Ta₂NiSe₅ nanosheets as a novel broadband saturable absorber for solid-state pulse laser generation

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ABSTRACT Two-dimensional (2D) ternary chalcogenides have attracted great attentions because of their novel chemical and physical properties arising from the synergistic effect and stoichiometric variation with the additional third element compared with their binary counterparts. Here, high-quality 2D tantalum nickel selenide (Ta₂NiSe₅) nanosheets are successfully fabricated by a liquid-phase exfoliation (LPE) method. The ultrafast excited carrier relaxation time and nonlinear optical absorption response are investigated and reveal that the prepared 2D Ta₂NiSe₅ nanosheets have excellent broadband saturable absorption properties, which are further illustrated by three passively Q-switched (PQS) all-solid-state lasers operating at 1.0, 2.0 and 2.8 μm with the Ta₂NiSe₅ nanosheet-based saturable absorber (SA). Furthermore, mode-locked laser operation with the pulse width as short as 356 fs is also realized at 1.0 μm. This work not only demonstrates the excellent nonlinear optical properties and optical modulation performance of Ta₂NiSe₅, but also paves the way for exploring the photonic and optoelectronic properties of ternary chalcogenide materials.

Keywords: ternary chalcogenides, Ta₂NiSe₅, saturable absorbers, passively Q-switched lasers, ultrafast lasers

INTRODUCTION

Since the discovery of graphene in 2004 [1], two-dimensional (2D) materials have attracted significant attentions due to their unique properties caused by the low dimensions and quantum confinement effect. Until now, thousands of 2D materials have been discovered, such as graphene, black phosphorus (BP), topological insulators (TIs), transition metal dichalcogenides (TMDs), and MXenes, which have been endowed with various appli-

cations in catalyst [2], energy storage [3], bio-pharmaceuticals [4,5], optoelectronics [6–8], and ultrafast laser generations [9–14]. These 2D materials have their own advantages and disadvantages. For example, graphene has outstanding thermal conductivity and electron mobility but low on-off ratio and optical absorption [15]; the bandgap of BP could be adjusted from visible to mid-infrared by changing the number of layers, but it is easily oxidized under air [16]; TMDs are antioxidative, but can only response in the visible range [17]. Therefore, it is still necessary to explore new materials with better performance.

Recently, ternary chalcogenide materials have been extensively studied by scientists due to their unique structures, outstanding chemical and physical properties, and great potential for applications in nanoscale devices. Compared with traditional mono- and binary counterparts, ternary chalcogenides have been anticipated to be more appealing due to the synergistic effect and stoichiometric variation arising from the additional third element [18]. Ta₂NiSe₅, a typical ternary chalcogenide material, has a quasi-one-dimensional layered structure stacked loosely by van der Waals interaction and is composed of layers of Ni single chains and Ta double chains along the *a*-axis [19,20]. The structure of Ta₂NiSe₅ characterizes the zigzag waved 2D layer consisting of the NiSe₄ tetrahedral single chains that are interconnected on both sides by the [TaSe₆]₂ dimer chains *via* sharing Se-Se edges, which consist of two [TaSe₆] octahedral single chains by edge sharing of Se atoms [21,22]. This twisted chain structure leads to great anisotropic properties of Ta₂NiSe₅ in the layer plane. Besides, a recent study also shows that Ta₂NiSe₅ is a zero-gap and direct bandgap

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semiconductor, with a transition to an excitonic insulator (EI) occurring near 326 K [23]. Below this temperature, flat band at the top of the valence band occur, which is ascribed to the EI effect [24]. The combination of direct bandgap and EI phase provides an unprecedented opportunity to study the effect of electron states in exciton formation on photoexcitation [21]. The unique band structure gives rise to a broadband light-matter interaction which may be useful for broadband functional photoelectric devices. However, most of the research of Ta_2NiSe_5 focuses on its own physical properties [25–27], its nonlinear optical properties and applications are rarely studied.

Herein, the high-quality 2D Ta_2NiSe_5 nanosheets were fabricated through the commonly used liquid-phase exfoliation (LPE) method. Atomic force microscopy (AFM), transmission electron microscopy (TEM), Raman spectra, X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS) and linear transmission spectrum were used to study the structure, surface morphology and optical properties of the prepared 2D Ta_2NiSe_5 nanosheets. The ultrafast optical excited carrier dynamics and broadband nonlinear optical response of the prepared 2D Ta_2NiSe_5 nanosheets were investigated by the nondegenerate ultrafast pump-probe measurement and open-aperture Z-scan method. Furthermore, the broadband passively Q-switched (PQS) lasers operating at 1.0, 2.0 and 2.8 μm and mode-locked laser operating at 1.0 μm were successfully realized with the 2D Ta_2NiSe_5 nanosheets as the saturable absorber (SA), which further illustrates the broadband nonlinear saturable absorption properties of 2D Ta_2NiSe_5 nanosheets.

EXPERIMENTAL SECTION

Characterization

The characterization instruments and models are as follows: AFM (dimension Icon AFM); TEM (JOEL JEM 2100F microscope); SEM (Hitachi S-4800 microscope); EDS (Oxford INCA Penta FETx3 spectrometer); XRD (Bruker AXS D8-advance XRD); Raman (high-resolution Horiba Jobin-Yvon LabRAM-800 Raman spectrometer); XPS (ESCALAB 250 spectrometer); linear transmission spectra (Hitachi U-3500 spectrophotometer).

Nondegenerate ultrafast pump-probe measurement

The pump source was a Ti:sapphire laser with a pulse width of 100 fs and repetition rate of 1.0 kHz. The pump beam at the wavelength of 400 nm with a fluence of $\sim 300 \mu\text{J cm}^{-2}$ was used to excite the photocarriers in the

sample, while the probe beam at the wavelength of 800 nm was used to probe the internal relaxation process of the sample. The pump and probe light were focused at the same point while the pump fluence was 20 times that of the probe fluence. The pump-induced change of the probe was detected using a lithium tantalate pyroelectric detector (DET-L-PYC5-R-P, Newport) and a lock-in amplifier referenced to a 500 Hz chopped pump.

Open-aperture Z-scan measurements

The light source was a homemade optical parametric oscillation (opo) laser (30 ps, 20 kHz). The input light was divided into two parts by the 50/50 beam splitter: one part was collected by a power meter (Thorlabs S470C), another part was focused by a lens ($f = 60$), transmitted through the sample, and measured by another power meter. The sample was fixed on the stepper motor controlled by a computer program.

PQS lasers

The compact laser cavity was 20 mm long with different gain media (Nd:YVO₄, Tm:YLF and Er:YSGG). Three fiber-coupled laser diodes (LD) with 200 μm core diameter and 0.22 numerical aperture were used as the pump sources for the three gain media: 808 nm for Nd:YVO₄, 792 nm for Tm:YLF, and 967 nm for Er:YSGG. The input mirrors (IMs) were antireflection-coated at the corresponding pump wavelength and high-reflection-coated at the corresponding output wavelength with a curvature radius of 200 mm, while the flat output couplers (OCs) with a transmission of 10% for the corresponding output wavelength. All the gain media were wrapped by indium foil and mounted in a copper block with water cooling at 15°C to remove the excess thermal effect. The output spectra of 1.0, 2.0 and 2.8 μm were measured by Yokogawa AQ6370C with a resolution of 0.02 nm, APE WaveScan with a resolution bandwidth of 0.4 nm and an Omni- λ 300 with a resolution of 10 nm, respectively. Typical pulse trains at all wavelengths were recorded by Tektronix with 1 GHz bandwidth.

Mode-locked lasers

The z-type resonator was 3.5 m long with Yb:KGW as the gain medium. A fiber-coupled diode laser at the wavelength of 976 nm with a 105 μm fiber-core diameter and a numerical aperture of 0.22 was used as the pump sources. Based on the ABCD propagation matrix method, the laser mode radii were calculated to be 35 and 50 μm on the gain medium and SA, respectively. The radius on the SA was slightly larger than that on the gain medium to

protect the SA from high peak power laser damage. The output coupler was a flat mirror with 1% transmission at 1020–1100 nm. A Gires-Tournois interferometer negative-dispersion mirror (GTI) with a total of -500 fs^2 group delay dispersion (GDD) per round was used to compensate the intracavity GDD. A noncollinear autocorrelator (APE, Pulse Check150) and a spectrum analyser (Agilent N9000A) were used to measure the pulse duration and the frequency spectrum. The digital oscilloscope and spectrometer were same as those mentioned in PQS lasers.

RESULTS AND DISCUSSION

Preparation and characterization of 2D Ta_2NiSe_5 nanosheets

Up to now, large Ta_2NiSe_5 single crystal can be synthesized by chemical vapor transport (CVT) and other methods [21]. However, exfoliating 2D Ta_2NiSe_5 nanosheets from large crystals is still challenging. Compared with mechanical exfoliation methods, LPE is more convenient, practicable and suitable for mass production of 2D layered materials [28–30]. In our experiment, the ultrathin 2D Ta_2NiSe_5 nanosheets were fabricated by the LPE method. Firstly, the commercial Ta_2NiSe_5 single crystal with purity of 99.9999% was ground into powder and ultrasonically exfoliated in isopropyl alcohol (IPA) for a few hours. To remove the thermal effect, the ice bags were used in the ultrasonic machine to keep the temperature constantly. Secondly, the exfoliated solution was

centrifuged at 5000 r min^{-1} for 15 min to obtain the supernatant for later use. Then, the prepared supernatant was spin-coated on a sapphire substrate uniformly and dried in a vacuum oven for 1 h. Finally, the 2D Ta_2NiSe_5 nanosheets were exfoliated successfully.

AFM and TEM were utilized to investigate the surface morphologies of the prepared 2D Ta_2NiSe_5 nanosheets. As shown in Fig. 1a and b, AFM image and the height profile demonstrate that the exfoliated Ta_2NiSe_5 nanosheets are uniformly dispersed on the sapphire substrate with an average thickness of approximately 10 nm, corresponding to 15 layers thick (the interlayer spacing of Ta_2NiSe_5 is approximately 0.66 nm [21]). TEM and high-resolution TEM (HRTEM) images are presented in Fig. 1c and d. As can be seen, the clear lattice fringe of Ta_2NiSe_5 nanosheets with an interplanar distance of 0.26 nm, corresponding to the (006) planes, indicates that the exfoliated nanosheets still retained a good lattice structure. The components of the Ta_2NiSe_5 nanosheets were examined by scanning electron microscopy (SEM) mapping and energy-dispersive X-ray spectroscopy (EDS) measurements. As shown in Fig. 1e, the shades of color of EDS mapping image demonstrates the atomic ratio of Ta, Ni, and Se is approximately 2:1:5. And the atomic ratio determined by EDS shown in Fig. 1f quantitatively proves it, indicating the purity of the exfoliated 2D Ta_2NiSe_5 nanosheets.

The measured XRD spectrum of the 2D Ta_2NiSe_5 nanosheets is shown in Fig. 2a. All the patterns are constant with the simulated pattern [31], indicating the single-

Figure 1 (a, b) AFM image and the typical height profile of the Ta_2NiSe_5 nanosheets; (c, d) TEM and HRTEM images of the Ta_2NiSe_5 nanosheets; (e, f) SEM mapping and EDS analysis with the corresponding atomic ratio of the Ta_2NiSe_5 nanosheets.

Figure 2 (a) XRD pattern of the Ta_2NiSe_5 nanosheets; (b) Raman spectra of the Ta_2NiSe_5 nanosheets; (c–e) XPS of the elements Ta, Se and Ni in the Ta_2NiSe_5 nanosheets; (f) linear transmission spectrum of the Ta_2NiSe_5 nanosheets.

crystalline nature of the exfoliated Ta_2NiSe_5 nanosheets. Typical Raman peaks excited by a 532 nm laser source are presented in Fig. 2b. Three typical peaks located at the frequencies of 97, 123 and 236 cm^{-1} are obviously observed [32]. XPS was also used to characterize the Ta_2NiSe_5 nanosheets. The fitted peaks of Ta $4f_{7/2}$ (28.2 eV) and $4f_{5/2}$ (26.4 eV), Se $3d_{5/2}$ (59.2 eV) and Ni $2p_{3/2}$ (856.1 eV) are shown in Fig. 2c, d and e. The satellite peaks near the Ni $2p_{3/2}$ and Se $3d_{5/2}$ may be caused by charge-transfer [20]. Fig. 2f shows the visible-near infrared transmission spectra (the background of the substrate and Fresnel reflection has been subtracted), demonstrating the 2D Ta_2NiSe_5 nanosheets maintains good optical absorption over a broadband range.

Broadband nonlinear optical absorption response

To better study the ultrafast optical excited carrier dynamics and nonlinear optical absorption properties of the 2D Ta_2NiSe_5 nanosheets, the nondegenerate ultrafast pump-probe and the broadband open-aperture Z-scan measurements were performed. The experimental setup is shown in Figs S1 and S2, and the details are described in the EXPERIMENTAL SECTION. The result of nondegenerate ultrafast pump-probe measurement is shown in Fig. 3. The fitting formula of the nondegenerate pump-probe measurement is described as a bi-exponential decay

function [33]:

$$\frac{\Delta T}{T_0} = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2), \quad (1)$$

where $\Delta T/T_0$ means the time dependent normalized transmission changes, ΔT is the transmittance of the probe laser beam without the pump laser, T_0 is the variation in the probe transmission with the pump laser excitation, A_1 and A_2 are the relative amplitudes of the double temporal components, τ_1 and τ_2 are typical relaxation times attributed to the intra-band carrier-phonon scattering and the inter-band carrier recombination. There exists another typical relaxation time, intra-band carrier-carrier scattering time, which is very short (~ 10 – 200 fs) and can hardly be detected due to the limited resolution of our experimental setup [33]. The positive $\Delta T/T_0$ signal shown in Fig. 3 reveals photobleaching signatures caused by Pauli blocking effects, which were induced by an excitation based on hot carrier dynamics [34]. By fitting this curve, the typical relaxation times τ_1 and τ_2 were determined to be 8.6 and 276.9 ps. The picosecond scale relaxation time indicated that 2D Ta_2NiSe_5 nanosheets could be used in ultrafast photonic process, e.g., SA in ultrafast mode-locked lasers.

The typical open-aperture Z-scan curves and the corresponding nonlinear transmittance curves at the wavelengths of 1.0, 2.0 and $2.8\text{ }\mu\text{m}$ are shown in Fig. 4a–f,

Figure 3 Nondegenerate ultrafast pump-probe curve of the Ta₂NiSe₅ nanosheets.

which were fitted by the following Equations (2) and (3) [35]:

$$T_n = 1 - \beta I_0 L_{\text{eff}} / 2^{\frac{3}{2}} \left(1 + \frac{Z^2}{Z_0^2} \right), \quad (2)$$

$$T = 1 - \Delta R / (1 + I_0 / I_s) - N, \quad (3)$$

where T_n is the nonlinear transmittance, β is the nonlinear absorption coefficient, L_{eff} is the effective thickness, Z is the relative position of the sample, Z_0 is the Rayleigh length of the beam, T is the transmittance, ΔR is the modulation depth, I_0 and I_s are the peak power intensity and the saturation intensity, and N is the unsaturable loss. The Pauli blocking effect is also responsible for the change of nonlinear transmittance, which results in the energy levels of the conduction band being filled by the

excited electrons from the valence band, blocking the further optical absorption [36]. From those fitted curves, the unsaturable loss, saturation fluence, modulation depth and nonlinear absorption coefficients of 2D Ta₂NiSe₅ nanosheets were obtained and summarized in Table 1. It is indicated that the prepared 2D Ta₂NiSe₅ nanosheets have the excellent broadband saturable absorption properties and can be used for PQS laser pulse generation.

Broadband PQS solid-state lasers

To further experimentally demonstrate the broadband saturable absorption properties of the 2D Ta₂NiSe₅ nanosheets, a compact two-mirror laser cavity with different gain media were employed to generate PQS laser pulses. The laser experimental setup is shown in Fig. S3 and the details are described in the EXPERIMENTAL SECTION. To generate PQS lasers efficiently, the material must satisfy the second threshold condition [37]:

$$\frac{F_{\text{sat},A}}{\Delta R \tau} \leq \frac{2hc\omega_{\text{eff},L}^2}{m\lambda\sigma_{\text{em},L}\omega_{\text{eff},A}^2 T_R}, \quad (4)$$

where $F_{\text{sat},A}$ is the saturable energy fluence, τ is the recovery time of the material, h is the Planck constant, c is

Table 1 Summary of the broadband nonlinear saturable absorption properties of the 2D Ta₂NiSe₅ nanosheets

Wavelength (μm)	N (%)	I_s (MW cm ⁻²)	ΔR (%)	β (×10 ⁶ cm GW ⁻¹)
1.0	5.32	16.24	15.9	-2.32
2.0	3.18	30.21	10.8	-1.83
2.8	2.95	30.16	8.09	-1.5

Figure 4 Open aperture Z-scan (a–c) and nonlinear transmittance (d–f) curves of the 2D Ta₂NiSe₅ nanosheets at (a, d) 1.0, (b, e) 2.0 and (c, f) 2.8 μm.

the light velocity, λ is the laser wavelength, $\omega_{\text{eff},A}$ and $\omega_{\text{eff},L}$ are the effective laser radii at the position of SA and laser crystal, $\sigma_{\text{em},L}$ is the stimulated emission cross-section of the laser crystal, T_R is the laser cavity round-trip time, and m is a cavity constant ($m = 1, 2$ for ring and linear cavities). The calculation results with different gain media and cavity parameters are summarized in Table S1. The value of the right side of Equation (4) is calculated to be much bigger than that of the left side, which indicates that the Ta_2NiSe_5 nanosheet-based SA should be suitable for generating PQS laser with the designed conditions.

All the experimental results of the Ta_2NiSe_5 SA-based PQS lasers are summarized in Table 2. The average output power and single pulse energy *versus* absorbed pump power and the corresponding output spectra of the Ta_2NiSe_5 SA-based PQS lasers at different wavelengths are shown in Fig. S4. Obvious spectral blueshift and line width compression occurred in the PQS operation, which were caused by the insertion loss induced by the 2D Ta_2NiSe_5 nanosheet-based SA [38]. The typical pulse profiles and pulse trains of the PQS lasers under the maximum output power at the three different wave-

lengths are shown in Fig. 5. The minimum pulse widths at the wavelengths of 1.0, 2.0 and 2.8 μm were measured to be 355, 302 and 280 ns, corresponding to the repetition rates of 65, 61 and 60 kHz. The output power instability was measured to be less than 4% for all the three PQS lasers. The beam quality factor M^2 was determined to be 1.3 for 1.0 μm , 1.6 for 2.0 μm and 1.5 for 2.8 μm respectively. Those pulse trains remained stable for 0.5 h and no obvious damage was observed on the 2D Ta_2NiSe_5 SA in all the laser operation. And after storage for two weeks in air at room temperature, the SA could still be used, demonstrating the excellent oxidation resistance of the 2D Ta_2NiSe_5 nanosheets.

CW mode-locked laser

Ultrafast laser generation is another key capability of SAs, which is realized by the mode-locked laser operation. It is much harder to realize mode-locked lasers than PQS lasers with a 2D material SA, especially for solid-state lasers. The fundamental properties of laser crystal, the saturable absorption properties of SA, and the cavity design parameters were all needed to be taken into con-

Table 2 Experimental results of the 2D Ta_2NiSe_5 SA-based PQS lasers at different wavelengths

Wavelength (μm)	Output power (mW)	Pulse width (ns)	Repetition rate (kHz)	Single pulse energy (μJ)	Peak power (W)
1.0	185	355	65	2.7	7.7
2.0	471	302	61	7.9	29.2
2.8	230	280	60	3.8	13.6

Figure 5 Typical pulse trains of the Ta_2NiSe_5 SA PQS lasers at the wavelengths of (a, d) 1.0, (b, e) 2.0 and (c, f) 2.8 μm .

sideration for the solid-state mode-locked laser operation. The following condition must be satisfied for the stable continuous-wave (CW) mode-locked solid-state laser generation, [39]:

$$F_{\text{sat},A} \Delta R < \frac{(PT_R)^2}{F_{\text{sat},L} A_{\text{eff},L} A_{\text{eff},A}} = \frac{(PT_R)^2 \times m \sigma_{\text{em},L} \lambda}{h c \times \pi \omega_{\text{eff},L}^2 \times \pi \omega_{\text{eff},A}^2}, \quad (5)$$

where P is the laser power in the laser cavity, T_R is the round-trip time, $A_{\text{eff},A}$ and $A_{\text{eff},L}$ are the laser mode areas on SA and laser crystal. The right-hand of the equation means the mode-locked pulse energy while the left hand means the minimum intracavity pulse energy. Substituting the designed experimental parameters into Equation (5) for calculation, the left-hand side was calculated to be $38.7 \mu\text{J cm}^{-2}$, much smaller than that of the right-hand side ($172.3 \mu\text{J cm}^{-2}$). It is demonstrated that the designed experimental condition is suitable for generating the mode-locked laser. The experimental details and setup diagram are described in the EXPERIMENTAL SECTION and Fig. S5.

In the mode-locked laser operation, the unstable Q-switched mode-locking (QML) regime was realized firstly. By increasing the pump power and carefully adjusting the resonator, the QML turned into stable CW mode-locked (CWML) operation. As shown in Fig. 6a and b, the pulse duration was measured to be 356 fs by sech^2 pulse shape fitting and the related spectrum had a full width half maximum (FWHM) of 3.6 nm at the

maximum average output power of 536 mW. The corresponding time bandwidth product of 0.359 is slightly larger than the Fourier transform-limited value (0.315), indicating the slight chirp of the output pulse. Fig. 6c presents the CWML typical pulse trains with different time scales. The recorded radio frequency spectrum with a wide and a narrow span are shown in Fig. 6d and e. A fundamental beat note near 41.7 MHz and the corresponding signal-to-noise ratio of 68 dB were observed, which matched well with the cavity round-trip time. Moreover, the output power instability (root mean square (RMS)) was measured to be less than 3% over 2 h and the beam quality was determined to be 1.2. Table 3 summarizes the comparison between different 2D material-based mode-locked lasers. It is obvious that the 2D Ta_2NiSe_5 SA-based mode-locked laser has better performance than most of other 2D materials, except the shortest pulse width for Ref. [43]. Because Yb:CALGO has the ultra-wide spectrum, it is easier to obtain ultra-short pulses. This result verifies that Ta_2NiSe_5 could be an excellent optical modulator for ultrafast laser generations.

CONCLUSIONS

In conclusion, the 2D Ta_2NiSe_5 nanosheets were fabricated by the LPE method. The ultrafast optical excited carrier dynamics and nonlinear optical absorption properties were investigated by the nondegenerate ultrafast pump-probe measurement and the broadband open-

Figure 6 (a, b) Measured autocorrelation trace and the corresponding spectra; (c) recorded CWML pulse trains with different time scales; (d, e) recorded radio frequency spectra with a wide and a narrow span.

Table 3 Comparison of 2D material SA-based mode-locked lasers

Materials	Gain medium	Peak power (kW)	Pulse energy (nJ)	Pulse width (fs)	Refs.
Ta ₂ NiSe ₅	Yb KGW	36.1	12.8	356	This work
Ta ₂ NiS ₅	EDF ^a	4.39	6.37	1450	[39]
ReSSe	EDF	0.31	0.275	888	[40]
NiPS ₃	EDF	0.00068	4.46	6,520,000	[41]
Graphene	Yb KGW	13.8	5.9	428	[42]
BP	Yb CALGO	23.8	6.5	272	[43]
WS ₂	Yb YAG	4.2	3.1	736	[44]

a) EDF: erbium-doped fiber

aperture Z-scan measurement, and the results reveal the excellent broadband saturable absorption properties of the prepared 2D Ta₂NiSe₅ nanosheets. Furthermore, broadband PQS lasers operating at 1.0, 2.0 and 2.8 μm and femtosecond scale CWML solid-state laser were also achieved based on the Ta₂NiSe₅ nanosheets as the SA. The excellent nonlinear saturable absorption properties of the 2D Ta₂NiSe₅ nanosheets revealed by this work demonstrate the huge potential of Ta₂NiSe₅ for pulse laser generation and all-optical signal processing applications.

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Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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Ta_2NiSe_5 纳米片作为一种新型的宽带可饱和吸收体用于全固态脉冲激光的产生

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摘要 三元硫化化合物与其二元的同类相比, 因其多出的第三种元素而产生的协同作用和化学计量变化带来了新奇的物理化学性质, 从而受到了广泛的关注. 在本文中, 我们通过液相剥离法成功制备了高质量的二维硒化钽镍(Ta_2NiSe_5)纳米片, 并进一步研究了其超快载流子弛豫特性以及非线性光学吸收特性, 从而发现了所制备的 Ta_2NiSe_5 纳米片具有出色的宽带可饱和吸收性能. 此外, 利用所制备的 Ta_2NiSe_5 纳米片作为可饱和吸收体, 实现了在1.0, 2.0和2.8 μm 处的全固态调Q脉冲激光. 同时, 在1.0 μm 处也实现了脉冲宽度短至356 fs的固体连续锁模激光. 这项工作不仅证明了 Ta_2NiSe_5 具有优异的非线性光学特性和光调制性能, 而且为探索三元硫化化合物材料的光子和光电特性铺平了道路.