Experimental Investigation of Double-End Pumped Tm, Ho: GdVO$_4$ Laser at Cryogenic Temperature

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Abstract: We describe comparatively cryogenically cooled Tm, Ho: GdVO$_4$ lasers with an emission wavelength of 2.05 µm under continuous wave and pulse operating mode. By varying the transmittance of output couplers to be 0.40 for a continuous wave laser, the maximum output power of 7.4 W was generated with a slope efficiency of 43.3% when the absorbed pump power was increased to 18.7 W. For passively Q-switched lasers, the output characteristics were researched through altering pump mode radius. When the pump mode radius focused into the Tm, Ho: GdVO$_4$ center equaled near 600 µm, the peak power was increased to be the maximum value of 9.9 kW at the absorbed pump power of 11.8 W. The pulse energy of 0.39 mJ was achieved at the same absorbed pump power with repetition of 5.7 kHz.

Keywords: solid-state; diode-pumped; Q-switched; infrared and far-infrared lasers

1. Introduction

Solid-state pulse lasers at a ~2 µm wavelength band from Tm: $^3$F$_4$→$^3$H$_6$ and Ho: $^5$I$_7$→$^5$F$_{17}$ energy levels are attractive due to the extensive application of laser lidar systems to achieve environmental detection and for medical instruments to conduct surgical treatment [1,2]. In addition, the pulse lasers at ~2 µm can also be utilized as pump sources of OPOs to obtain the mid-IR laser [3–5]. Tm/Ho ions doped into different hosts can generate laser emitting at ~2 µm. The vanadate crystal hosts possess large phonon coupling energy, low crystal symmetry, and great thermal conductivity [6]. Especially compared with the YVO$_4$ crystal, the GdVO$_4$ crystal exhibits higher thermal conductivity and lower thermal expansion coefficient that is beneficial for weakening thermal effects [7]. Rare earth ions such as Tm$^{3+}$ and Ho$^{3+}$ doped into vanadate hosts exhibit a broadly spectral band at a pump wavelength of ~800 nm and great absorption/emission cross sections [8] which facilitate the laser crystal to efficiently absorb pump light, thus improving laser performances. Tm-doped vanadate laser [9] pumped by laser diodes with ~800 nm wavelength, Ho-doped vanadate laser [10] in-band pumped by Tm-lasers or laser diodes, and Tm, Ho-codoped vanadate lasers [11,12] pumped by laser diodes have been extensively investigated under continuous wave or pulse operating modes. Tm, Ho-codoped lasers with sensitization ions Tm$^{3+}$ and activation ions Ho$^{3+}$ can be pumped by laser diodes with ~800 nm wavelengths and simultaneously exhibit excellent Q-switching performance due to the strong stored energy capability of Ho$^{3+}$ ions. Besides, the performances of Tm, Ho-codoped vanadate lasers depend strongly on the temperature of active media. At cryogenic temperature, Tm, Ho-codoped lasers operate under the quasi-four level system which is beneficial to reduce upconversion losses ($^5$I$_7$, $^3$F$_4$→$^5$H$_5$, $^3$H$_6$) of the Tm, Ho-codoped crystals.
Furthermore, the positive energy transfer process between Tm$^{3+}$(3F4) and Ho$^{3+}$(5I7) was significantly strengthened which obviously increases the population proportion reserved in 5I7 energy level.

Passively Q-switched lasers with saturable absorbers usually exhibit some advantages of compact, simple geometry, and low cost. The Cr-doped ZnS crystal is one of the typical SAs with a large optical damage threshold [13] that enables it to undertake strong oscillating laser intensity. The Cr:ZnS crystal also has great absorption/emission cross-sections at ~2 μm [14] which facilitate to get excellent Q-switching performances for the Tm$^{3+}$/Ho$^{3+}$ doped lasers with an emitting wavelength of ~2 μm [15–17]. Based on Cr$^{2+}$:ZnS SA, Tm, Ho-codoped laser with different hosts such as LLF [18], YLF [19], and KLu (WO4)$_2$ [20] have been presented. At cryogenic temperature, we also had demonstrated PQS Tm, Ho-codoped vanadate lasers with Cr:ZnS SA [21,22]. The highest peak power of ~9.1 kW was achieved with the pulse duration of 32.7 ns [23]. In this paper, to improve the peak power, the comparative research for the PQS lasers with different pump mode radius was experimentally conducted.

2. Experimental Setup

The laser (shown in Figure 1) was designed to be a U-shape resonator that makes it possible to pump a laser crystal from each end of the crystal. The pump beams from two fiber-coupled (400 μm diameter, 0.22 numerical aperture) LDs emitting at ~800 nm were collimated and focused by plano-convex lens (F1, F2) into the active crystal from each end of it. The focused beam radius was 400 μm or 600 μm depending to the focus length of the output mirror (M2). The output mirror (M2) was a plane mirror with different transmittance ($T_{\text{oc}}$) of 0.20, 0.25, and 0.40 at ~2 μm. The mirror (M1) with the 2000 mm curvature was coated in anti-reflective film at ~800 nm and coated in high-reflective film at ~2 μm. The dichroic mirrors (M3, M4) placing at 45° relatively to the oscillating light path were anti-reflective at ~800 nm and high-reflective at ~2 μm. The distances between M2 and M4, M4 and M3, and M3 and M1 were 35 mm, 60 mm, and 45 mm, respectively. The total cavity length is at 140 mm. To improve the absorbed pump power without crystal fracture, an 8 mm long Tm, Ho: GdVO$_4$ crystal (a-cut) with a 4 × 4 mm$^2$ cross section was chosen as the gain medium with 4at.% Tm$^{3+}$ and 0.4at.% Ho$^{3+}$ concentration. The Tm, Ho: GdVO$_4$ was wrapped in indium foil and held in copper heat-sinks connected with a small dewar. During the operating of the laser, the dewar was full of liquid-N2 to effectively remove the heat generated in the crystal for high power operation. The M5 and M6 in Figure 1 denoted the plane windows with anti-reflective film at ~800 nm and ~2 μm. The distance between M5 and M6 is 22 mm. Under the pump laser beam radius of 400 μm or 600 μm, the actual measured absorption efficiency of the Tm, Ho: GdVO$_4$ crystal was over 90%. A Cr:ZnS SA (2 mm thickness, 9 × 9 mm$^2$ cross section) with the unsaturated transmission of ~82% was used as Q-switch crystal placed in a brass heat-sink filled with flowing water. It was inserted between the dichroic mirror M3 and the end mirror M1 with 15 mm distance from the mirror M1.

![Figure 1. Sketch of experimental setup.](image-url)
3. Experimental Results and Discussion

At first, focusing the pump laser beam into Tm, Ho: GdVO₄ crystal with a near 400 µm mode radius, we conducted experimental research on Tm, Ho: GdVO₄ lasers. Through changing output couplers with different transmittance, the CW and PQS lasers were characterized. To avoid the fracture of gain crystal, the total absorbed pump power did not exceed 18.7 W. The output powers for the CW and PQS lasers were shown in Figure 2 with fitted lines. When the transmittance of OC equals 0.40, the maximum output power for CW and PQS operating mode were achieved to be 7.4 W ($\eta = 43.3\%$) and 5.4 W ($\eta = 32.8\%$), $\eta$ denoted the slope efficiency.

Since the high transmittance of OC caused the large resonator loss, the oscillating laser intensity in the resonator was too weak to enable the SA bleached to generate stable Q-switching phenomenon at low pump power. The stable Q-switching for the laser with 0.40 transmittance OC was not achieved until the absorbed pump power was up to 10.7 W. In comparison with this case, the PQS laser with OC transmittance of 0.20 can only generate stable Q-switched pulse trains at the absorbed pump power of less than 10.1 W. The PQS laser with transmittance of 0.25 can achieve a stable pulse operating within the entire range of absorbed pump power (3.5–18.7 W). Furthermore, the laser generated moderate CW output power of 6.2 W ($\eta = 35.6\%$) and average output power of 4.5 W ($\eta = 26.5\%$) at the absorbed pump power of 18.7 W.

The minimum pulse duration of ~36 ns was achieved for the PQS lasers with a transmittance of 0.20 and 0.25 when the absorbed pump power was increased to the respective maximum value of 10.1 W and 18.7 W, as shown in Figure 3a. The PQS lasers with transmittance of 0.25 and 0.40 generated approximate pulse energy, 0.26 mJ and 0.28 mJ, when the absorbed pump power was increased to 18.7 W, as shown in Figure 3b. The roughly equivalent repetition rates (shown in Figure 4a) were almost increased linearly with the increase of pump power. In comparison, the peak power of ~7.3 kW was achieved for the PQS laser with transmittance of 0.25 at 18.7 W absorbed pump power (shown in Figure 4b), larger than that of other two cavities. Compared with reference [23] with an approximate geometry, the pulse performance was slightly inferior due to the oscillating mode in the resonator.

![Figure 2. Output power of CW and PQS lasers vs. absorbed pump power.](image-url)
The energy and duration of PQS lasers, and then peak power, are relative to some parameters determined by the geometry of resonator and the pump laser intensity. To improve the pulse peak power, we increase the pump laser-mode radius focused into the gain crystal to ~600 µm by replacing the focus lens F1 with the other lens with a focus length of 75 mm for the laser with the 0.25 transmittance of OC. These experimental results were shown in Figure 5, Figure 6. For comparison, the results from the laser with ~400 µm pump mode radius were simultaneously plotted in the figures. The output power and slope efficiency declined slightly due to the slight mode-mismatch between laser-mode and pump-mode (shown in Figure 5).
In addition, the maximum absorbed pump power that can exhibit stable Q-switching phenomenon did not exceed 11.8 W which may attribute to the changing of the oscillating laser-mode in the cavity due to thermal effect of laser crystal. The pulse properties of the PQS laser were shown in Figure 6. It is obvious from Figure 6a that the pulse duration is narrower than that of the laser with 400 μm pump mode radium within the total range of absorbed pump power (3.6–11.8 W). The pulse repetition was significantly low varying
from 0.8 kHz to 5.7 kHz with the increase of pump power (shown in Figure 6b). The narrowest pulse duration of 39 ns was obtained at the absorbed pump power of 11.8 W with the repetition rate of 5.7 kHz. The maximum energy of 0.39 mJ was achieved at absorbed pump power of 11.8 W (shown in Figure 6c). The maximum peak power is up to 9.9 kW (shown in Figure 6d), evidently greater than that of the laser with 400 µm pump mode radius. At the maximum absorbed pump power of 11.8 W, the single pulse trace were recorded through scattering the laser into a fast PIN photodiode connected to a Lecroy digital oscilloscope (600 MHz bandwidth), as shown in Figure 7. We also measured the emission wavelength of the CW and Q-switched lasers with various output couplers. The output laser wavelength kept in about 2.05 µm.

![Single pulse trace](image)

**Figure 7.** Single pulse trace at the maximum absorbed pump power of 11.8 W.

### 4. Conclusions

In brief, we have researched the properties of the diode-pumped PQS Tm, Ho: GdVO₄ lasers with U-shaped resonator geometry at cryogenic temperature. With the pump mode-radius of near 400 µm and OC transmittance of 0.25, the PQS laser exhibited stable Q-switching performance within the greatest range of absorbed pump power (3.5–18.7 W), though output power was less than that of the laser with OC transmittance of 0.40. At the 18.7 W absorbed pump power, the PQS laser generated the maximum peak power of ~7.3 kW with the pulse duration of ~36 ns. Increasing the pump mode-radius to ~600 µm, the repetition rate was obviously low, changing from 0.8 kHz to 5.7 kHz, in comparison with the laser with transmittance of 0.25 and 400 µm pump mode-radius, though the stable Q-switching can only be realized within the range of 3.6 W–11.8 W. The largest pulse peak power of 9.9 kW was achieved with the maximum energy of 0.39 mJ at absorbed pump power of 11.8 W. The future work will focus on narrowing the pulse duration and enhancing the pulse peak power through optimizing the resonator geometry.

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