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Passively Q-Switched Operation of a Tm,Ho:$LuVO_4$ Laser with a Graphene Saturable Absorber

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Abstract: A passively Q-switched (PQS) operation of Tm,Ho:$LuVO_4$ laser is experimentally demonstrated with a graphene saturable absorber (SA) mirror. An average output power of 1034 mW at 54.5 kHz is acquired with an 8% optical–optical conversion efficiency. The energy per pulse of 40.4 μJ and a peak power of 56.07 W are achieved; the narrowest pulse width of 300 ns is acquired, and the output wavelengths of Tm,Ho:$LuVO_4$ are 2075.02 nm in a continuous wave (CW) regime and 2057.03 nm in a PQS regime.

Keywords: Tm,Ho:$LuVO_4$ laser; PQS; graphene saturable absorber

1. Introduction

Solid-state lasers emitting at 2 μm with ultra-short pulses are used in many fields, such as remote sensing, medicine, and gas detection, as well as frequency conversion of mid-IR wavelengths, due to their high peak power and pulse energy [1–4]. A passively Q-switched (PQS) with a saturable absorber (SA) is a compact way, in which microsecond (μs) pulsed Q-switching operation in the mid-Mid-infrared wavelength range can be achieved. Recently, many SAs, such as carbon nanotubes, two-dimensional (2D) materials and ion-doped crystals, with broadband saturable absorption at 1–3 μm, have been used for passive Q-switching operations [5–8]. The carbon nanotubes are typically a one-dimensional (1D) SA material, which has been widely applied in fiber lasers emitting at wavelengths of 1–2 μm [5,9], but its performance is poor when used in solid-state lasers emitting at 2 μm, because its bandwidth is limited by the diameter of single-walled carbon nanotubes, and its broadband saturable absorption characteristics rely on mixing single-walled carbon nanotubes with different diameters [9]. 2D materials are low-cost materials offering excellent performance and are used as the SA for PQS and mode-locked mode operations, due to their ultrafast recovery time, moderate modulation depth, high nonlinear effects and broadband saturable absorption [10,11]. Compared with the 1D and 2D SAs, ion-doped crystals, such as the Cr:ZnS crystal, have inherent defects which affect the stability, electronic structures and optical properties of ion-doped crystals [8,12].

Among the 2D materials, graphene is a 2D sheet of sp2-bonded carbon atoms with a honeycomb lattice [13]: this has attracted attention from workers in many disciplines, especially as it has special capabilities with regard to nonlinear saturable absorption. Graphene has very good thermal conductivity and optical properties, due to its zero-bandgap structure, and pure non-defective single-layer graphene with a thermal conductivity of up to 5300 W/m·K and its optical absorption is decided, independent of optical frequencies and optical conductivity constants [14]. Therefore, graphene is used as an SA in fiber and solid-state laser devices at a 1–2 μm wavelength range to achieve stable PQS and mode-locked laser emissions, owning to its ultrafast recovery time and moderate modulation depths [14–18]. Loiko et al. have demonstrated that a PQS mode of Ytterbium lasers with a graphene SA possessing a 1.9-μJ pulse energy and a 190-ns pulse duration were achieved from Yb-doped calcium niobium gallium garnet disordered garnet crystal [15]. Li et al. demonstrated a PQS mode operation of Nd:LiF_4 laser with an SA of graphene in 2016. The output wavelengths of 1.31 and 1.32 μm and an average output power of 1.33 W were acquired with the largest pulse energy of 17.3 μJ [16]. Serres et al. demonstrated a Tm:$KLu(WO_4)_2$ laser with an SA in 2015, and a 310-mW average output power was achieved [17]. Duan et al. demonstrated a PQS mode Ho:YVO_4 laser at 2052.1 nm with a graphene SA in 2016, and a 265.2-ns pulse width at 131.6 kHz was acquired [14]. Zhang et al. demonstrated a fiber laser operating at 1.94 μm with a graphene SA in 2012, and a 3.6-ps pulse width and a 0.4-nJ energy at 6.46 MHz were obtained in a thulium-doped fiber laser [18].

Vanadate crystals are of particular interest as a potential laser host material, because they are suitable for rare-earth ions doped or co-doped lasers, such as Nd:$GdVO_4$, Nd:$GdVO_4$, Tm,Ho:YVO_4, Tm,Ho:$GdVO_4$, Ho:LVO_4 and Tm,Ho:$LuVO_4$ [8,19–25]. Nd:$GdVO_4$ and Nd:YVO_4 lasers have been demonstrated at 1 μm wavelength range [26,27]. Tm,Ho:YVO_4 and Tm,Ho:$GdVO_4$ have been used as the laser crystal in continuous wave (CW), PQS, and acousto-optically (AO) Q-switched mode operation, and PQS Tm,Ho:YVO_4 and Tm,Ho:$GdVO_4$ laser were demonstrated with an SA of a 2 mm-thick Cr:ZnS crystal with a pulse width of less than 100 ns and a pulse energy over 100 μJ [8,28]. However, 2D materials were rarely used as an SA for Tm^{3+} and Ho^{3+} co-doped vanadate crystals in PQS laser operations. Compared with other vanadate crystals, the $LuVO_4$ crystal has larger absorption and emission cross-sections in the vicinity of 800 nm and 1.064 μm, respectively [29]. In addition, various Ho:$LuVO_4$ lasers (e.g., CW, Q-switched, actively mode-locked and single-longitudinal mode Ho:$LuVO_4$ laser) have been demonstrated [14,21–24], which show that the $LuVO_4$ crystal is an attractive host material at 2 μm wavelength range. We demonstrated an AO Q-switched Tm,Ho:$LuVO_4$ laser in 2018. An average output power of 3.77 W was achieved at a pulse repetition frequency of 10 kHz with an incident pump power of 14.7 W, and a pulse energy of 2.54 mJ was obtained at 1 kHz with a pulse duration of 69.9 ns [25]. However, the Tm,Ho:$LuVO_4$ crystal is a new laser crystal at 2 μm wavelength range, and its use therein has rarely been reported, and in particular, it has never been reported in use in PQS-mode operation.

In this paper, We demonstrated a PQS-mode operation of Tm,Ho:$LuVO_4$ laser with a graphene SA at 77 K. A Tm,Ho:$LuVO_4$ crystal was dual end-faces pumped by a laser diode (LD) with a center wavelength of 798.6 nm and the output power of 13 W. A pulse energy of 40.4 μJ and an average output power of 1034 mW were acquired at 2057.03 nm, and the narrowest pulse width was 300 ns.

2. Experimental Setup

The experimental setup for the PQS mode operation of a Tm,Ho:$LuVO_4$ laser is shown in Figure 1. A $^5I_7 \rightarrow ^5I_8$ laser transition of Ho^{3+} in a Tm,Ho:$LuVO_4$ crystal was used to achieve a laser emission with a 2 μm wavelength range. A Tm,Ho:$LuVO_4$ crystal was used in a resonator cavity with a 150-mm physical cavity length, and the physical length from a dichroic mirror (M5) to a 300-mm concave radius mirror (M6) was 60 mm. An LD (nLight Corp., Vancouver, WA, USA, NL-PPS50-10027) with a center output wavelength of 798.6 nm, corresponding to the output power of 13 W, was used as the pump source for the Tm,Ho:$LuVO_4$ laser. The temperature of the LD was selected at 298.15 K in the experiment, and the output power of LD was coupled to a fiber (a core diameter was 400 µm and numerical aperture (NA) was 0.22). Tm,Ho:$LuVO_4$ with the mass percentages of 5% and 0.5% for Tm and Ho was cut along *a*-axis, of which the dimension was 4 mm×4 mm×8 mm. The end-faces of the laser crystal were coated at pump wavelengths from 790 to 810 nm and its laser wavelength range from 1.9 to 2.2 µm with a transmission efficiency over 99.5% was used. The laser crystal was cooled at 77 K. In addition, the laser crystal was located in the middle of M5 and M6.

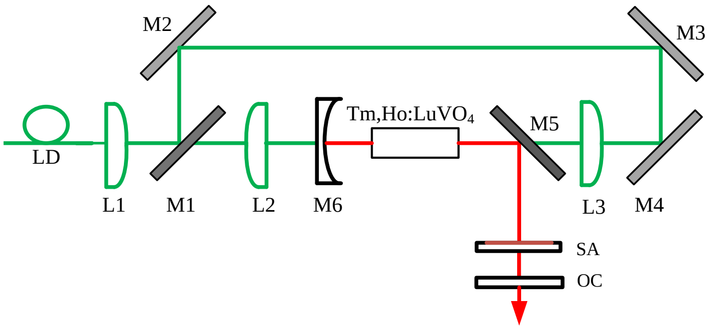

Figure 1. Experimental setup of the passively Q-switched Tm,Ho:$LuVO_4$ laser.

A configuration with double-end pumping was chosen to relieve the thermal loading of the laser crystal. The pumped laser from the LD was divided into two beams after being collimated by a collimation lens (L1) and a split light mirror (M1). Then, One of the divided pumped laser was refocused on one end-face of the laser crystal by a focusing lens (L2), and the other pumped laser was reflected by the mirrors (M2, M3 and M4) and refocused on one end-face of the laser crystal by a focusing lens (L3). The focal lengths of L1, L2 and L3 were 25, 50 and 50 mm, respectively, and the pump spots with 800 µm in diameter were placed at the input surfaces of the laser crystal. A flat 45° mirror was used as a splitting light mirror (M1), which was coated at 790–810 nm with a 50%-transmission-efficiency and 50%-reflection-efficiency material on one face and another high-transmission material ($T > 99.0\%$) on the other face. Three flat 45° mirrors were used as reflection mirrors (M2, M3 and M4), which were coated at 790–810 nm with a high-reflectivity ($R > 99.5$) material on one face. A dichroic mirror (M5) was a plano mirror placed at 45° with respect to the incident light, and it was coated with a high-transmission material working at 798.6 nm on two faces and another high-reflection material working at 2000–2100 nm on one face. A concave mirror with a radius of 300 mm (M6) was coated with a high-transmission material working at 798.6 nm on two faces, and was coated at a high-reflectivity material working at 2000–2100 nm on its concave face. A plane mirror coated with a 2% or 5% transmittance at 2000–2100 nm was used as an output coupler (OC) mirror of the laser. The mirror made from a CaF_2 crystal was used as the substrate of the SA, and a graphene crystal was chosen as the material for the SA. The graphene material dissolved in ethyl alcohol was coated onto the surface of one face at the CaF_2 mirror with a spin coating machine (KW-4A, Chinese Academy of Sciences, Beijing, China).

3. Experimental Results and Discussion

Two kinds of OC mirrors (with transmittances of 2% and 5%) were chosen in CW and PQS mode operation of an *a*-cut Tm,Ho:$LuVO_4$ laser to achieved optimal output performances. In CW and PQS mode operations, the output power and the average output power of the laser are shown in Figure 2. Under the CW mode operation, output powers of 2310 and 2398 mW were achieved with 2% and 5% transmittances of the OC mirror, and optical–optical conversion efficiencies were 17.8% and 18.5%, respectively. In the PQS mode operation, a graphene SA mirror placed between M5 and OC mirror was located near the OC mirror. The transmittance of a few-layer graphene material at

2075.72 nm was measured and found to have been approximately 88.6%, and the modulation depths were 69.0% (*T* = 2%) and 58.3% (*T*= 5%). The laser spot radii on the surface of M6, left end face of laser crystal, right end face of laser crystal, M5, graphene SA and the OC mirror were calculated to be approximately 445, 416, 395, 367, 310 and 310 μm, respectively, by the ABCD matrix without considering the thermal lens effect. The average output powers of 604 and 1034 mW were achieved with 2% and 5% transmittances of the OC mirror, respectively, corresponding to optical–optical conversion efficiencies of 6.0% and 8.0%. In the PQS mode operation of Tm,Ho:$LuVO_4$ laser, the pump threshold power was approximately 5 W with a 2% or 5% transmittance of the OC mirror. The laser was operated under a stable condition, and the pump power of 10.03 W or 13 W was injected into the laser cavity with a 2% or 5% transmittance of the OC mirror to avoid the damage of the graphene SA. Compared with the high transmittance of the OC mirror, a low transmittance of OC was chosen to acquire a stable PQS mode operation, due to more energy being stored in the crystal, but the damage threshold of the SA was easily reached, and the graphene SA was damaged at a peak power density of approximately 0.019 MW/cm^2 at 2057.03 nm with a 2% transmittance of the OC mirror in the experiment.

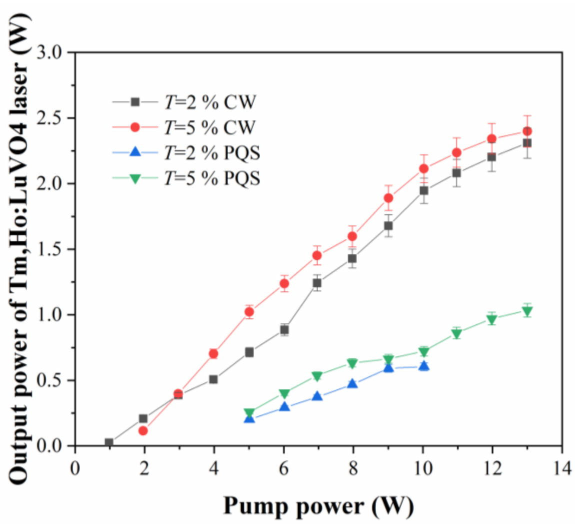

Figure 2. Output power of Tm,Ho:$LuVO_4$ laser in CW and PQS mode operations verse the pump power.

Under the PQS mode operation, the pulse repetition frequency (PRF) of the Tm,Ho:$LuVO_4$ laser is shown in Figure 3. As can be seen, the PRF increased with increasing pump power, and the highest PRFs were 35.92 kHz (*T* = 2%) and 54.5 kHz (*T* = 5%), respectively, corresponding to energies per pulse of 16.82 and 18.97 μJ. In addition, the maximum pulse energy of 40.4 μJ was achieved with a PRF of 24.01 kHz (*T* = 5%) and an average output power of 970 mW (*T* = 5%), corresponding a pulse width of 1.429 μs. The pulse widths of Tm,Ho:$LuVO_4$ laser are shown in Figure 4, and the narrowest pulse width of 300 ns was acquired under a 2% transmittance of the OC mirror. The pulse widths were 2.521 and 8.250 μs with the pump powers of 6.96 and 5.01 W, respectively for a 5% transmittance of the OC mirror. With a detector (Thorlabs, Newton, NJ, USA, PDA10PT-EC) and an oscilloscope with a bandwidth of 1 GHz (Tektronix, Beaverton, OR, USA, DPO4104), the typical Q-switched pulse trains were recorded in 40 and 200 μs time scales (Figure 5). Therefore, the highest pulse energy and the peak power of the Tm,Ho:$LuVO_4$ laser were calculated to be 40.4 μJ and 56.07 W based on the findings in Figure 2.

A 721A IR laser wavelength meter with a measuring range of 1300–5000 nm (Bristol Instruments Inc., Victor, NY, USA) was used to obtain an output wavelength of Tm,Ho:$LuVO_4$ laser in CW and PQS modes operations (Figure 6). An output wavelength of 2075.72 nm was achieved in the CW mode operation, and 2057.03 nm was achieved in the PQS mode operation.

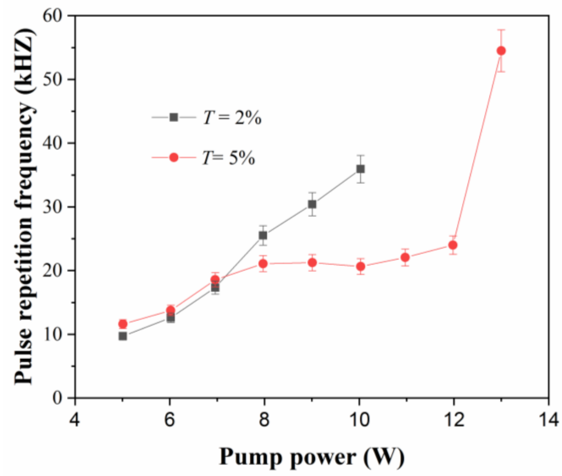

Figure 3. PRF of the PQS Tm,Ho:$LuVO_4$ laser verse the pump power.

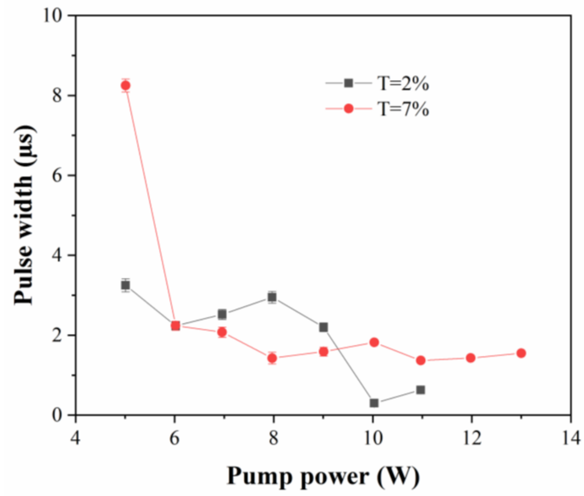

Figure 4. Pulse widths of Tm,Ho:$LuVO_4$ laser verse the pump power.

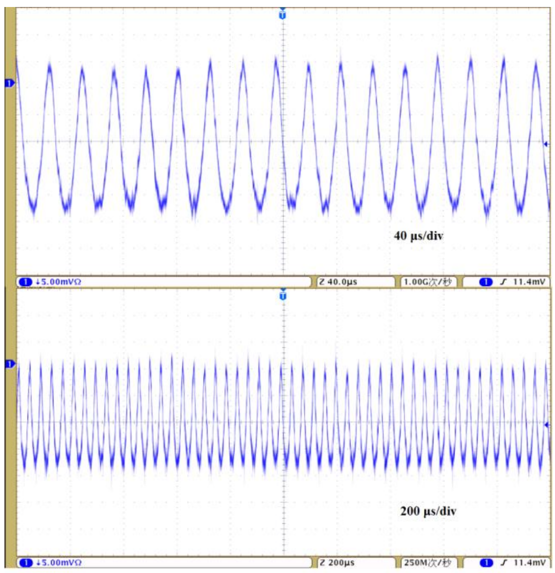

Figure 5. The pulse trains in 40 μs and 200 μs time scales.

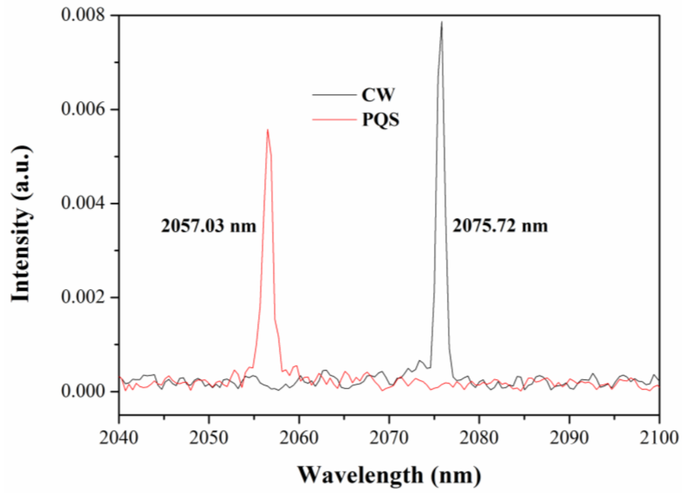

Figure 6. The output wavelengths of the Tm,Ho:$LuVO_4$ laser in CW and PQS mode Operations.

A slit scanning beam profiler (BP109-IR2, Thorlabs Inc., Newton, NJ, USA) was used to acquire beam quality factors of Tm,Ho:$LuVO_4$ laser. Output beam profiles of Tm,Ho:$LuVO_4$ laser were measured, and 2D and 3D graphics are shown in Figure 7. In addition, beam quality factors ${M_x}^2$ and ${M_y}^2$ were measured to be 1.19 and 1.19, respectively, at approximately 1-W average output power from the PQS Tm,Ho:$LuVO_4$ laser.

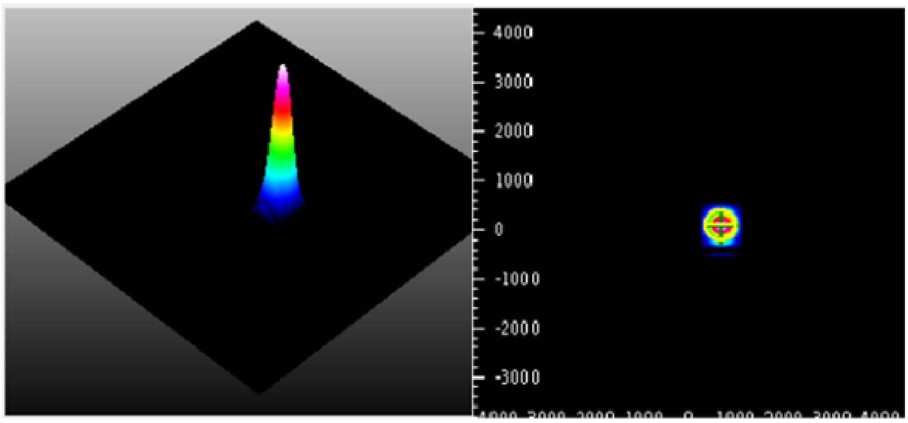

Figure 7. 2D and 3D output beam profiles of Tm,Ho:$LuVO_4$ laser.

4. Conclusions

In conclusion, we have experimentally demonstrated a Tm,Ho:$LuVO_4$ laser under the PQS mode operation with a graphene SA for the first time. A pulse energy of 40.4 μJ and an average output power of 1034 mW were acquired at 2057.03 nm. In addition, the beam quality factors ($M_x^2 = 1.19$ and $M_y^2 = 1.19$) were obtained at about 1-W average output power from the PQS Tm,Ho:$LuVO_4$ laser.

Author Contributions: In this paper, W.W., L.L., H.Z. and X.Y. conceived and designed the experiments; J.Q., Y.L. and Y.S. performed the experiments; W.W. and L.L. analyzed the data; W.Y. and Y.Y. contributed reagents, materials and analysis tools; S.L. and C.X. wrote the paper.

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Conflicts of Interest: We declare that this article does not have any conflicts of interest because the author's order is sorted by actual contribution for the paper.

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