Synthesis of WS$_{1.76}$Te$_{0.24}$ alloy through chemical vapor transport and its high-performance saturable absorption

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Layered transitional metal dichalcogenides (TMDs) are drawing significant attentions for the applications of optics and optoelectronics. To achieve optimal performances of functional devices, precisely controlled doping engineering of 2D TMDs alloys has provided a reasonable approach to tailor their physical and chemical properties. By the chemical vapor transport (CVT) method and liquid phase exfoliation technique, in this work, we synthesized WS$_{1.76}$Te$_{0.24}$ saturable absorber (SA) which exhibited high-performance of nonlinear optics. The nonlinear saturable absorption of the WS$_{1.76}$Te$_{0.24}$ SA was also measured by the open aperture Z-scan technique. Compared to that of the binary component WS$_2$ and WTe$_2$, WS$_{1.76}$Te$_{0.24}$ SA has shown 4 times deeper modulation depth, 28% lower saturable intensity and a much faster recovery time of 3.8 ps. The passively Q-switched laser based on WS$_{1.76}$Te$_{0.24}$ was more efficient, with pulse duration narrowed to 18%, threshold decreased to 28% and output power enlarged by 200%. The promising findings can provide a method to optimize performances of functional devices by doping engineering.

2D transitional metal dichalcogenides (TMDs) materials with formula MX$_2$ (M = Mo, W; X = S, Se, Te) have attracted intense attentions thanks to their unique layered structures, attractive carrier mobility, adjustable band-gap, strong light-matter interaction and stable chemical properties$^{1-9}$. The abundant physical and chemical properties of TMDs are widely applied to photodetectors, logic devices, memories, catalysis, transistors and lasers. The discrepancy of strong covalent bonds intra layers and weak van der Waals inter layers allows down-top and top-down methods to obtain the 2D TMDs nanosheets. For example, chemical vapor deposition (CVD) and wet chemical synthesis are used to obtain the 2D TMDs nanosheets by the methods of down-top$^{10,11}$. It is also desirable to combine two different mature methods of chemical vapor transport (CVT) and mechanical stripping to achieve the nanomaterials (top-down)$^{12,13}$. TMDs can potentially serve as SAs, such as molybdenum disulfide and tungsten disulfide, which already exhibited promising applications with much larger modulation depth than graphene$^{14-18}$. The band-gaps of MoS$_2$ and WS$_2$ are about 1.6~1.9 eV in the visible range, indicating the natural MoS$_2$ and WS$_2$ are far from serving as saturable absorbers in highly developed infrared lasers. In recent years, the defects have been introduced into TMDs in order to extend the bandwidth of TMDs SAs. It has been proved by theories and experiments that M or X vacancy defects in TMDs can reduce their band-gaps$^{19-22}$. S. Wang reduced the band-gap of MoS$_2$ by introducing defects$^{19}$. MoS$_2$ with S defects can be used as a broadband saturable absorber. The passively Q-switched lasers in the range of 1.06, 1.42 and 2.1 μm were realized based on the MoS$_2$ SA with S defects, corresponding pulse duration of 970, 729 and 410 ns, respectively$^{19}$. X. Guan et al. experimentally realized 2.7 μm self-Q-switching laser of Er:Y$_2$O$_3$ based on WS$_2$ SA with pulse width of 1.36 μs$^{20}$. The passively Q-switched lasers at the wavelengths of 1.5, 2.0, 2.7 μm are based on the binary TMDs with defects$^{19-22}$. However, M or X vacancy defects in MX$_2$ make its structure unstable, so M or X vacancy defects in TMDs are difficult to repeatedly synthesized. Furthermore it is less feasible to regulate intentional defects, for example, the 2D MX$_2$ often appears to be both triangle and hexagon due to the local condition. Therefore, there is an urgent need to tune the band-gaps of the TMDs so that they can perform stably in the near-infrared and mid-infrared range.

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Inspired by the history of Si semiconductor, the doping engineering appears to be the key to tailor physical and chemical properties of TMDs. Mixed chalcogenides or mixed metal elements of two different TMDs can control the band gap, such as WS2-Se2(1-x)25 and MoxW1-xS224. However, it has been proven that only a few hundred milli-electron volts (meV) could be realized, i.e. 300 meV for WS2-Se2(1-x) and 170 meV for MoxW1-xS2 solid solutions respectively. P. Yu et al. experimentally showed that 2H-WS2 and Td-WTe2 can form stable layered WSe2-Tc0.5-x alloys23, with a phase transition from 2H-to-Td (x = 1−0.6 for 2 H structure; x = 0.5 and 0.4 for 2 H and 1 Td structures; x = 0−0.3 for 1 Td structure) controlled by the complete composition. The electronic structures changing from semiconducting to metallic enable wide tunability of the optical and electronic properties. Extraordinary physical properties of alloys are needed for in-depth study where the alloys showed some unique advantages compared to 2D binary TMDs, making them fundamentally and technically important in applications of optics and optoelectronics. One of the impressive physical properties of mono- and few-layer alloy is that TMDs display surprisingly excellent nonlinear optical properties, Y. Wang et al. studied the nonlinear optics properties of alloys of Bi2Te3-xSex with lower saturable intensity, deeper modulation depth16.

TMDs alloying still remains challenging resulted from the lattice mismatch of their parent counterparts. Here we synthesized WS1.76Te0.24 alloy by doping Te2− ions in WS2 (2 H) structure. The nonlinear optics properties of WS1.76Te0.24 SA were 4 times deeper modulation depth, 28% lower saturable intensity and a much faster recovery time of 3.8 ps compared to those of WS2 and WTe2. To find out whether pulsed laser’s performance can be promoted by alloying, passively Q-switched lasers were investigated based on WS2, WS1.76Te0.24 and WTe2 SAs at the wavelength of 1060 nm. We found that the passively Q-switched laser based on WS1.76Te0.24 was more efficient, with pulse duration narrowed to 18%, threshold decreased to 28% and output power enlarged by 200%. The promising findings can provide a method to optimize performances of functional devices by doping engineering.

Methods

Synthesis and characterization of WSxTe2−x SAs. The WS1.76Te0.24 monocrystalline was prepared by the chemical vapor transport (CVT) method with well-controlled temperature. There were two steps to obtain WS1.76Te0.24 monocrystalline. Firstly, WS1.76Te0.24 polycrystalline was synthesized by heating a mixture of sulphur (Strem Chemicals 99.9%), tungsten (Strem Chemicals 99.9%) and tellurium (Strem Chemicals 99.9%) with stoichiometric amounts at 750 °C for 48 hours in an evacuated and sealed quartz ampoule (8 mm ID, 10 mm OD, 300 mm length). Considering the powerful exothermicity of the reaction, the mixture was slowly preheated to 750°C for 12 hours to avoid explosion. Secondly, WS1.76Te0.24 was grown by CVT method in a double zone furnace (300 mm length). The mixture of grinded 0.2 mg WS1.76Te0.24 monocrystalline in 4 ml acetone solvent was sonicated in high power ultrasonic bath for 2 hours. Finally, we span and coated the dispersion on SiO2 plate to obtain WS1.76Te0.24 SA after the acetone was easily removed by volatilization in the air.

Material characterization. Transmission electron microscopy (TEM) and energy dispersive spectroscopy (EDS) were adopted to learn the morphology of the WS1.76Te0.24 nanoflakes. TEM images in Fig. 1e–g showed the layered structures of WS2, WS1.76Te0.24, and WTe2, respectively, where the gray scale was directly proportional to the thickness. The observed well exfoliated nanoflakes with layered structure implied rigid mechanical property. The insets were the Selected Area Electron Diffraction (SAED) of WS2, WS1.76Te0.24, and WTe2 nanoflakes. The SAED showed that WS2, WS1.76Te0.24 and WTe2 were monocrystalline with 2 H, 2 H and Td phases, respectively. The diffraction of six-fold symmetry spots displayed the hexagonal lattice of WS1.76Te0.24 nanoflake. EDS measurement was also produced to determine the element ratio of the three samples as shown in Fig. 1h–j. It can be seen that the ratio of S to Te in WS1.76Te0.24 is 1.76 to 0.24, indicating an efficient doping of Te ions in WS2 framework. As shown in Fig. 1k–m, the atomic force microscopy (AFM) was carried out to measure the three SAs thicknesses. The thicknesses of WS2, WS1.76Te0.24 and WTe2 nanoflakes were about 15.6, 14.9, and 16.3 nm, corresponding to 23, 19 and 27 layers, respectively. To learn more about the WS1.76Te0.24 alloy, EDS mapping was adopted shown in Fig. 1n. The green, red and yellow parts were the distribution of tungsten, sulphur, and tellurium element, respectively. The uniform doping of Te in WS2 of WS1.76Te0.24 was obtained. Furthermore, the WS1.76Te0.24 SA with no additional dangling bonds is stable in the air. The high chemical stability was due to the substitution of atoms in the alloy TMDs.

Raman spectroscopy was employed to learn the detailed lattice vibration modes of WS1.76Te0.24 affected by doping engineering where Te2− replaced the S2− in the WS2 structure. The characterization was carried out by using a Jobin Yvon LabRam 1B Raman spectrometer with laser source at 532 nm. The comparison of the Raman fingerprints among the three samples in the range of 200−450 cm−1 is shown in Fig. 2a. In Fig. 2a, the characteristic peaks at 353.2 and 422.7 cm−1 were assigned as the in-plane (E2g) and out-of-plane (A1g) vibrational modes corresponding to WS2 nanoflakes. For the Td-WTe2, the spectrum just showed the A1 Raman mode at 217.8 cm−1. The characteristic bands of WS1.76Te0.24 showed the “two mode behavior” as the coexistence of vibrations of WS2 and WTe2.
and WTe₂. The E₂g and A₁g peaks of WS₁.₇₆Te₀.₂₄ at 352.5 and 411.5 cm⁻¹ are resulted from the corresponding modes in WS₂. The red-shift of A₁g (0.7 cm⁻¹) and E₂g (11.2 cm⁻¹) mode is attributed to the significant changes in the electron-phonon coupling soften by the doping of Te. The frequency broadened at A₁ (217.8 cm⁻¹) was

Figure 1. (a) Scheme of chemical vapor transport (CVT) for crystallization of WS₁.₇₆Te₀.₂₄ in a temperature gradient. Monocrystalline photograph and atomic structure of (b) WS₁.₇₆Te₀.₂₄, (c) WS₂, (d) WTe₂, TEM and SEAD characterizations of few-layer nanosheets of (e) WS₂, (f) WS₁.₇₆Te₀.₂₄, and (g) WTe₂. Corresponding full EDS scanning of (h) WS₂, (i) WS₁.₇₆Te₀.₂₄, and (j) WTe₂. AFM images and thickness measurement of typical nanosheets and height measurement recorded at different sections of (k) WS₂, (l) WS₁.₇₆Te₀.₂₄, and (m) WTe₂. (n) EDS mapping of WS₁.₇₆Te₀.₂₄. The clear morphology implies the uniformity of component distribution.
originated from the reduced structural symmetry arising from lattice distortion due to the different atomic radius of Te and S. In earlier studies, TMDs alloys, e.g. Mo$_x$W$_{1-x}$S$_2$ and WS$_2$Se$_{2(1-x)}$, have the similar frequency shift.

Raman shifts further confirm the expected structural and compositional evolution in the WS$_{1.76}$Te$_{0.24}$ alloy. Figure 2b showed linear transmittance spectra of WS$_{1.76}$Te$_{0.24}$ SA with WS$_2$ and WTe$_2$ as contrasts. The typical absorption peaks of WS$_{1.76}$Te$_{0.24}$ corresponded to the trait of TMD 2H phase. The peaks located at the wavelength of 906 (A) and 859 nm (B) coincided with inter-band transitions. A, B are resulted from spin-orbit splitting of transitions$^{16}$, while C and D (685 and 592 nm) are due to the higher density transition$^{16}$. The transmittance spectrum of WS$_2$ showed the TMD absorption with absorption peaks at 814 (E) and 426 (F) nm. WTe$_2$ displayed semi-metallic phase absorption characteristic with broadband absorption. According to the Tauc plot by extrapolating the linear absorption versus photon energy curve, optical bandgaps of WS$_{1.76}$Te$_{0.24}$, WS$_2$ SAs were calculated

Figure 2. (a) Raman spectra and vibration modes of few-layer WS$_{1.76}$Te$_{0.24}$ nanosheets. (b) Comparison of recorded transmittance spectra and corresponding fitted line of WS$_2$, WS$_{1.76}$Te$_{0.24}$ and WTe$_2$. (c) The refractive index of WS$_2$, WS$_{1.76}$Te$_{0.24}$, and WTe$_2$ based on the relationship of Kramers-Kronig. (d) The open-aperture Z-scan measurements of WS$_2$, WS$_{1.76}$Te$_{0.24}$ and WTe$_2$ flakes at 1060 nm. (e) An ultrafast signal of WS$_{1.76}$Te$_{0.24}$ proved that the relaxation time was ~3.8 ps.
to be 1.2 eV and 1.9 eV, respectively. The electronic structure of WS$_{1.76}$Te$_{0.24}$ strongly depends on the coordination environment of W and its d-electron counts. The Te doping in WS$_2$ shortens the band gap by changing the coordination environment of W corresponding to the ab initio method. Thus, the physics properties of WS$_{1.76}$Te$_{0.24}$ were tailored by ion doping.

The ellipsometer is a conventional method to measure the film’s refractive index. However, ellipsometer has strict requirements on the samples for uniform surface, large size, and thin thickness. Due to its low spatial resolution, it is difficult to obtain refractive index of nanomaterials in nanometer size. Benefitting from the Lorentz-Drude model and Kramers-Kronig (K-K) relationship of the dielectric function, we calculated the corresponding refractive index from the transmittance spectrum. Figure 2c shows the fitting curve of the reflectance spectra, where the refractive index parameters were obtained by the K-K relationship.

In order to understand the incorporation mechanism by Te doping into WS$_2$ and the corresponding effect on optical nonlinear properties of 2D WS$_{1.76}$Te$_{0.24}$, we performed Z-scan measurement with a femtosecond laser (1060 nm, 175 fs) as the excitation source. The results of WS$_2$, WS$_{1.76}$Te$_{0.24}$, and WTe$_2$ SAs are shown in Fig. 2d. The increase of transmittance was easily observed with the increase of laser intensity, resulting from the nonlinear saturable absorption effect. The mechanism of saturable absorption can be explained as Pauli blocking principle in the conduction band. However, significant differences in saturable absorption efficiency and sensitivity among the three samples can be clearly distinguished in Fig. 2d. Based on the nonlinear optical theory, the transmittance is expressed in the form of

$$T = 1 - A_s \cdot \exp \left( \frac{I}{I_{sat}} \right) - A_{nsi}$$

where $A_s$ is the modulation depth, $A_{nsi}$ is the non-saturable components, $I_{sat}$ is the saturable intensity, and $I$ is the incident light intensity. The data was fitted with the Eq. 1, the modulation depth and the saturable intensities were obtained as presented in Table 1. The WS$_{1.76}$Te$_{0.24}$ saturation intensity and modulation depth were 0.88 GW/cm$^2$ and 4.98, respectively. When WS$_2$ became saturated above threshold of 3.15 GW/cm$^2$, the modulation depth was 1.14%. The saturation intensity and modulation depth of WTe$_2$ were 3.7 GW/cm$^2$ and 1.6%, respectively. Compared to binary component of WS$_2$ and WTe$_2$ SA, WS$_{1.76}$Te$_{0.24}$ SA performed 4 times deeper modulation depth and 28% lower saturable intensity, resulting from bandgap evolution of WS$_{1.76}$Te$_{0.24}$.

The bandgap evolution of WS$_{1.76}$Te$_{0.24}$ is used to interpret the lower saturable intensity. As shown in the Fig. 3, the bandgap of WS$_2$ SA is 1.9 eV larger than the photon energy ($\hbar \omega$) of 1060 nm laser. The saturable absorption of WS$_2$ is resulted from the defect states. As shown in Fig. 3, under the excited light, the electrons in valence band of WS$_2$ are transferred to the defect states. The electrons in the defect states jump to the conduction band with one more photon each. Therefore, there are two platforms that the transition of one electron from valence band to conduction band of WS$_2$ and the transition requires two photons. Compared to that of WS$_2$, the optical bandgap

| Materials | n | $\alpha_0$ (10$^5$ cm$^{-1}$) | $\alpha_{nl}$ (10$^7$ cm/GW) | Im$\chi^{(3)}$ (10$^{-6}$ esu) | FOM (10$^{-14}$ cm$^2$ esu) | $\Delta$ (%) | $I_{sat}$ (GW/cm$^2$) |
|-----------|---|-----------------|-----------------|-----------------|-----------------|--------|-----------------|
| WS$_2$    | 6.19 | 0.90 | 0.41 | 4.98 | 5.53 | 1.15 | 3.15 |
| WS$_{1.76}$Te$_{0.24}$ | 10.2 | 2.25 | 0.53 | 17.5 | 7.78 | 4.47 | 0.89 |
| WTe$_2$  | 8.29 | 1.08 | 0.38 | 8.28 | 7.66 | 1.60 | 3.70 |

Table 1. SA Results for Different Two-dimensional Materials.

Figure 3. Schematic diagram of linear absorption in WS$_2$, WS$_{1.76}$Te$_{0.24}$, and WTe$_2$ SAs.
of WS$_{1.76}$Te$_{0.24}$ is 1.2 eV covering 1.0 µm, so the electrons directly transfer from valence band to the conduction band with one absorbed photon. In WTe$_2$, the semi-metal characteristic makes it possess higher electron concentration in the conduction band. The higher concentration of electrons has stronger reflection on the excitation light as shown in Fig. 3. Therefore, compared to the binary component of WS$_2$ and WTe$_2$, WS$_{1.76}$Te$_{0.24}$ has stronger photon absorption at 1.0 µm. The stronger photon absorption of WS$_{1.76}$Te$_{0.24}$ can increase the number of absorbed photons to produce more electrons at the same laser intensity. Eventually, the saturable intensity of WS$_{1.76}$Te$_{0.24}$ is lowered.

Suppose at a certain photon frequency, optical absorption satisfies \( \frac{d\alpha}{d\omega} = -\alpha(\omega)I \). Here the absorption coefficient \( \alpha(\omega) \) is expressed as \( \alpha(\omega) = \alpha_0 + \alpha_N I \). \( d\alpha/d\omega \) is the propagation distance in the sample. The third-order nonlinear optics susceptibility \( \chi^{(3)} \) can be expressed as

\[
\chi^{(3)}(\text{esu}) = \left(10^{-7}\text{cm}^2/\text{W}^2\right)\alpha_N \text{cm}^{-1} \text{W}^{-1} \text{esu}
\]

here \( c \) is the speed of light, \( \lambda \) is the laser wavelength, \( n \) is the refractive index, the discrepancy caused by the linear absorption, namely figure of merit (FOM): \( \text{FOM} = \left|\chi^{(3)}/\alpha_0\right| \). Based on the model 2, we can obtain WS$_{1.76}$Te$_{0.24}$ with \( \alpha_N \sim 10^{11} \text{cm/GW} \), \( \chi^{(3)} \sim 10^{-7} \text{esu} \), \( FOM \sim 10^{-11} \text{esu} \). Compared to previous works, the FOM of WS$_{1.76}$Te$_{0.24}$ perform one order of magnitude larger than that of graphene, graphene oxide, MoS$_2$/NMP dispersions \( \sim 10^{-13} \text{esu} \). That suggests a promising potential to achieve efficient nonlinear performance by alloying TMDs. However, one should note that FOM varies with different experiment conditions such as the wavelength, pulse width and so on. For convincing comparison, we carried out the Z-scan on the same condition and the nanosheets were prepared by the same parameters of liquid-phase exfoliation and spin-coating technique. The results are shown in Table 1. It is unambiguous that the FOM value of WS$_{1.76}$Te$_{0.24}$ SA was larger than those of WS$_2$ and WTe$_2$ SAs, which indicated the enhanced nonlinear performance of WS$_{1.76}$Te$_{0.24}$.

The pump-probe system was adopted to study the carrier relaxation that reflects the optical response of materials. The degenerated pump probe system is easy to align and the relaxation time is corresponded to the carrier-phonon coupling. The ultrafast signal was measured using a Ti: Sapphire laser with pulse duration of 120 fs, repetition rate of 76 MHz, fluence of 200 µJ/cm$^2$ at 395 nm as the pump and the probe beam was at 790 nm with much lower fluence. The probe reflection was a function of the delay time that was detected by a Si photodetector and amplified by a lock-in amplifier. As shown in Fig. 2e, the ultrafast signal of WS$_{1.76}$Te$_{0.24}$ flakes with absorption bleaching was obtained. The signal amplitude was as large as \( \sim 250\% \), implying excellent nonlinear optics property. Notably, the decay time was 3.8 ps fitted by a single exponential function. The decay time of WS$_{1.76}$Te$_{0.24}$ was significantly shorter than 13 ps of WS$_2$ and 5 ps of WTe$_2$, as a result of higher density of trapping states induced by Te doping in the nanoflake.

Investigation of the WS$_{1.76}$Te$_{0.24}$ saturable absorption in passively Q switched laser at 1.0 µm.

To identify whether the boosted saturable absorption effect of WS$_{1.76}$Te$_{0.24}$ did favor in Q-switched laser, we set up a passively Q-switched Yb:Gd$_3$S$_2$Al$_2$O$_7$ (Yb: GSAO) laser to investigate the performance of WS$_{1.76}$Te$_{0.24}$ and WTe$_2$ SAs. In Fig. 4a, the schematic of experiment setup was shown. A laser diode of 976 nm was served as pump source, which was coupled in a fiber of a core diameter of 105 µm and the numerical aperture of 0.22. A doublet lens was employed to focus the beam at 105 µm within the Yb:GSAO crystal. In a cooled down system, the Yb:GSAO gain medium was wrapped with indium foil and mounted in a copper holder with water-cooled at 21 °C. The 11 mm linear cavity composed of 1060 nm high reflectivity M1 and 18% transmittance M2. The as-prepared three samples on SiO$_2$ were inserted into the cavity serving as the saturable absorber. The pump-probe system was adopted to study the carrier relaxation that reflects the optical response of materials. The degenerated pump probe system is easy to align and the relaxation time is corresponded to the carrier-phonon coupling. The ultrafast signal was measured using a Ti: Sapphire laser with pulse duration of 120 fs, repetition rate of 76 MHz, fluence of 200 µJ/cm$^2$ at 395 nm as the pump and the probe beam was at 790 nm with much lower fluence. The probe reflection was a function of the delay time that was detected by a Si photodetector and amplified by a lock-in amplifier. As shown in Fig. 2e, the ultrafast signal of WS$_{1.76}$Te$_{0.24}$ flakes with absorption bleaching was obtained. The signal amplitude was as large as \( \sim 250\% \), implying excellent nonlinear optics property. Notably, the decay time was 3.8 ps fitted by a single exponential function. The decay time of WS$_{1.76}$Te$_{0.24}$ was significantly shorter than 13 ps of WS$_2$ and 5 ps of WTe$_2$, as a result of higher density of trapping states induced by Te doping in the nanoflake.

In this work, we have experimentally demonstrated the enhanced nonlinear optical properties of WS$_{1.76}$Te$_{0.24}$ by alloying WTe$_2$ and WS$_2$. We synthesized ternary WS$_{1.76}$Te$_{0.24}$ by CVT method. The SAED, EDS and Raman spectra showed good quality of the alloy WS$_{1.76}$Te$_{0.24}$ nanosheets. The saturable absorption of WS$_{1.76}$Te$_{0.24}$ at 1.06 µm was significantly more efficient than binary parents WTe$_2$ and WS$_2$ as evidenced by Z-scan and pump-probe results.
where WS$_{1.76}$Te$_{0.24}$ SA showed 4 times deeper modulation depth, 28% lower saturable intensity and a much faster recovery time of 3.8 ps. The passively Q-switched laser based on WS$_{1.76}$Te$_{0.24}$ was found more efficient, with pulse duration narrowed to 18%, threshold decreased to 28% and output power enlarged twice. The doping engineering SAs can improve the Q-switched lasers performance with lower energy consumption, narrower pulse width, and larger average output power. The promising findings can provide a method to optimize performances of functional devices by doping engineering.

Data availability
Data Availability For original data, please contact xiezhenda@nju.edu.cn.

Figure 4. (a) Experimental setup of the LD pumped passively Q-switched Yb: GSAO laser at 1060 nm. (b) The output powers with increasing incident pump powers. (c) Pulse repetition rates. (d) Variations of pulse duration with increasing pump powers. The Q-switched lasers performance by the WS$_2$, WS$_{1.76}$Te$_{0.24}$ and WTe$_2$ SAs: (e) the oscilloscope tracings. (f) the single pulse tracings (g) the optical spectra.

| Sample | WS$_2$ | WS$_{1.76}$Te$_{0.24}$ | WTe$_2$ |
|--------|--------|------------------------|---------|
| Wavelength (nm) | 1061.1 | 1065.9 | 1058.0 |
| Output power (mW) | 247.5 | 350 | 152.8 |
| Pulse Duration (µs) | 1.285 | 230 | 550 |
| Repetition rate (kHz) | 141.6 | 271.1 | 170.8 |

Table 2. Experiment results of Q-switched lasers based on three SAs.
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Author contributions

Xinjie Lv, Gang Zhao, Zhenda Xie, Jinlong Xu and Shining Zhu conceived the original idea. Zhengting Du, Chi Zhang and Jinlong Xu designed and carried out the experiment. Zhengting Du and Chi Zhang contributed to the experimental characterization and interpretation. Zhengting Du and Mudong Wang contributed to the EDS measurement. Zhengting Du, Xuejin Zhang and Jian Ning contributed to the Raman spectrum measurement. Zhengting Du, Chi Zhang and Jinlong Xu produced the manuscript and interpreted the results. All authors participated in discussions and reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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