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# Passively Q-Switched Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ Laser Based on $MoTe_2$ Saturable Absorber

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**ABSTRACT** A passively-Q-switched Yb:$Lu_{1-x-y}Y_xLa_yVO_4$ laser based on a two-dimension (2D) molybdenum ditelluride ($MoTe_2$) saturable absorber (SA) is reported for the first time to the best of our knowledge. High quality few layered 2D $MoTe_2$ nanosheets were fabricated by liquid phase exfoliation (LPE) method and used as the SA, whose saturable absorption properties around 1.0 $\mu$m were characterized with a saturation fluence of 3.02 $\mu J/cm^2$ and a modulation depth of 8.3%. In the passively Q-switched laser operation, the shortest pulse width of 500 ns was obtained with an average output power of 0.33 W at a pulse repetition rate of 117 kHz, corresponding to the maximum single pulse energy of 2.8 $\mu$J and the peak power of 5.6 W.

**INDEX TERMS** Solid lasers, optical saturation, nonlinear optics.

## I. INTRODUCTION

Passive Q-switched (PQS) solid state lasers with an appropriate SA is an efficient way to generate nanosecond pulses. Nowadays, 2D materials have become more and more favorable in optoelectronic devices manufacture field, among of which using as SAs is a popular application due to their variable bandgap, strong photoluminescence, ultrafast carrier dynamics and high nonlinear optical response. A series of 2D materials have been proved to be good candidates for SAs, such as graphene [1], [2], black phosphorus (BP) [3], [4], topological insulator (TI) [5] and the transitional metal dichalcogenides (TMDs). As synthetic 2D materials, the TMDs have the structure of a transition metal sandwiched between two chalcogen planes, such as WS2, MoS2, WSe2, and MoSe2, etc., exhibiting unique optical, mechanical and electronic characteristics, which make TMDs a great competitor to other 2D material SAs [6]–[10]. Recently, a new TMDs family member $MoTe_2$ has drawn great interests, the fabrication method, electronic application and semimetallic properties are widely studied [11]–[13]. The band structure of $MoTe_2$ varies from 0.88 eV indirect semiconductor for bulk to 1.02 eV direct semiconductor for monolayer with the nano-sheet thickness. If different Te vacancies were introduced, the band gap could be extended to around 0.33 eV, thus $MoTe_2$ can be used as SA for near or mid-infrared lasers [14]–[20]. Compared with other TMDs family members, the $MoTe_2$ possesses smaller bandgap, which allows valence to conduction band electronic transitions through 1.0 $\mu$m photon absorption, making $MoTe_2$ a suitable SA for 1.0 $\mu$m (~1.2 ev bandgap) PQS lasers [21]. But it seems that the $MoTe_2$ has not received enough attention in SA applications for lasers operating at 1.0 $\mu$m region. Only very recently, a Yb:YCOB/$MoTe_2$ microchip laser and a Yb:KLuW/$MoTe_2$ laser were reported, producing high pulse repetition rate pulses (~MHz) [22], [23].

Yb:$REVO_4$ (RE=Gd, Y or Lu) crystals are widely applied in generating 1.0 $\mu$m laser due to its polarized laser output, high transition cross sections, high thermal conductivity, low thermal expansion, positive dn/dT coefficient and weak thermal lensing [24]–[26]. Compared with the ordered Yb:$REVO_4$ crystals, the mixed crystals, such as Yb:LuxY1-x$VO_4$, Yb:YxGd1-x$VO_4$ and Yb:LuxGd1-x$VO_4$, have broadened Yb spectral bands and longer radiative lifetime, which are interesting for shortening the pulse width in Mode-locked lasers and enlarging the pulse energy in PQS lasers. The laser operations of the mixed vanadate crystals are reported intensively in recent years [27], [28]. It was proved that the spectral broadening and the energy storage capacity enlarging were determined by the difference of ions radii in the host

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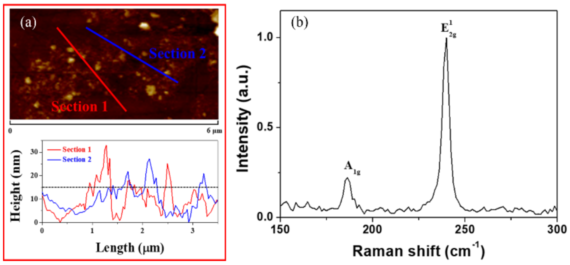


**FIGURE 1.** (a) AFM image and typical height profile of the prepared $MoTe_2$ SA; (b) Raman spectrum of the prepared $MoTe_2$ SA at room temperature.

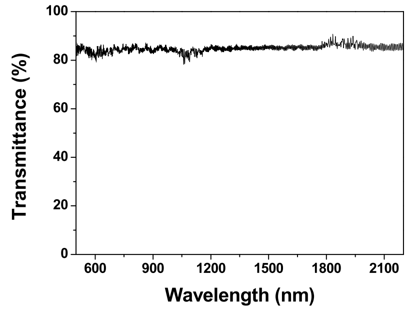


**FIGURE 2.** Linear transmission of $MoTe_2$ film.

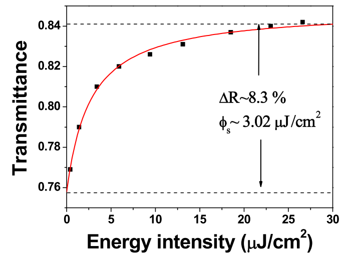


**FIGURE 3.** $MoTe_2$ nonlinear transmission versus incident pulse fluence.

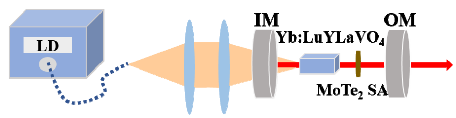


**FIGURE 4.** Experimental setup of Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$/$MoTe_2$ laser.

materials [29]. Inspired by this idea, we can propose that when mixing the rare earth ion La in the mixed vanadate crystal, a larger energy storage capacity can be expected due to the much larger radius of the La ion. Thanks to the rapid development of the crystal growth technology, the mixed vanadate crystals with three cations of Lu, Y, La has already been grown with excellent optical quality and perfect power scaling ability [30]. We expect a good performance in PQS operation with the usage of Yb:$Lu_{1-x-y}Y_xLa_yVO_4$ mixed crystal as the laser medium.

In this paper, a PQS Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$/$MoTe_2$ laser was demonstrated. The maximum single pulse energy, shortest pulse duration and highest pulse repetition rate were 2.8 $\mu$J, 500 ns and 117 kHz. The saturable absorption property of the $MoTe_2$ around 1.0 $\mu$m was investigated through open-aperture Z-scan measurement. To the best of our knowledge, this is the first Yb:$Lu_{1-x-y}Y_xLa_yVO_4$ laser with TMDs SA.

## II. CHARACTERIZATION OF $MoTe_2$ SA

The few layered $MoTe_2$ SA was prepared with the LPE method on a $CaF_2$ substrate. The atomic force microscopy (AFM) was applied to characterize the thickness of the $MoTe_2$ SA, as shown in Fig. 1(a), the maximum thickness of the $MoTe_2$ SA was about 15 nm (average value), corresponding to ~23 layers $MoTe_2$ nanosheets (the interlayer spacing in the $MoTe_2$ was 0.65 nm). Raman scattering spectrum of the $MoTe_2$ SA was measured by Raman spectroscopy with a 632 nm laser source and the results was shown in Fig. 1(b). Two typical Raman peaks, $A_{1g}$ at 179 cm$^{-1}$ and $E^1_{2g}$ at 240 cm$^{-1}$ were detected. The peak $E^1_{2g}$ is much stronger than the peak $A_{1g}$ due to the multilayer of the $MoTe_2$ SA, which accorded with the previous reported results well [31].

The linear transmission of the $MoTe_2$ SA was measured from 450 nm to 2250 nm with a spectrometer. As can be seen in Fig.2, it had an average transmission of 80% at 1050 nm.

The nonlinear optical properties of the $MoTe_2$ SA were measured by an open aperture Z-scan method employing a home-made picosecond fiber laser operating at 1030 nm with pulse width of 15 ps and pulse repetition rate of 100 kHz. With a lens of 75 mm focal length, the laser beam waist was focused to be around 100 $\mu$m. The corresponding nonlinear transmittance as a function of incident light energy intensity is shown in Fig. 3. The transmittance of the $MoTe_2$ SA increased with the scaling of the laser energy intensity, which indicated a very sensitive saturable absorption behavior. By fitting the optical transmittances, the nonsaturable loss, saturation fluence and modulation depth were determined to be 16%, 3.02 $\mu$J/cm$^2$ and 8.3%. The big modulation depth is beneficial to generate short pulse duration and large pulse energy. The results indicated that the prepared 2D $MoTe_2$ SA should be suitable for 1.0 $\mu$m PQS lasers.

## III. EXPERIMENTAL SETUP OF THE PQS LASER

The laser experimental setup is shown in Fig.4, the pump source was a fiber coupled laser diode with center wavelength at 976 nm, a numerical aperture of 0.22 and fiber core diameter of 400 $\mu$m. By using an optical collimating and focusing system, the pump light was 1:1 focused into the Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ crystal with a radius of 200 $\mu$m. A compact concave-plane resonator was employed to investigate the PQS Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ laser, the cavity length was 20 mm. The input mirror (IM) with the curvature radius of 200 mm was a dichroic mirror, which was antireflection coated at 976 nm (T > 95%) and high reflection coated at 1.1~1.2 $\mu$m (R > 99.5%). The output mirror (OM) was a plane mirror with partial transmission of 5% at 1.1~1.2$\mu$m. The crystal was oriented for light propagation along the crystallographic a-axis (a-cut). The dimensions were 3(a)×3(c)×3(a) mm$^3$; both input and output faces were polished to laser quality and remained uncoated. The 2D $MoTe_2$ SA was placed between the crystal and the OM. To remove the heat generated in the experiment, the crystal

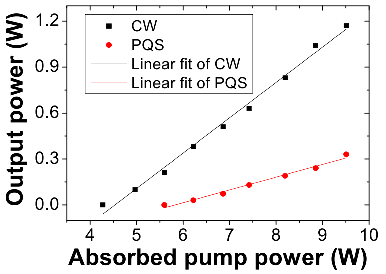


**FIGURE 5.** CW and PQS output power versus absorbed pump power.

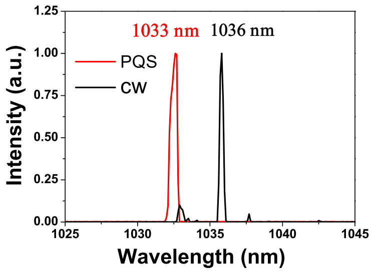


**FIGURE 6.** Spectra of CW and PQS Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$ laser.

was wrapped with indium foil and mounted in a water cooled copper block, the water temperature was maintained at 15 °C.

## IV. RESULTS AND DISCUSSIONS

Firstly, the continuous wave laser was demonstrated. As can be seen in Fig. 5, the threshold was 4.27 W absorbed pump power, the maximum CW output power of 1.17 W at an absorbed pump power of 9.51 W was obtained, corresponding to an optical-optical conversion efficiency of 12.3% and a slope efficiency of 23%. The PQS average output power was investigated when the $MoTe_2$ SA was inserted in the laser cavity and placed between the crystal and the OM. The threshold was 5.60 W, a little bit higher than that of the CW operation. The maximum average output power of 0.33 W at an absorbed pump power of 9.51 W was obtained, corresponding to an optical-optical conversion efficiency of 3.5% and a slope efficiency of 8.3%. Both the CW and PQS laser performance had very good linearity, which indicated that higher power scaling could be expected. The center wavelength of the CW and PQS were measured to be 1036 nm and 1033 nm, as can be seen in Fig. 6. The wavelength of PQS laser was blue-shifted compared to the CW operation, which was the main character of the quasi-three level laser system. This resulted from the requirement for higher gain under a higher cavity loss, the shift of laser emission line toward short wavelength side upon the increase of the cavity loss.

The pulse repetition rate (*PRR*) and pulse duration ($\Delta\tau$) versus the absorbed pump power is shown in Fig. 7(a). With the increasing of the absorbed pump power, the *PRR* increased from 38 to 117 kHz, while the pulse duration decreased from 2 $\mu$s to 500 ns. The single pulse energy ($E_p$) can be defined as $P_{average}/PRR$, and the peak power can be defined as $E_p/\Delta\tau$, the pulse energy and peak power versus the absorbed pump power is shown in Fig. 7(b). Under high pump power, the increasing tendency of the peak power is rapider than the single pulse energy. A maximum single pulse energy

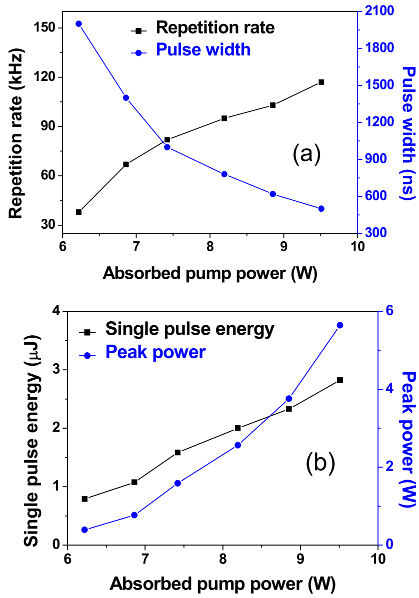


**FIGURE 7.** (a) The pulse repetition rate and pulse width versus the absorbed pump power; (b) The pulse energy and peak power versus the absorbed pump power.

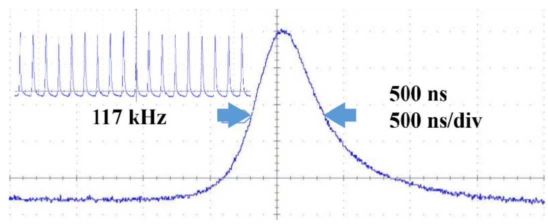


**FIGURE 8.** The pulse profile and the pulse train (inset) at the absorbed pump power of 9.51 W.

**TABLE 1.** Comparison of Yb doped PQS laser with $MoTe_2$ SA.

| Laser | $P_{max}$(W) | *PRR* (kHz) | $E_p$(μJ) | $\Delta\tau$(ns) | $P_p$(W) |
|---|---|---|---|---|---|
| Yb:YCOB /$MoTe_2$ [22] | 1.58 | 700 | 2.25 | 52 | 40.8 |
| Yb:KLuW /$MoTe_2$ [23] | 2.06 | 2180 | 1.30 | 36 | 36.1 |
| This work | 0.33 | 117 | 2.80 | 500 | 5.6 |

of 2.8 $\mu$J and a highest peak power of 5.6 W were obtained under an absorbed pump power of 9.51 W. We estimated the laser facula on the SA was about 143 $\mu$m, so the laser energy density on the $MoTe_2$ SA can be calculated to be higher than the saturation fluence at highest pump power.

The pulse train and single pulse temporal profile were recorded by an oscilloscope (Tektronix 1 GHz bandwidth) and the optical signals were detected by an InGaAs photodetector with a rise time of 35 ps (EOT, ET-2000, USA). Fig. 8 shows the shortest pulse width of 500 ns with the pulse repetition rate of 117 kHz at an absorbed pump power of 9.51 W. The timing jitter of the pulse train was less than 5%, and the instabilities of the output power of the PQS laser was measured to be 3.2% at 0.5 hour. Using the knife edge method, we measured the M2 factor to be 2.65 in the horizontal direction and 2.79 in the vertical direction at the pump power of 9.51 W.

The Yb doped PQS laser results ever obtained with $MoTe_2$ SA were summarized in Table 1, in which the maximum output power($P_{max}$), pulse repetition rate ($PRR$), single pulse energy ($E_p$), pulse duration ($\Delta\tau$) and peak power ($P_p$) are listed. From the table, we can get that our experiment has the potential to obtain passively Q-switched lasers with high pulse energy.

## V. CONCLUSION

In this paper, a PQS Yb:$Lu_{0.74}Y_{0.23}La_{0.01}VO_4$/$MoTe_2$ laser was demonstrated for the first time to the best of our knowledge. The shortest pulse width of 500 ns was obtained with an average output power of 0.33 W at a pulse repetition rate of 117 kHz, corresponding to the maximum single pulse energy of 2.8 $\mu$J and peak power of 5.6 W. The nonlinear optical parameters of the prepared $MoTe_2$ was investigated using the open aperture Z-scan method, the saturation fluence and the modulation depth was measured to be 3.02 $\mu J/cm^2$ and 8.3%. It is indicated that $MoTe_2$ is a good SA for 1.0 $\mu$m laser and the passively Q-switched Yb lasers with $MoTe_2$ as SA are attractive for seeding of high pulse energy 1.0 $\mu$m region amplifiers.

## REFERENCES

[1] J. Hou, B. Zhang, J. He, Z. Wang, F. Lou, J. Ning, R. Zhao, and X. Su, "Passively Q-switched 2 $\mu$m Tm: YAP laser based on graphene saturable absorber mirror," *Appl. Opt.*, vol. 53, no. 22, pp. 4968–4971, Aug. 2014.

[2] T. L. Feng, S. Z. Zhao, K. J. Yang, G. Q. Li, D. C. Li, J. Zhao, W. C. Qiao, J. Hou, Y. Yang, J. L. He, L. H. Zheng, Q. G. Wang, X. D. Xu, L. B. Su, and J. Xu, "Diode-pumped continuous wave tunable and graphene Q-switched Tm: LSO lasers," *Opt. Express*, vol. 21, no. 21, pp. 24665–24673, Oct. 2013.

[3] H. Zhang, J. He, Z. Wang, J. Hou, B. Zhang, R. Zhao, K. Han, K. Yang, H. Nie, and X. Sun, "Dual-wavelength, passively Q-switched Tm: YAP laser with black phosphorus saturable absorber," *Opt. Mater. Express*, vol. 6, no. 7, pp. 2328–2335, Mar. 2016.

[4] Z. Chu, J. Liu, Z. Guo, and H. Zhang, "2 $\mu$m passively Q-switched laser based on black phosphorus," *Opt. Mater. Express*, vol. 6, no. 7, pp. 2374–2379, Mar. 2016.

[5] X. Liu, K. Yang, S. Zhao, T. Li, W. Qiao, H. Zhang, B. Zhang, J. He, J. Bian, L. Zheng, L. Su, and J. Xu, "High-power passively Q-switched 2 $\mu$m all-solid-state laser based on a $Bi_2Te_3$ saturable absorber," *Photon. Res.*, vol. 5, no. 5, pp. 461–466, Mar. 2017.

[6] C. Luan, X. Zhang, K. Yang, J. Zhao, S. Zhao, T. Li, W. Qiao, H. Chu, J. Qiao, J. Wang, L. Zheng, X. Xu, and J. Xu, "High-peak power passively Q-switched 2-$\mu$m laser with $MoS_2$ saturable absorber," *IEEE J. Sel. Top. Quantum Electron.*, vol. 23, no. 1, Jan./Feb. 2016, Art. no. 1600105.

[7] J. Lan, X. Zhang, Z. Zhou, B. Xu, H. Xu, Z. Cai, N. Chen, J. Wang, X. Xu, R. Soulard, and R. Moncorgé, "Passively Q-switched Tm: $CaYAlO_4$ laser using a $MoS_2$ saturable absorber," *IEEE Photon. Technol. Lett.*, vol. 29, no. 6, pp. 515–518, Mar. 15, 2017.

[8] S. Wang, H. Yu, H. Zhang, A. Wang, M. Zhao, Y. Chen, L. Mei, and J. Wang, "Broadband few-layer $MoS_2$ saturable absorbers," *Adv. Mater.*, vol. 26, no. 21, pp. 3538–3544, Jun. 2014.

[9] C. Luan, K. Yang, J. Zhao, S. Zhao, L. Song, T. Li, H. Chu, J. Qiao, C. Wang, Z. Li, S. Jiang, B. Man, and L. Zheng, "$WS_2$ as a saturable absorber for Q-switched 2 micron lasers," *Opt. Lett.*, vol. 41, no. 16, pp. 3783–3786, Feb. 2016.

[10] X. Liu, K. Yang, S. Zhao, M. Li, W. Qiao, T. Li, S. Zhang, L. Zheng, L. Su, and J. Xu, "High repetition rate all-solid-state pulsed 2 $\mu$m laser based on selenide molybdenum saturable absorber," *IEEE J. Sel. Topics Quantum Electron.*, vol. 24, no. 5, Sep./Oct. 2018, Art. no. 1600306.

[11] L. Zhou, K. Xu, A. Zubair, A. D. Liao, W. Fang, F. Ouyang, Y.-H. Lee, K. Ueno, R. Saito, T. Palacios, J. Kong, and M. S. Dresselhaus, "Large-area synthesis of high-quality uniform few-layer $MoTe_2$," *J. Amer. Chem. Soc.*, vol. 137, no. 37, pp. 11892–11895, Aug. 2015.

[12] Y.-Q. Bie, G. Grosso, M. Heuck, M. M. Furchi, Y. Cao, J. Zheng, D. Bunandar, E. Navarro-Moratalla, L. Zhou, D. K. Efetov, T. Taniguchi, K. Watanabe, J. Kong, D. Englund, and P. Jarillo-Herrero, "A $MoTe_2$-based light-emitting diode and photodetector for silicon photonic integrated circuits," *Nature Nanotechnol.*, vol. 12, no. 12, pp. 1124–1129, Oct. 2017.

[13] Y. Qi *et al.*, "Superconductivity in Weyl semimetal candidate $MoTe_2$," *Nature Commun.*, vol. 7, Mar. 2016, Art. no. 11038.

[14] D. Mao, B. Du, D. Yang, S. Zhang, Y. Wang, W. Zhang, X. She, H. Cheng, H. Zeng, and J. Zhao, "Nonlinear saturable absorption of liquid-exfoliated molybdenum/tungsten ditelluride nanosheets," *Small*, vol. 12, no. 11, pp. 1489–1497, Mar. 2016.

[15] G. Wang, "Wavelength-switchable passively mode-locked fiber laser with mechanically exfoliated molybdenum ditelluride on side-polished fiber," *Opt. Laser Technol.*, vol. 96, pp. 307–312, Nov. 2017.

[16] B. Yan, B. Zhang, H. Nie, H. Wang, G. Li, X. Sun, R. Wang, N. Lin, and J. He, "High-power passively Q-switched 2.0 $\mu$m all-solid-state laser based on a $MoTe_2$ saturable absorber," *Opt. Express*, vol. 26, no. 14, pp. 18505–18512, Jul. 2018.

[17] Z. Yan, T. Li, S. Zhao, K. Yang, D. Li, G. Li, S. Zhang, and Z. Gao, "$MoTe_2$ saturable absorber for passively Q-switched Ho,Pr: $LiLuF_4$ laser at~3 $\mu$m," *Opt. Laser Technol.*, vol. 100, pp. 261–264, Mar. 2018.

[18] Y. Zhang, J. Wang, X. Guan, B. Xu, H. Xu, Z. Cai, J. Yin, P. Yan, X. Xu, D. Li, and J. Xu, "$MoTe_2$-based broadband wavelength tunable eye-safe pulsed laser source at 1.9 $\mu$m," *IEEE Photon. Technol. Lett.*, vol. 30, no. 21, pp. 1890–1893, Nov. 1, 2018.

[19] J. Wang, Z. Jiang, H. Chen, J. Li, J. Yin, J. Wang, T. He, P. Yan, and S. Ruan, "High energy soliton pulse generation by a magnetron-sputtering-deposition-grown $MoTe_2$ saturable absorber," *Photon. Res.*, vol. 6, no. 6, pp. 535–541, Jun. 2018.

[20] J. Wang, H. Chen, Z. Jiang, J. Yin, J. Wang, M. Zhang, T. He, J. Li, P. Yan, and S. Ruan, "Mode-locked thulium-doped fiber laser with chemical vapor deposited molybdenum ditelluride," *Opt. Lett.*, vol. 43, no. 9, pp. 1998–2001, May 2018.

[21] A. Kumar and P. K. Ahluwalia, "Electronic structure of transition metal dichalcogenides monolayers 1H-$MX_2$ (M = Mo, W; X = S, Se, Te) from ab-initio theory: New direct band gap semiconductors," *Eur. Phys. J. B*, vol. 85, no. 6, pp. 186–189, Jun. 2012.

[22] Y. Ma, K. Tian, X. Dou, J. Yang, Y. Li, W. Han, H. Xu, and J. Liu, "Passive Q-switching induced by few-layer $MoTe_2$ in an Yb: YCOB microchip laser," *Opt. Express*, vol. 26, no. 19, pp. 25147–25155, Jun. 2018.

[23] K. Tian, Y. Li, J. Yang, X. Dou, H. Xu, W. Han, and J. Liu, "Passively Q-switched Yb: $KLu(WO_4)_2$ laser with 2D $MoTe_2$ acting as saturable absorber," *Appl. Phys. B, Lasers Opt.*, vol. 125, p. 24, Feb. 2019.

[24] V. E. Kisel, A. E. Troshin, N. A. Tolstik, V. G. Shcherbitsky, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, and M. I. Kupchenko, "Spectroscopy and continuous-wave diode-pumped laser action of $Yb^{3+}$: $YVO_4$," *Opt. Lett.*, vol. 29, no. 21, pp. 2491–2493, Nov. 2004.

[25] C. Kränkel, D. Fagundes-Peters, S. T. Fredrich, J. Johannsen, M. Mond, G. Huber, M. Bernhagen, and R. Uecker, "Continuous wave laser operation of $Yb^{3+}$: $YVO_4$," *Appl. Phys. B, Lasers Opt.*, vol. 79, no. 5, pp. 543–546, Sep. 2004.

[26] J. Liu, X. Mateos, H. Zhang, J. Wang, M. Jiang, U. Griebner, and V. Petrov, "Characteristics of a continuous-wave Yb: $GdVO_4$ laser end pumped by a high-power diode," *Opt. Lett.*, vol. 31, no. 17, pp. 2580–2582, Sep. 2006.

[27] H. Zhang, Y. Yu, Y. Cheng, J. Wang, X. Tao, M. Jiang, and H. Xia, "Thermal properties measurement and laser operation of a new Yb: $Gd_{0.68}Lu_{0.32}VO_4$ crystal," *Opt. Express*, vol. 16, no. 15, pp. 11481–11486, Aug. 2008.

[28] J. Liu, H. Zhang, X. Mateos, W. Han, V. Petrov, and J. Wang, "Low quantum defect laser oscillation of a new mixed $Yb_{0.009}$: $Y_{0.575}Gd_{0.416}VO_4$ crystal," *Opt. Express*, vol. 16, no. 22, pp. 17729–17734, Nov. 2008.

[29] H. Xu, H. Yu, Z. Wang, S. Han, Y. Wang, Z. Pan, Y. Zhang, S. Sun, J. Wang, and H. Zhang, "Thermal and laser characteristics of Nd doped $La_{0.11}Y_{0.89}VO_4$ crystal," *Opt. Express*, vol. 20, no. 15, pp. 16524–16531, Aug. 2012.

[30] B. Zhao, Y. Ye, J. Chen, H. Lin, G. Zhang, X. Mateos, J. M. Serres, M. Aguiló, F. Díaz, P. Loiko, U. Griebner, V. Petrov, and W. Chen, "Growth, spectroscopy, and laser operation of 'mixed' vanadate crystals Yb: $Lu_{1-x-y}Y_xLa_yVO_4$," *Opt. Mater. Express*, vol. 8, no. 3, pp. 493–502, Feb. 2018.

[31] M. Grzeszczyk, K. Gołasa, M. Zinkiewicz, K. Nogajewski, M. R. Molas, M. Potemski, A. Wysmołek, and A. Babiński, "Raman scattering of few-layers $MoTe_2$," *2D Mater.*, vol. 3, no. 2, Apr. 2016, Art. no. 025010.