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To cite this article: Lihao Guo et al 2022 Nanotechnology 33 315701

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Nanotechnology 33 (2022) 315701 (8pp)

MoS₂/MXene pillared nanocomposite for ultrafast photonics applications

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Received 21 January 2022, revised 12 March 2022 Accepted for publication 20 April 2022 Published 11 May 2022



Abstract

In this work, we used nanocomposite saturable absorbers (SAs) in order to precisely design and modulate the process of compositing the light absorption by band gap engineering. Due to the higher absorption intensity of our MoS_2/MX ene nanocomposite, we have successfully shortened the pulse duration (1.2 μ s) of SA with enhancing saturable absorption intensity

 $(7.22 \text{ MW cm}^{-2})$, and the ultra-fast fiber laser based on this nanocomposite SA has shown wider Q-switching stable range in the case of high pump power. This strategy can efficiently improve the performance of SA and shows the potential application prospect of nanocomposites in nonlinear optics.

Supplementary material for this article is available online

Keywords: MXene, composite, saturable absorbers, Q-switching, ultrafast photonics

1. Introduction

Saturable absorbers (SAs) are the critical component of the ultra-fast laser fiber which can effectively convert the continuous wave into ultra-fast optical pulses, namely the non-linear optics [1, 2]. With the rapidly increasing demands in semiconductor industry [3], optical communications [4], metamaterial absorber [5], and etc, the adequate SAs are required to replace the traditional light source such as sapphire [6], owing to their advantages, Inc., low-cost, simple synthesis process and shorter achievable pulse durations [7, 8]. The present SAs include traditional SAs represented by semiconductor saturable absorber mirrors (SESAM), and low-dimensional nanomaterials based SAs [9–11]. To date, although SESAM have been studied for many years, their application and development are still limited by the shortage

of adjustable absorption [12], which has been proved as a crucial parameter determining the performance of SAs [3]. Another type of SAs, the low-dimensional nanomaterials (especially two-dimensional (2D) nanomaterials) based SAs, have gradually replaced the SESAM ascribing to their unique properties [13], e.g. switchable bandgap, high carrier mobility, etc, which can broaden the adjustment scope of nonlinear absorption [14]. For example, unlike the SESAM with limited operation bandwidth, the graphene based SAs demonstrate broadband nonlinear optical response and ultrafast carrier colling rate [15, 16]. Furthermore, because the third-order nonlinear optical susceptibility of MoS_2 is higher than graphene, the ultra-broadband nonlinear optical response can be achieved [17–19].

It has been confirmed that the light absorption which effected by bandgap structure influences the performance of SAs. However, comparing with the intrinsically gapless band structure [16], even if the bandgap (1.29 eV) of the bulk MoS₂ can be adjusted to 1.80 eV as the thickness decreases to

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monolayer [20], the operation bandwidth of single SA material is still deficient, which limits further enhancement of the SAs' performance. As a solution, there are several methods available for broadening the adjustable range of light absorption and improving the SAs' performance such as doping Se into MoS_2 nanosheets [21], compounding MoS_2 and WS₂ or MoSe₂ and WSe₂ [22, 23], etc. However, because of the same structure and properties of MoS2 and their derivative, the enhancement of these methods is restricted. The MXene, as a new member of the 2D material family [24, 25], their nonlinear optical response has been found with efficient saturable absorption and negligible lossy nonlinear absorption components in the near infrared region [26], which makes MXene become a suitable candidate for SA [27-30]. Thus, exploring SAs based on MXene/MoS₂ hybrid nanomaterials may be an effective way to design and fabricate the adequate SAs.

In this work, referring to this design strategy, we fabricated a nanocomposite SA based on $MoS_2/MXene$ nanocomposite to further improve the performance of SA. The results show that $MoS_2/MXene$ -based SA has a smaller modulation depth (2.1%) than MoS2 (1.6%) and a lager saturable absorption intensity (7.22 MW cm⁻²) than pure MXene (0.47 MW cm⁻²). Moreover, the ultra-fast fiber laser system based on $MoS_2/MXene$ SA shows a better Q-switching characteristics, and comparing with the systems based on pure MoS_2 , WS_2 or MXene, our work has achieved an excellent pulse width (1.2 μ s) owing to the suitable modulation depth and saturable absorption intensity. All of this means that this strategy may be applied to fabricate higher performance ultra-fast fiber lasers in the future and meet the requirement of other high-tech fields.

2. Experimental section

2.1. Preparation of $Ti_3C_2T_x$ MXene nanosheets

The commercial Ti₃AlC₂ (MAX phase) powders purchased from Forsman Scientific Co. were used to prepare Ti₃C₂T_x MXene nanosheets through a previously reported method [31]. In brief, gently add 1.3 g LiF into 20 ml 9 M HCl with continuous stirring before adding MAX phase powders. After LiF completely dissolving, MAX phase powders were slowly added to avoid the side reactions. The reaction continued 24 h at 35 °C under magnetic stirring and then the product was washed with deionized water (DI water) until the pH value reached 6. Then the above supernatant was ultrasonicated intercalated for 1 h in ice bath. Finally, the Ti₃C₂T_x MXene nanosheets were gained after centrifugation at 3500 rpm for 30 min.

2.2. Synthesis of MoS₂/MXene composite

A microwave assisted hydrothermal process was used to synthesis MoS_2/MX ene composite. In detail, the 0.2 g $Ti_3C_2T_x$ MXene nanosheets were redistribute into 20 ml DI water and transferred to a Teflon lining, and after adding 1.5 g thioacetamide (TAA) the reaction system A was prepared. The reaction system B was obtained by ultrasonic dispersing 0.01 g MoO₃ into 20 ml DI water. Then, the reaction system B was added into reaction system A and the mixture was heated to 150 °C in 3 min with assisting of microwave and kept for 1 h. The product was centrifugated and washed several times. And after freeze drying the $MoS_2/MXene$ composite was obtained.

2.3. Q-switching experiment set-up

The concentration of the material on the end face of the fiber can be controlled by a 'drop after drop' method, to observe the characteristics of the laser pulse at different concentrations. We have built an erbium-doped all fiber passively Q-switched laser system showed in, which consist of a laser diode (centre wavelength of 976 nm, output power ranging from 0 to 600 mW), a 980/1550 nm wavelength division multiplexer (WDM), a polarization controller (PC), a MXene/MoS₂ or MXene as saturable absorbers (SA), a polarization independent isolator (PI-ISO) and a 10:90 output coupler (OC). The total cavity length of the laser is about 5.1 m. Pump light is coupled into the cavity through WDM, and 0.56 m erbium-doped (liekki Er-110-4/125) provide gain for the erbium-doped fiber laser. PI-ISO ensure the unidirectional transmission of the laser in the cavity and prevent the reverse light. PC can change the polarization state of the beam in the cavity and optimize the working state of the laser. 10% port of OC is connected with collimator to measure laser pulse characteristics, and 90% port is connected with ring cavity.

2.4. Characterization and measurement

The compositions and morphologies of samples were characterized by transmission electron microscope (TEM JEOL JEM-2100F), filed-emission scanning electron microscope (FE-SEM FEI Apreo HiVac), atomic force microscope (Oxford), Raman spectroscopy (Renishaw inVia), and X-ray diffraction spectrometer (XRD Brucker D8 Advance).

3. Result and discussion

3.1. Synthesis and characterization of MoS₂/MXene nanocomposite

Firstly, the MXene nanosheets were fabricated by minimally intensive layer delamination (MILD) method [31]. After the Al layer was selective etched from MAX phase, the $Ti_3C_2T_x$ was obtained because of the strong Ti–C band. The etched MXene was exfoliated to nanosheets in the subsequent intercalation process. The scanning electron microscopy (SEM) images of MAX powders and MXene nanosheets (figures 1(a) and (b)) show that the particles were successfully transformed into nanosheets. Moreover, the contrast of nanosheets in transmission electron microscopy (TEM) image testifies the thin thickness of MXene, which is quantitated as



Figure 1. Characterizations of MXene nanosheets and $MoS_2/MXene$ nanocomposite. (a), (b) SEM images of MAX powders, MXene nanosheets. (c) TEM images of MXene nanosheets and (d) $MoS_2/MXene$ nanocomposite. (e) SEM image of $MoS_2/MXene$ nanocomposite. (f) AFM image of $MoS_2/MXene$ composite (insert is AFM of MXene nanosheets). (g) XRD pattern of MXene nanosheets and $MoS_2/MXene$ nanocomposite. (h) Raman spectrum of $MoS_2/MXene$ nanocomposite. (i) Absorption spectrum of MXene and $MoS_2/MXene$ composite aqueous solution.

 \sim 1.5 nm by atomic force microscopy (AFM) (insert of figure 1(f)).

With abundant surface terminated groups [32], such as -O, -OH, -F [33], the excellent hydrophilic MXene nanosheets (figure S1 (available online at stacks.iop.org/NANO/33/ 315701/mmedia)) can be easily dispersed into hydrothermal reaction system and composited [34]. The MoS_2/MX ene nanocomposite was synthesized through microwave assisted hydrothermal process with MXene, MoO₃, and TAA as precursor. Because of the rapid heating process and the interaction between TAA and terminated groups on MXene surface, the burst nucleation occurred on the MXene surface, as shown in Finger 1d. Moreover, due to anchoring effect of MoS₂, the MXene nanosheets were connected with the bigger size of nanocomposite than pure MXene nanosheets, as can be seen in figure 1(d). According to the SEM image of MoS_2/MX ene (figure 1(e)), the originally flat morphology of MXene has been obviously changed (figure 1(b)) and the crumpled morphology can effectively solve the serious aggregation issue of nanosheet during drying and the more exposed nanocomposite may become a reason of the excellent performance [35]. The height topography and surface morphology of MoS_2/MX ene were measured by AFM (figure 1(d)), which revealed that the thickness of MoS_2/MX ene nanocomposite is ca. 13 nm and the surface morphology mutually corroborate with TEM image. The element distribution in EDS (figure S2) shows that there is no damage to the element composition of MXene and the corresponding distribution location of element Mo and S proves the presence of MoS_2 .

Comparing the XRD patterns of MAX phase (figure S3) and MXene, both the disappeared diffractions peak at 39° (figure 1(g)), corresponding to the (104) lattice plane of Ti₃AlC₂ MAX and the shift of (002) peak at 9.7° indicating the successfully prepared of MXene nanosheets [36, 37]. The MoS₂ was successfully introduced with the presence of diffraction peaks at 14.3°, 33.4°, 39.6° and 59.6° which can be indexed as the (002), (101), (103) and (110) lattice planes



Figure 2. The nonlinear optical absorption of (a) the $MXene/MoS_2$ SA and (b) MXene SA. (c) The SA transfer technology. (d) The set-up of erbium-doped all fiber passively Q-switched laser system.

diffraction peaks of 2H-MoS₂ (JCPDS No.37-1492) (figure 1(g)) [38, 39]. The left shift of (002) peak from 6.8° to 5.4° means a border interlayer distance of MXene due to the introduction of MoS₂ [40, 41]. The successful synthesis of MoS₂/MXene nanocomposite is further confirmed by Raman spectrum (figure 1(h)), where the typical E_{2g}^{1} and A_{1g} modes of 2H-MoS₂ at 373 cm⁻¹ and 401 cm⁻¹ can be clearly observed with no change of MXene Raman peaks [42, 43]. As can be seen in figure 1(i), the UV–vis–NIR absorption spectrum shows that MoS₂/MXene nanocomposite have a stronger absorption in near-infrared regions than MXene, which is beneficial for their application as a SA.

3.2. Nonlinear optical responses of MoS₂/MXene nanocomposite saturable absorbers

Before assembling SA into laser system, the nonlinear optical absorption of SA should be measured first. The nonlinear optical absorption of the MoS_2/MX ene SA and MXene SA were characterized using the twin-detector technique, which is reported in our previous work [44], viz. manipulating a home-made passively mode locked fiber laser at 1565 nm,

with 900 fs pulse duration, and 44.7 MHz pulse repetition rate (details in Experiment section).

Comparing the results in figures 2(a) and (b), the I_{sat} , ΔT of MoS₂/MXene SA and MXene SA are 7.22 MW cm⁻², 2.1% and 0.47 MW cm⁻², 3.54%, respectively, which means that these two types SAs have the same saturable absorption, modulation depth and saturation intensity. However, the saturable absorption intensity of MoS₂/MXene nanocomposite SA is 15 times higher than MXene SA. Thus, under the same pump power the MoS₂/MXene nanocomposite SA will achieve higher light-to-light conversion efficiency.

3.3. Ultrafast photonics applications of fiber laser system

The MoS₂/MXene and MXene were tightly attached to the end face of the fiber by dropping material alcohol solution on the FC/APC fiber and evaporating the alcohol (figure 2(c)), and then the erbium-doped all fiber passively Q-switched laser systems were set up (figure 2(d)). According to the optical spectrum of MXene and MoS₂/MXene (figure S4), the central wavelength λ_0 and width can be known (λ_0 (MXene) = 1560.8 nm, $\Delta\lambda$ (MXene) = 5.12 nm, λ_0



Figure 3. Pulse waveform diagram under different pump power (a) $MoS_2/MXene SA$, (b) MXene SA. The shortest pulse width (c) $MoS_2/MXene SA$, (d) MXene SA.

 $(MoS_2/MXene) = 1558.4 \text{ nm}, \Delta \lambda \quad (MoS_2/MXene) = 4.92 \text{ nm}).$ Then the stable pulse trains of $MoS_2/MXene$ SA and MXene SA under different pump power are shown in figures 3(a) and (b), which depicts the stable Q-switching mechanism presenting between 270 mW pump power and of 600 mW pump power using nanocomposite SA, while for MXene SA, the Q-switching threshold decreased to 200 mW but vanished at 320 mW. Moreover, the higher Q-switching damage threshold will let this nanocomposite SA can be applied in more fields.

The shortest pulse duration of these two SAs in Q-switching erbium doped fiber laser system are shown in figures 3(c) and (d) (single pulse at Q-switching damage threshold, viz. 600 mW for MoS₂/MXene SA and 320 mW for MXene SA, respectively). A shorter duration of 1.2 μ s was achieved with MoS₂/MXene nanocomposite SA which is a brilliant performance improvement comparing with MXene SA (2.1 μ s). This improvement is owing to the nanocomposite SA's higher saturable absorption intensity (7.22 MW cm⁻²) as mentioned above, which leads a stronger bleaching effect on the laser and a narrower width pulse was

achieved. It has been confirmed that the saturable absorption intensity of MoS_2/MX ene is improved comparing with the pure MXene, caused by the composite process. So, the pulse-narrowing phenomenon can be explained through the mechanism that in Q-switching process the pulse width is determined by relationship between the gain and loss of the system. When the gain become lager, the more population inversion can be accumulated, and the SA can become saturable more rapidly, so the pulse width is narrowed. Moreover, the absorption capacity of MoS_2/MX ene is enhanced, which has a certain narrowing effect on pulse.

The larger output power and pulse energy of MoS_2/MX ene are other improvements caused by higher saturable absorption intensity. As shown in figures 4(a) and (b), due to the higher Q-switching damage threshold (600 mW), the MoS_2/MX ene nanocomposite SA based laser system can be manipulated at a wider pump power range. Thus, the largest output power and pulse energy can be achieved to more than quadruply higher state, viz. 4.2 mW and 42.6 nJ for MoS_2/MX ene SA and 0.82 mW and 10.5 nJ for MXene SA. Even at identical pump power our



Figure 4. Pulse energy, output power change with pump power (a) $MoS_2/MXene SA$, (b) MXene SA. The variation of pulse width and repetition frequency with pump power (c) $MoS_2/MXene SA$, (d) MXene SA.

	$\Delta T (\%)$	Single energy (nJ)	$I_{\rm sat}$ (MW cm ⁻²)	Pulse width (μ s)	repetition rate range (kHz)	References
Graphene	1.5	28.7	_	3.89	10.36-41.8	[45]
Bi ₂ Se ₃	30	4		9.5	2.6-12	[<mark>46</mark>]
MoS_2	1.6	63.2	13	7.5	6.5–27	[18]
WS ₂	0.99	11	36.2	1.73	27.2—84.8	[47]
$Ti_3C_2T_x$	3	125	0.4	2.31	70.67–96	[30]
$Ti_3C_2T_x$	3.54	10.5	0.47	2.1	48.58–76.57	This work
$Ti_3C_2T_x/MoS_2$	2.1	42.6	7.22	1.2	65.96–98.52	This work

Table 1. Performance comparison of $Ti_3C_2T_x/MoS_2$ with other materials.

 MoS_2/MX ene nanocomposite SA also shows better performance, e.g. 10.2 nJ and 0.73 mW for MoS_2/MX ene SA at 300 mW pump power comparing with 6.9 nJ and 0.48 mW for MXene SA at same condition.

The reducing trend of repetition rate of Q-switching fiber laser system with increasing pump power is a typical Q-switching characteristic which can be obviously observed with both two SAs (figures 4(c) and (d)). More specifically, the repetition rate raised from 65.96 kHz to 98.52 kHz and pulse duration reduced from 2.7 μ s to 1.2 μ s for nanocomposite laser system, while as for MXene laser system, this variation presented in the range of 48.58 kHz to 76.57 kHz and 3.98 μ s to 2.1 μ s. Moreover, within the wider adjustable range of pump power (270–600 mW), the larger repetition rate (98.52 kHz) and narrower pulse duration (1.2 μ s) can be achieved with MoS₂/MXene nanocomposite SA based laser system, and all this improvement can be attributed to the composite process caused higher absorption intensity.

Moreover, through theoretical calculation the power density of the MoS_2/MX ene nanocomposite SA based laser

system is approximate 0.05 MW cm^{-2} which is lower than the saturable absorption intensity during Q-switching process. Due to all optical fiber structure, the system possesses stronger anti-interference ability and robustness comparing with other space structure system. So, the performance of system didn't show evident degeneration during the Q-switching operation.

In table 1, we compare MXene SA, $MoS_2/MXene$ SA with the other 5 single nanomaterials SA that work around 1.5 μ m. Comparing with single nanomaterial SAs based on graphene, WS₂, MoS₂, and MXene, our MoS₂/MXene nanocomposite SA possesses the shortest pulse width which is related to their absorption intensity and ΔT . As a result, our MoS₂/MXene nanocomposite SA has excellent photo bleaching capability and improved performance [45–47].

Comparing with the single component materials such as graphene, Bi₂Se₃, MoS₂, and MXene, the excellent photo bleaching capability and improved performance of MoS_2/MX ene composite can be attributed to the adjustable band structure and electron migration process of this composite. It has been proved that the MXene possess metallic electron conductivity and when combing MXene with other materials such as MoS₂ the electron in MoS₂ will rapidly transfer to the MXene and this migration cause the variation of band structure of MoS₂ then affect the optical properties [48]. And this regulation can be further optimized to obtain more suitable band structure by adjusting the ratio of MoS₂ and MXene, which is not possessed for single component nanomaterials. Moreover, the synthesis process of MoS2/ MXene composite is simplified because of abundant surface terminal groups as mentioned above, and this also means that there are a great many of combination mode for MXene based composite, which indicates the more potential to design and fabricate SA or other absorbers with better performance using this method [49].

4. Conclusions

In summary, in pursuit of higher SAs' performance, we took advantage of nanocomposite materials' abundantly adjustable range of light absorption and proposed a MoS₂/MXene nanocomposite SA design strategy. With microwave assisting hydrothermal method the MoS₂/MXene nanocomposite SA was successfully fabricated, and this SA possessed 7.22 MW cm⁻² absorption intensity and 2.1% ΔT . After assembling into fiber laser system, the result shows that the Q-switching pulse presents in the wide pump power range of 270-600 mW and the narrowest pulse duration can achieve 1.2 μ s which is outstanding for this parameter, meanwhile the pulse energy is still at a relatively high level. All this have proved that this MoS₂/MXene nanocomposite SA has an excellent performance meaning this strategy may lead more potential nanocomposite SAs to be used in the high-performance nonlinear optics and ultra-fast lasers.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (51903197, 61904134), Fundamental Research Funds for the Central Universities (JC2110, JB211305), Wuhu and Xidian University special fund for industry-university-research cooperation (No.: XWYCXY-012020012), and Open Fund of Zhijiang Lab (2021MC0AB02).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

L G designed the project. L G, Y Z, L L, Q G, X L, and R N, synthesiszed the materials. J L, X W, Z Z, and Z W tested the optical performance. L G analyzed data and wrote the paper. J W took charge of optics section. W H and W W took charge of materials section.

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References

- Jiang T, Yin K, Wang C, You J, Ouyang H, Miao R and Zhang H 2019 Photonics Res. 8 78
- [2] Yamashita S 2019 APL Photonics 4 034301
- [3] Liu X, Guo Q and Qiu J 2017 Adv. Mater. 29 1605886
- [4] Boyd R W 2003 Nonlinear Optics (New York: Academic)
- [5] Mahmud S, Islam S S, Almutairi A F and Islam M T 2020 IEEE Access 8 129525
- [6] Spence D E, Kean P N and Sibbett W 1991 Opt. Lett. 16 42
- [7] He J, Dong H, Deng R and Chen L 2016 Opt. Eng. 55 086109
- [8] Song Y F, Li L, Tang D Y and Shen D Y 2013 Laser Phys. Lett. 10 125103
- [9] Chen B, Zhang X, Wu K, Wang H, Wang J and Chen J 2015 Opt. Express 23 26723
- [10] Mahmud S, Islam S S, Mat K, Chowdhury M E H, Rmili H and Islam M T 2020 *Results Phys.* 18 103259
- [11] Mahmud S, Karim M, Islam S S, Shuvo M M K, Akter T, Almutairi A F and Islam M T 2021 IEEE Access 9 117746
- [12] Ursula K 2003 Nature 424 831
- [13] Guo B, Xiao Q I, Wang S h and Zhang H 2019 Laser Photonics Rev. 13 1800327
- [14] Zhang M, Wu Q, Zhang F, Chen L, Jin X, Hu Y and Zhang H 2019 Adv. Opt. Mater. 7 1800224
- [15] Martinez A and Sun Z P 2013 Nat. Photon. 7 842
- [16] Yamashita S 2012 J. Lightwave Technol. 30 427
- [17] Wang K, Wang J, Fan J, Lotya M, O'Neill A, Fox D and Blau W J 2013 ACS Nano 7 9260
- [18] Luo Z, Huang Y, Zhong M, Li Y, Wu J, Xu B and Weng J 2014 J. Lightwave Technol. 32 4679

- [19] Wang S, Yu H, Zhang H, Wang A, Zhao M, Chen Y and Wang J 2014 Adv. Mater. 26 3538
- [20] Woodward R and Kelleher E 2015 Appl. Sci. 5 1440
- [21] Wei R, Qiao T, Tian X, Zhang H, He X, Hu Z and Qiu J 2017 Nanotechnology 28 215206
- [22] Mao D, She X, Du B, Yang D, Zhang W, Song K and Zhao J 2016 Sci. Rep. 6 23583
- [23] Liu W J, Liu M L, Liu B, Quhe R G, Lei M, Fang S B and Wei Z Y 2019 Opt. Express 27 6689
- [24] Naguib M, Kurtoglu M, Presser V, Lu J, Niu J, Heon M and Barsoum M W 2011 Adv. Mater. 23 4248
- [25] Xu B and Gogotsi Y 2020 Chin. Chem. Lett. 31 919
- [26] Jiang X, Liu S, Liang W, Luo S, He Z, Ge Y and Zhang H 2018 Laser Photonics Rev. 12 1700229
- [27] Xu N, Li H, Gan Y, Chen H, Li W, Zhang F and Zhang H 2020 Adv. Sci. 7 2002209
- [28] Gao L, Ma C, Wei S, Kuklin A V, Zhang H and Agren H 2021 ACS Nano 15 954
- [29] Jhon Y I, Koo J, Anasori B, Seo M, Lee J H, Gogotsi Y and Jhon Y M 2017 Adv. Mater. 29 1702496
- [30] Wang L, Li X, Wang C, Luo W, Feng T, Zhang Y and Zhang H 2019 ChemNanoMat 5 1233
- [31] Halim J, Lukatskaya M R, Cook K M, Lu J, Smith C R, Naslund L A and Barsoum M W 2014 Chem. Mater. 26 2374
- [32] Cui W, Hu Z-Y, Unocic R R, Van Tendeloo G and Sang X 2021 Chin. Chem. Lett. 32 339
- [33] Xiu L, Wang Z and Qiu J 2020 Rare Met. 30 1237
- [34] Yin J, Zhan F, Jiao T, Deng H, Zou G, Bai Z and Peng Q 2020 Chin. Chem. Lett. 31 992

- [35] Yang Z, Jiang L, Wang J, Liu F, He J, Liu A and Lu G 2021 Sensors Actuators B 326 128828
- [36] Lipatov A, Alhabeb M, Lukatskaya M R, Boson A, Gogotsi Y and Sinitskii A 2016 Adv. Electron. Mater. 2 1600255
- [37] Wang Y, Feng W and Chen Y 2020 *Chin. Chem. Lett.* **31** 937
 [38] Wang X, Li H, Li H, Lin S, Ding W, Zhu X and Sun Y 2020
- *Adv. Funct. Mater.* **30** 0190302
 [39] Liu J-B, Hu J-Y, Liu C, Tan Y-M, Peng X and Zhang Y 2021 *Rare Met.* **40** 1536
- [40] Zhang S, Ying H, Huang P, Wang J, Zhang Z, Yang T and Han W Q 2020 ACS Nano 14 17665
- [41] Wu S, Wang H, Li L, Guo M, Qi Z, Zhang Q and Zhou Y 2020 Chin. Chem. Lett. 31 961
- [42] Yu Y, Nam G H, He Q, Wu X J, Zhang K, Yang Z and Zhang H 2018 Nat. Chem. 10 638
- [43] Hu T, Wang J, Zhang H, Li Z, Hu M and Wang X 2015 Phys. Chem. Chem. Phys. 17 9997
- [44] Ma M, Wen W, Zhang Y, Dou C, Wang J, Xie L and Wei Z 2019 J. Mater. Chem. C 7 6900
- [45] Jinzhang W, Zhengqian L, Min Z, Chenchun Y, Hongyan F, Zhiping C and Wei Q 2012 *IEEE Photonics J.* 4 1295
- [46] Shuqing C, Yu C, Man W, Ying L, Chujun Z and Shuangchun W 2014 *IEEE Photonics Technol. Lett.* 26 987
- [47] Ahmad H, Ruslan N E, Ismail M A, Reduan S A, Lee C S, Sathiyan S and Harun S W 2016 Appl. Opt. 55 1001
- [48] Li J, Li Z, Liu X, Li C, Zheng Y, Yeung K W K and Wu S 2021 Nat. Commun. 12 1224
- [49] Shuvo M M K, Hossain M I, Rahman S, Mahmud S, Islam S S and Islam M T 2021 *IEEE Access* 9 126466