4: The 1.9 mJ output pulse of the *Q*-switched Ho:YLF laser pumped by the Tm:$GdVO_4$ laser.

CONCLUSION

We have shown that the Tm:$GdVO_4$ laser wavelength can be operated at an absorption peak of Ho:YLF through careful analysis of the spectroscopic data of these laser materials. A diode-end-pumped QCW Tm:$GdVO_4$ laser operating at 1892 nm was demonstrated by implementing an output coupler transmission of 5%, and by inserting a Brewster plate and a 100 µm etalon. This laser was used to pump a Ho:YLF laser with a resonator design that enabled double-pass pumping and polarisation selection of the Ho:YLF laser output. Both the free-running and *Q*-switched performances of the Ho:YLF laser were evaluated, the best result of which was an energy of 1.9 mJ in an 18 ns pulse, at a wavelength output of 2050 nm. This is the first time to our knowledge that a Tm:$GdVO_4$ laser has been used to pump a Ho^{3+} laser.

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