Research article

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Ultrafast mode-locking in highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes for 1.9- μm infrared femtosecond pulsed lasers

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Abstract: Metallic 2D materials can be promising saturable absorbers for ultrashort pulsed laser production in the long wavelength regime. However, preparing and manipulating their 2D structures without layer stacking have been nontrivial. Using a combined experimental and theoretical approach, we demonstrate here that a metallic titanium carbide ($\text{Ti}_3\text{C}_2\text{T}_x$), the most popular MXene 2D material, can have excellent nonlinear saturable absorption properties even in a highly stacked state due to its intrinsically existing surface termination, and thus can produce mode-locked femtosecond pulsed lasers in the 1.9- μm infrared range. Density functional theory calculations reveal that the electronic and optical properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene can be well preserved against significant layer stacking. Indeed, it is experimentally shown that 1.914- μm femtosecond pulsed lasers with a duration of 897 fs are readily generated within a fiber cavity using hundreds-of-layer stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene saturable absorbers, not only being much easier to manufacture than mono- or few-layered ones, but also offering character-conserved tightly-assembled 2D materials for advanced performance. This

work strongly suggests that as-obtained highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes can serve as superb material platforms for versatile nanophotonic applications, paving the way toward cost-effective, high-performance photonic devices based on MXenes.

Keywords: femtosecond mode-locked laser; 1.9- μm infrared laser; layer stacking; 2D material; saturable absorber; $\text{Ti}_3\text{C}_2\text{T}_x$ MXene.

1 Introduction

Since the discovery of graphene [1], 2D materials have attracted great research attention due to their unusual outstanding physical properties [2–7]. Particularly in recent years, photonic technologies using 2D materials have been among the most important nanophotonic issues, which include exciton-trion-based photoluminescence [8, 9], single photon emission [10, 11], exotic nonlinear optics [12–14], and plasmonics [15–17]. In these applications, obtaining and maintaining well-defined 2D structures are essential for their advanced photonic operation, which have required complicated and/or sophisticated processes compared to that of their bulk counterparts. Mechanical exfoliation has been an efficient way to provide high-quality 2D materials from van der Waals layered materials through the physical expansion of interlayer spacing using sticky tapes [18]. However, this method is not suitable for mass production of 2D materials. On the contrary, chemical exfoliation can rather easily produce a large amount of 2D materials from their parent layered materials using intercalation and/or chemical surface modification of the constituent layers, but this method likely deteriorates the structures of obtained 2D materials and needs complicated chemical processes [19, 20]. Generally, 2D materials are prone to surface oxidation under air and/or aqueous environments and to avoid this, they are often coated by protective films or mixed with polymers.

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2D transition metal carbides called MXenes are new emerging 2D materials [21, 22] which possess superb physical properties in various fields such as electrochemical capacitance [23, 24], chemical catalysis [25], composite reinforcement [26], electromagnetic interference shielding [27], light-to-heat conversion for solar harvesting [28], quantum dots [29], and photothermal therapy [30] and detection [31], as well as including energy-efficient water purification [32] which was first addressed by graphene technologies [33, 34].

Despite numerous studies on 2D materials for saturable absorption performance in laser optics [35–51], metallic 2D materials had not been investigated until our recent study because metallic conductors are generally known as poor or incompetent saturable absorbers (SAs). The astounding saturable absorption and mode-locking performance of metallic 2D transition-metal carbonitrides were first observed in our study in which near-infrared mode-locked femtosecond lasers were successfully generated using 2D transition-metal carbonitride saturable absorbers (SAs) [52], opening the door to MXene-based nonlinear optics [52–57]. Especially, we witnessed its well-operating performance even with a large degree of layer stacking, suggesting the need for in-depth researches on this intriguingly phenomenon [52].

According to the variation of chemical elements, atomic structures, and termination species, MXenes can possess hundreds of different 2D material members. Among such a wide range of choices, titanium carbide ($\text{Ti}_3\text{C}_2\text{T}_x$) has been the most popular and predominantly employed in practical applications, overwhelming the use of other MXene materials. Based on our work described above, Jiang et al. showed the promising potential of mono- and/or few-layer $\text{Ti}_3\text{C}_2\text{T}_x$ SAs in pulsed laser technologies [54], but which still required sophisticated processes for delamination and dispersion of $\text{Ti}_3\text{C}_2\text{T}_x$ as usual in 2D material application.

On the other hand, concerning the laser spectral range, long-wavelength laser pulses beyond the 1500-nm telecommunication near-infrared regime have recently become of great interest due to their critical role in medical, military, and security technologies. However, many 2D materials are not applicable to this important field due to their inappropriate bandgap sizes or inferior material properties. Particularly, fiber laser systems in the spectral range of 1800–2000 nm have attracted great attention due to its prominent merits as described next. As water has a high absorption rate at 1950 nm, when a 1900-nm laser is irradiated onto biological tissues, ultrafine heating can be attained allowing exquisite tissue cutting in medical applications, compared to 1000 and/or 1500-nm lasers.

Furthermore, lasers of this spectral range can suppress bleeding through coagulation in surgical applications, indicating its superb potential in medical applications. In the aspect of micromachining, most of plastics have remarkable absorption around 2000 nm and thus precise and efficient mechanical processing such as cutting, welding, and marking can be achieved using 1900-nm lasers.

This study is aimed to investigate whether the superb saturable absorption performance of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes could be maintained against significant layer stacking and if it is attained, unveil the origin of this phenomenon. The second goal of this research is to explore whether their spectral range for mode-locking could be extended to the 1900 nm-infrared region. These two factors are both crucial for the development of advanced practical photonic devices based on $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes.

First, we theoretically showed that the electronic and optical properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes are almost unaffected by layer stacking, particularly around the Fermi energy level, due to the intrinsic presence of their unique surface termination, in stark contrast to what observed in other 2D materials such as graphene and MoS_2 . This fact was experimentally validated further by showing that hundreds-of-layer stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs, which are definitely beyond the regime of mono- and/or few-layer 2D materials, can be excellent optical modulators with a large modulation depth and can produce ultrafast pulsed lasers with a duration as short as 897 fs in a fiber cavity, serving as superb mode-lockers in 1914-nm infrared laser applications. These results suggest that highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ could widely serve as material platforms for developing cost-effective, high-performance nanophotonic devices operating at long-wavelength conditions, which include 3000-nm deep infrared or terahertz laser systems.

2 Theoretical electronic and optical characterization

Density functional theory (DFT) calculations were performed for in-depth study of the layer stacking effect on the electronic and optical properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, graphene, and MoS_2 2D materials as implemented in the Atomistic Toolkit package [58, 59]. Specifically, the electronic structures of these three 2D materials were comparatively investigated for their monolayer and bulk-thick forms (Figure 1). The density mesh cutoff energy was set as 150 hartree and the Monkhorst-Pack grid of k-sampling for the electronic structure calculations of

bulk-thick (or monolayer) forms were $6 \times 6 \times 4$ ($6 \times 6 \times 1$), $7 \times 7 \times 5$ ($7 \times 7 \times 1$), and $12 \times 12 \times 3$ ($12 \times 12 \times 1$) for $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, graphene, and MoS_2 , respectively. The optimized dimensions of their hexagonal systems were $6.24 \times 6.24 \times 9.94$ Å, $3.25 \times 3.25 \times 12.89$ Å, and $4.96 \times 4.96 \times 6.87$ Å, respectively. To obtain optical absorption spectra, the susceptibility tensor was first calculated using the Kubo-Greenwood formula shown below [60]:

$$\chi_{i,j}(\omega) = -\frac{e^2 \hbar^4}{m^2 \epsilon_0 V \omega^2} \sum_{n,m} \frac{f(E_m) - f(E_n)}{E_m - \hbar\omega - i\hbar\Gamma} \pi_{nm}^i \pi_{nm}^j \quad (1)$$

where π_{nm}^i is the i -component of the dipole matrix element between states m and n , f is the Fermi function, Γ is the broadening parameter, and V is the volume element. Then, the frequency-dependent dielectric constants are calculated using the relation of $\epsilon(\omega) = 1 + \chi(\omega)$. From the imaginary part of dielectric constants, we finally obtained the optical absorption spectra of the systems.

The Dirac linear dispersion observed in graphene, which can induce massless fermions, has significantly changed to a normal parabolic dispersion upon layer stacking along with the appearance of additional electronic bands. Meanwhile, the electronic band gap of monolayer MoS_2 distinctly decreased upon layer stacking and changed its mode from a direct to indirect transition, as generally seen in 2D transition-metal dichalcogenide (TMDC) semiconductors. In contrast to such considerable electronic variations of graphene and MoS_2 , we found that the electronic band structure of bulk-thick $\text{Ti}_3\text{C}_2\text{T}_x$ remained almost the same as that of monolayer $\text{Ti}_3\text{C}_2\text{T}_x$, particularly at the important region around the Fermi energy level.

$\text{Ti}_3\text{C}_2\text{T}_x$ is composed of a main structural body, which have five atomic layers of Ti–C–Ti–C–Ti, and surface terminations that are located on the top and bottom Ti layers (Figure 2a). We suppose that the above intriguing result stemmed from its intrinsically existing surface

Figure 1: The atomic geometries and electronic band structures of (top) monolayer and (bottom) bulk-stacked forms of (a, d) $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, (b, e) graphene, and (c, f) MoS_2 . The magenta dotted circles marked in (e) indicate the electronic dispersion relation around the Fermi energy level, which changes from (top) a linear to (bottom) parabolic regime upon layer stacking. The magenta arrows marked in (f) indicate electronic transition which changes from (top) a direct and (bottom) indirect mode upon layer stacking, along with distinct quantitative variation.

termination, serving as a buffer-like separator between $\text{Ti}_3\text{C}_2\text{T}_x$ bodies. The electronic density map measured along the top Ti layer of $\text{Ti}_3\text{C}_2\text{T}_x$ indicated that electron distribution around the Ti atoms was almost unaffected by layer stacking (Figure 2b).

Besides the fact that the presence of surface termination can effectively protect the characteristics of MXene monolayer from the influence of other adjacent ones, it is worth noting that surface termination engineering can also be a powerful means to regulate the electronic and/or optical properties of the MXene monolayer itself [21, 22, 61].

The stacking energy of graphene was calculated as $6.898 \text{ meV } \text{\AA}^{-2}$, while that of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was $56.691 \text{ meV } \text{\AA}^{-2}$, which was 8.2 times magnitude larger than

that of graphene. Such a large stacking energy of $\text{Ti}_3\text{C}_2\text{T}_x$ is attributed to hydrogen bonds formed between the surface terminations of adjacent MXene layers, whereas the stacking of graphene is governed by van der Waals interaction. It should be noted that we assumed a rather high density of hydrogen bonds between MXene layers to examine the interlayer bonding effect at a severe condition. Based on the number of hydrogen bonds involved in the layer stacking of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes, the average hydrogen-bond energy was calculated as 46.148 kJ/mol , which is reasonable considering the well-known hydrogen-bond energies of $\text{F-H}\cdots\text{F}$ ($161.5 \text{ kJ mol}^{-1}$) and $\text{O-H}\cdots\text{O}$ (21 kJ mol^{-1}), validating our computation method. Meanwhile, the van der Waals bond energy of the stacked

Figure 2: The electron density distribution, optical properties, and height profiles of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes.

(a) The layer-wise description of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene structure. (b) The calculated electron density maps (measured along the top Ti layer) and (c) the optical absorption spectra of monolayer and highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes. (d) The SEM image of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ flakes, clearly exhibiting the appearance of bulk-thick layer stacking when they are located vertically. (e) The height profiles of $\text{Ti}_3\text{C}_2\text{T}_x$ flakes measured using AFM.

graphene system was evaluated as small as 1.773 kJ/mol, showing an excellent agreement with the reported values of 1.112 and 1.717 kJ mol⁻¹ for AA and AB stacking of graphene, respectively. It is noteworthy that surface termination can offer a good interlayer mechanical stability of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes.

In order to further support the robust layer-independent photonic operation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, we also performed DFT calculations on the optical absorption behaviors of monolayer and bulk-thick $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes, and observed that the optical absorption properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was well conserved against layer stacking (Figure 2c). Based on these theoretical results, we suppose that as-obtained highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene could serve as a superb nanophotonic platform in a wide range of engineering applications, providing a character-conserved, tightly packed 2D material assembly with a good mechanical stability. For the experimental investigation of optical absorption, we also performed an IR spectrum measurement although it may not be exactly the same with the theoretical calculation because an IR spectrum includes atomic vibration, randomly oriented illumination onto MXene planes and so on. However, estimation for the range of significant optical absorption (or qualitative analysis) would be possible. Indeed, using an IR measurement, we were able to confirm significant optical absorption of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in the range of 400–2200 nm (Figure S1 in Supplementary Material).

3 Material and device preparation

For our experiments, we used commercially available $\text{Ti}_3\text{C}_2\text{T}_x$ MXene materials (Invisible Inc.) which was made by selective etching of Al atomic layers from Ti_3AlC_2 MAX materials using a HF solution followed by repeated centrifuging and decanting. Details of the MXene synthesis can be found elsewhere [21, 22]. The XPS measurement of these samples showed the typical peaks of $\text{Ti}_3\text{C}_2\text{T}_x$ (Figure S2 in Supplementary Material). For the preparation of MXene flakes suitable for our research, we mildly sonicated the MXene samples in deionized water (3000 rpm for 30 min) to obtain highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ flakes, which were thick enough to be beyond the 2D nanomaterial regime, but also sufficiently small to make a homogeneous film coating (Figure 2d). The aqueous solution of these $\text{Ti}_3\text{C}_2\text{T}_x$ flakes (~1 mg mL⁻¹) was dropped onto a slide glass and dried in air for 24 h for characterization using atomic force microscopy (AFM). The AFM analysis showed that the thickness and lateral dimension of the $\text{Ti}_3\text{C}_2\text{T}_x$ flakes spanned over 80–800 nm and 0.5–5 μm , respectively (Figure 2e).

This measured thickness corresponds to tens or hundreds of $\text{Ti}_3\text{C}_2\text{T}_x$ layer stacking because the thickness of $\text{Ti}_3\text{C}_2\text{T}_x$ monolayer is known as 0.98 nm, ensuring that the obtained $\text{Ti}_3\text{C}_2\text{T}_x$ flakes are definitely beyond the mono- or few-layered 2D material regime. The $\text{Ti}_3\text{C}_2\text{T}_x$ solution was then mixed with polyvinyl alcohol (PVA, 10 mg for the solution of 1.5 mL) and drop-cast onto a side-polished fiber device which had been prepared with a careful control of the side-to-core depth to be 6 μm for efficient evanescent coupling between $\text{Ti}_3\text{C}_2\text{T}_x$ SAs and the laser inside the fiber cavity.

The minimum insertion loss and polarization-dependent loss of this $\text{Ti}_3\text{C}_2\text{T}_x$ -deposited fiber-optic device were measured as 5.2 and 2.0 dB, respectively, at a wavelength of 1900 nm, ensuring tolerable optical losses. The insertion loss indicates the power loss resulting from the addition of the fiber device to the system. This loss can vary depending on the laser polarization, from which the concept of polarization-dependent loss comes out and it means the difference between the minimum and maximum insertion losses. The symmetry of the fabricated device is significantly broken due to side-polishing of the fiber and thus, the loss of this device is greatly polarization-dependent. To measure the polarization-dependent loss of the $\text{Ti}_3\text{C}_2\text{T}_x$ -deposited side-polished fiber optical device, we placed a polarization controller (PC) between a reference input beam source and the fabricated device and measured the variation of output loss as gradually changing the input beam polarization using the PC.

4 Nonlinear optical absorption performance

In order to experimentally validate our theoretical prediction for the superb photonic performance of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, we investigated the intensity-dependent optical transmission behavior of the fiber-optic device whose polished side was deposited with the PVA-mixed $\text{Ti}_3\text{C}_2\text{T}_x$ film (Figure 3a and b) as described in the previous section. The following formula was used for the fitting of the nonlinear optical transmission curve of the $\text{Ti}_3\text{C}_2\text{T}_x$ SA device [62]:

$$T(I) = 1 - \Delta T \exp\left(\frac{-I}{I_{\text{sat}}}\right) - T_{\text{ns}} \quad (2)$$

where $T(I)$ is the transmission, ΔT is the modulation depth, I is the input pulse energy, I_{sat} is the saturation energy, and T_{ns} is the nonsaturable loss. Noticeably, significant nonlinear optical absorption has occurred in

the $\text{Ti}_3\text{C}_2\text{T}_x$ SA device for the input of a 0.887-ps mode-locked laser pulses with a wavelength of 1900 nm and a repetition rate of 36.94 MHz. The saturation intensity of the $\text{Ti}_3\text{C}_2\text{T}_x$ SA device was 18.6 MW/cm^2 and its modulation depth was measured as high as 15% (Figure 3c), indicating the superb modulation performance of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs.

Figure 3: The nonlinear optical absorption behavior of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes. (a) The photo image and (b) schematic cross-sectional image of an optical fiber device whose side-polished surface was deposited with highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs. (c) The experimentally measured nonlinear optical transmission curve of the $\text{Ti}_3\text{C}_2\text{T}_x$ -deposited, side-polished fiber device.

5 Laser mode-locking performance

Besides nonlinear optical transmission properties, another important characteristic of SAs is passive mode-locking for ultrafast pulsed laser production, which has particularly been of great interest for the advance of long-wavelength laser technologies including 1.9- μm infrared region in recent years. In order to explore the mode-locking potential of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs,

We fabricated a ring-cavity Tm-Ho-codoped fiber laser system incorporated with the prepared fiber-optic device whose polished side was deposited with hundreds-of-layer stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs. The schematic of our laser system is depicted in Figure 4a. Noticeably, mode-locked femto-second laser pulses were readily generated by controlling the pump power with careful tuning of the polarization. Most of components in our laser system are not (or weakly) polarization-dependent, however, the $\text{Ti}_3\text{C}_2\text{T}_x$ SA device component is symmetry-broken due to side-polishing (Figure 3b) and thus, highly polarization-dependent. Consequently, a PC was required in our laser system to find an optimal condition of evanescent interaction between the SA and the laser beam for proper mode-locking operation, which can be achieved by gradually changing the polarization state of the laser beam using the PC (Figure 4a).

The output power of mode-locked lasers was 12.5 mW at a pump power of 274 mW. The period and repetition rate of the output pulses were measured as 59.6 ns and 16.77 MHz, respectively, which were compatible with the round-trip time and fundamental resonance frequency of the 12.33-m fiber cavity of our laser system (Figure 4d). The optical spectrum of the output pulses and the sech^2 fitting curve for solitons showed that the center wavelength and 3-dB bandwidth were 1913.7 and 4.33 nm, respectively (Figure 4b). From the analysis using a two-photon absorption-based autocorrelator, the temporal width of the output pulses was measured as short as 897 fs (Figure 4c), indicating the generation of femtosecond pulsed laser. Noticeably, the time-bandwidth product was 0.318, achieving almost transform-limited pulses. The electrical spectrum showed a sharp peak at a fundamental repetition rate of 16.77 MHz with a signal-to-noise ratio of 66 dB (Figure 4e), indicating that quite stable mode-locked lasers were successfully produced using highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs.

The previous study for mode-locked lasers using a nanoscale few-layered $\text{Ti}_3\text{C}_2\text{T}_x$ SA at the wavelength of 2000 nm [63] showed a larger pulse width (2.18 ps) than that (897 fs) of this study using a bulk-thick $\text{Ti}_3\text{C}_2\text{T}_x$

Figure 4: Laser mode-locking performance of highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ SAs.

(a) The schematic of the ring-cavity Tm-Ho-codoped fiber laser system. (b) The optical spectrum, (c) autocorrelation trace, (d) oscilloscope trace, and (e) electrical spectrum of output laser pulses. WDM, LD, SNR, and RBW denote wavelength division multiplexing, laser diode, signal to noise ratio, and resolution bandwidth, respectively.

SA. Hence, we conclude that, at least highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ can be as a good SA as nanoscale few-layered $\text{Ti}_3\text{C}_2\text{T}_x$ and comparison of current results even indicates its better performance. We also compared the nonlinear optical absorption and mode-locking characteristics of a highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene SA with those of various other SA materials at the wavelength of 1.8–2.0 μm and convinced its excellent performance as summarized in the Table 1.

6 Conclusions

For the first time, using a combined theoretical and experimental approach, we showed that $\text{Ti}_3\text{C}_2\text{T}_x$ MXene can well preserve its electronic and optical characteristics

against severe layer stacking and thus, highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene can serve as an excellent SA and/or mode-locker for 1.9- μm infrared optical switching and/or ultrafast pulsed laser production. The highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXene SA has the modulation depth as high as 15% and readily produced mode-locked femtosecond pulsed lasers with a duration as short as 897 fs at the wavelength of 1914 nm in a ring fiber cavity. Theoretical calculations indicated that intrinsically existing surface terminations play a decisive role in this stacking-independent photonic performance of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes.

By employing highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes in photonic applications, we can not only avoid complicated processes for delamination and dispersion of 2D materials, but also provide characteristic-conserved, tightly assembled 2D material platforms for advanced nanophotonic

Table 1: Output performance comparison of mode-locked fiber lasers using various SAs which include CNTs, 2D materials, gold nanorods, and topological insulators at the wavelength of 1.8–2.0 μm .

Saturable absorption materials	Fiber platform	Output wavelength (nm)	Repetition rate (MHz)	Modulation depth (%)	Saturation level	Pulse width (ps)	Refs.
CNTs	Fiber ferrule	1930	37	NA	NA	1.32	[64]
CNTs	Tapered fiber	1885	45	NA	NA	0.75	[65]
CNTs	Fiber ferrule	1870	45.5	NA	NA	0.45	[66]
Graphene	Fiber ferrule	1940	6.46	NA	NA	3.6	[67]
Graphene	Fiber ferrule	1935	16.937	NA	NA	2.1	[68]
Graphene	Fiber ferrule	1876	41.46	4	110 $\mu\text{J}/\text{cm}^2$	0.603	[69]
GO	Side-polished fiber	1950	33.25	7.1	14.38 W	0.59	[70]
Bi_2Te_3	Tapered fiber	1909.5	21.5	9.8	NA	1.26	[71]
Bi_2Te_3	Side-polished fiber	1935	27.9	20.6	29 W	0.795	[72]
Bi_2Se_3	Side-polished fiber	1912.12	18.37	13.4	28.6 W	0.835	[73]
Sb_2Te_3	Side-polished fiber	1945	39.5	NA	NA	0.89	[74]
Sb_2Te_3	Side-polished fiber	1930.07	14.51	38	3.3 MW/cm^2	1.24	[75]
MoS_2	Gold mirror	1905	9.67	13.6	23.1 MW/cm^2	843	[76]
MoS_2	Fiber ferrule	1927	13.9	12.5	108.7 MW/cm^2	1.51	[77]
WS_2	Side-polished fiber	1941	34.8	10.9	1.9 W	1.3	[78]
WS_2	Tapered fiber	1916	15.49	8.2	820 MW/cm^2	0.825	[79]
MoSe_2	Side-polished fiber	1912.6	18.21	4.4	25.7 W	0.92	[80]
MoSe_2	Fiber ferrule	1943.35	25.53	4.98	168.6 MW/cm^2	0.98	[81]
WSe_2	Microfiber	1863.96	11.36	1.83	3.7 MW/cm^2	1.16	[82]
MoTe_2	Microfiber	1930.22	14.353	5.7	8.3 MW/cm^2	0.952	[83]
Gold nanorods	Fiber ferrule	1982	37.49	4.1	35.5 MW/cm^2	4.02	[84]
BP	Fiber ferrule	1910	36.8	4.1	NA	0.739	[85]
CoSb_3	Side-polished fiber	1912.9	16.94	10	21 W	0.838	[86]
Highly stacked $\text{Ti}_3\text{C}_2\text{T}_x$	Side-polished fiber	1913.7	16.77	15	18.6 MW/cm^2	0.897	This work

NA: Not Available. Saturation level units of $\mu\text{J}/\text{cm}^2$, W, and MW/cm^2 are for saturation fluence, saturation power, and saturation intensity, respectively.

performance. This work suggests that the application of this work would not be limited to SAs, but also could be extended to numerous other photonic areas, providing many useful insights into the design of nanophotonic systems based on MXene 2D materials.

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