TOPICAL REVIEW

Two-dimensional transition metal dichalcogenides based composites for microwave absorption applications: a review

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Abstract
Two-dimensional structural transition metal dichalcogenides (2D TMDs) have the advantages of superb thermal and chemical stability, distinctive layered structures, and ultrathin thicknesses, which make them potential candidates in the microwave absorption field. The recent progress in 2D TMDs and their composite nanomaterials with enhanced microwave absorption performance are reviewed here. The synthesis methods, and the microwave absorption properties, including the maximum reflection loss value and effective absorption bandwidth of various 2D TMD nanocomposites, are described in detail. Furthermore, the current challenges and future prospects for the development of 2D TMDs are raised.

1. Introduction

With the advancement of fifth-generation technology, wireless communication and electronic devices have begun to flood people’s lives unconsciously. This phenomenon has caused serious electromagnetic leakage and interference pollution [1–5], and also proved to be insalubrity. Hence, the control of electromagnetic radiation and pollution is imminent. For the purpose of maintaining green sustainable development, protecting human health, and information security, researchers have devoted themselves to explore electromagnetic (EM) wave absorbing material with excellent properties [6–8]. It is of vital importance to easily synthesize thin, lightweight, economical, and high-performance EM wave absorbers with strong absorption and wide absorption bandwidth [9–12]. Plenty of absorbers, including dielectric absorbing materials, such as conducting polymers, carbonaceous materials, and ceramics, as well as magnetic-loss type absorbers, such as ferrites, have been extensively studied. However, it is always difficult for a unary-functional absorbent material to meet all the requirements of a rigorous microwave absorption application. It is well known that the structure of absorbent materials will strongly affect their absorbing performances. Two-dimensional (2D) materials exhibit satisfactory absorbing properties due to their potential to provide high interfacial polarizations. In addition, 2D materials can form conductive networks in the matrix at a relatively low filler loading level. In another word, thanks to the materials’ high aspect ratio, the percolation threshold in 2D material-based absorbing system are relatively low, which is beneficial for making lightweight and thinner absorbing layer in real application occasions [13, 14].

As a typical class of 2D materials, transition metal dichalcogenides (TMDs) could be utilized in many applications, including photodetectors, field effect transistors, sensors [15–20], and electrochemical energy storage [21–26]. Meanwhile, few-layer 2D TMDs have higher specific surface area than bulk TMDs. Thus, 2D TMDs are promising for EM wave absorption and shielding applications due to their characteristics of good electrical properties, high surface chemical activity, and suitable bandgap [27–30].

In 2D TMDs, transition metals typically exhibit a valence of +4, and chalcogens have a valence of −2. The electrons in the transition metal d orbitals have various arrangements, which makes the configurational changes of 2D TMDs rich [32], and the stability of different configurations vary greatly. According to their
different atomic arrangements, 2D TMD can be divided into 2H-TMD materials with semiconductor properties, 1T-TMD materials with metallic properties, and 1T′-TMD materials with topological properties [33, 34]. Some scholars have characterized large-scale WS$_2$ nanosheets containing mixed 2H and 1T phases (1T@2H WS$_2$) and 2H WS$_2$ by x-ray diffraction (XRD) and Raman spectroscopy (Raman) [31]. As shown in figure 1, the results of 1T@2H WS$_2$ have prominent multi-phase characteristics compared with 2H-WS$_2$. However, the loss mechanism of unary 2D TMDs is single, making its ability of attenuating EM waves limited. As a result, the wave absorption performance of 2D TMDs needs to be further improved.

Therefore, 2D TMDs are compounded with other materials to reduce the absorbing materials’ density, increase the attenuation mechanism of the material, improve the attenuation performance, and widen the width of the absorbing band. This paper reviews the research progress of 2D TMDs and their composites in the microwave absorption field. Firstly, the basic theory of microwave absorption is briefly introduced, including impedance matching and the related principles of attenuation characteristics. Then, the synthesis methods of 2D TMDs composites and their microwave absorption properties are discussed. Figure 2 shows several typical materials compounding with 2D TMDs for EM wave absorption, including carbon, conductive polymers, MXene, metal, and metal oxides. At the end of this paper, the current challenges and future development prospects of 2D TMDs composite in microwave absorption are discussed.

2. Microwave absorption theories

The EM wave entering on the surfaces of the material will undergo three different pathways: reflection, absorption, and transmission [35].

Figure 3 shows the reflection and absorption of EM waves by an absorber. The reflection of EM waves is mainly due to the mismatch of the surface impedance of the incident medium. The more significant the
impedance difference between the interfaces, the more EM waves are reflected. The absorption property of the EM wave incident into the material depends on the EM loss characteristic of the material itself. Usually, complex permittivity ($\varepsilon_r$), complex permeability ($\mu_r$), and attenuation constant ($\alpha$) are used to characterize the loss characteristics of the material. Therefore, to maximize the attenuation of EM waves, two principles must be satisfied [35, 36]: impedance matching and attenuation characteristics.

2.1. Impedance matching

It is necessary to make as much EM waves enter the material as possible, which depends on the impedance matching of the incoming wave between the absorbing material and the free-space interface, that is, the impedance matching characteristics [37]. The EM wave may be lost only when it enters the material, so impedance matching is the priority factor to improve the material’s absorbing performance. When the EM wave is irradiated from the free space with impedance $Z_0$ to the surface of the lossy medium with input impedance $Z_{in}$, the EM wave may be reflected and transmitted. The critical factor of how much EM wave is transmitted is whether the impedance is matched. Impedance matching degree ($|\Delta|$) could be calculated based on equation (1) [38]:

$$|\Delta| = |\sinh^2 (Kfd - M)| \quad (1)$$

where the two parameters, $M$ and $K$, could be calculated from permittivity and permeability:

$$K = 4\pi \sqrt{\mu'\varepsilon'} \cdot \sin \left( \frac{\varepsilon''/\varepsilon'\mu''/\mu'}{2} \right) / c \cdot \cos (\varepsilon''/\varepsilon') \cdot \cos (\mu''/\mu') \quad (2)$$

$$M = 4\mu'\varepsilon' \times \cos (\varepsilon''/\varepsilon') \times \cos (\mu''/\mu') / (\mu' \cos (\varepsilon''/\varepsilon') - \varepsilon' \cos (\mu''/\mu'))^2$$

$$+ \left[ \tan \left( \frac{\varepsilon''/\varepsilon' - \mu''/\mu'}{2} \right) \right]^2 (\mu' \cos (\varepsilon''/\varepsilon') + \varepsilon' \cos (\mu''/\mu'))^2 \quad (3)$$

where $\varepsilon'$ and $\varepsilon''$ are the real and imaginary part of $\varepsilon_r$, respectively; $\mu'$ and $\mu''$ are the real and imaginary part of $\mu_r$, respectively; and $c$ is the vacuum speed of light.

If $|\Delta|$ is close to zero at a given thickness, the impedance matching is satisfactory; otherwise, it is not. In addition, EM waves of specific wavelengths can also be attenuated by interferometric phase elimination. That is to say, absorbers can attenuate incident EM waves through special boundary conditions. The EM wave of a specific frequency will be reflected when the thickness $d$ of the absorbing materials is equal to an odd multiple of $(1/4)\lambda$ of the incident wave [39]. Also, the waves will be canceled utilizing coherent destructive interference. The quarter-wavelength wave theory is exhibited in equation (4) [40]:

$$d = \left( \frac{n}{4} \right) \lambda_0/(|\varepsilon_r||\mu_r|)^{1/2} \quad n = 1, 3, 5, 7 \ldots \quad (4)$$

where $d$ is the matching thickness, $f$ is the test frequency, and $c$ is the propagation rate of EM waves in vacuum. By adjusting the thickness of the absorbing layer, the phase difference between the surface and the bottom of the absorbing layer can be modulated. When the phase difference is an odd multiple of the half wavelength, the phases of the two waves are opposite. Under the circumstances, the interference shall cancel each other out, thus achieving the purpose of attenuating EM waves.
2.2. Attenuation characteristics

After the absorbing material satisfies the impedance matching principle, most of the EM waves can enter the material. Then it is necessary to rely on the material itself to lose EM waves to reduce the EM waves radiating outward, and the loss performance of the material is determined by \( \varepsilon_r \) and \( \mu_r \). The real part permittivity and permeability represent the ability of a material to store electrical and magnetic energy, respectively. In comparison, the imaginary part permittivity and permeability represent the ability of a material to lose electrical and magnetic energy, respectively. Thus, the attenuation ability for EM waves is mainly determined by \( \varepsilon'' \) and \( \mu'' \).

To quantify the loss capacity of materials, dielectric loss tangent and magnetic loss tangent are introduced:

\[
\tan \delta_\varepsilon = \frac{\varepsilon''}{\varepsilon'} \tag{5}
\]

\[
\tan \delta_\mu = \frac{\mu''}{\mu'} \tag{6}
\]

Theoretically, the higher the dielectric loss tangent and the magnetic loss tangent, the stronger the material’s ability to attenuate EM waves. However, blindly enhancing \( \varepsilon'' \) and \( \mu'' \) would deteriorate the impedance matching degree and is counterproductive to the overall absorption ability. In practical applications, various factors should be comprehensively considered to design and prepare wave-absorbing materials that meet the requirements of ‘thin, lightweight, wide-bandwidth, and strong absorption’. The realization of the attenuation characteristics of the material requires that the EM parameters meet specific requirements. The absorbing ability of a material is usually measured by the reflection loss (RL). RL shall be calculated from equations (7) and (8) [41]:

\[
\text{RL (dB)} = 20 \log_{10} \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \tag{7}
\]

\[
Z_{in} = Z_0 \sqrt{\mu_r \varepsilon_r \tan \frac{2\pi fd}{c} \sqrt{\mu_r \varepsilon_r}} \tag{8}
\]

in which \( Z_{in} \) and \( d \) are the input impedance and thickness of the absorbent material, respectively; \( c \) and \( f \) are the vacuum speed of light and frequency, respectively. The larger the value of RL is, the better the material absorbs EM waves. Generally, when the RL value is less than \(-10\) dB, the absorption can reach 90%, which is called effective absorption. The effective absorption frequency range an absorbent could cover is referred to as effective absorption bandwidth (EAB).

Besides RL value, according to the principle of microwave transmission, the specific amount of attenuation of EM waves by the material can be expressed by \( \alpha \), the attenuation coefficient, which is defined and calculated as follows [42]:

\[
\alpha = \left( \sqrt{2\pi f/c} \right) \times \sqrt{\left( \mu''\varepsilon'' - \mu'\varepsilon' \right)^2 + \left( \mu''\varepsilon' - \mu'\varepsilon'' \right)^2 + \left( \varepsilon'\mu'' - \varepsilon''\mu' \right)^2} \tag{9}
\]

where \( f \) is the frequency of the incident EM wave, and \( c \) is the speed of the EM wave in the vacuum.

Theoretically, the larger the \( \alpha \), the higher the attenuation efficiency of the material is. In summary, the absorbing ability of a material is determined by the impedance matching and attenuation characteristics, and its absorption efficiency is often measured by RL value.

3. Microwave absorption properties of 2D TMD-based nanomaterials

Nowadays, 2D TMDs, such as WS\(_2\) and MoS\(_2\), are favored by researchers because of their large specific surface area, good electrical properties, as well as appropriate surface chemical activity. But the loss mechanism of these 2D TMDs is single. Therefore, composite treatment with other materials has become an effective way to improve the EM wave absorbing ability of 2D TMD-based microwave absorbers.

3.1. 2D TMD nanomaterials for microwave absorption

When pure 2D TMDs nanosheets are used as microwave absorbing materials without any composite treatment, it is challenging to apply them in real applications. For example, Zhang et al have successfully prepared WS\(_2\) nanosheets by hydrothermal method. When used as an EM wave absorber with a filler loading of 40 wt.%, the strongest RL is \(-15.6\) dB at a thickness of 5.5 mm, needing further improvements [43].
Structural and phase manipulation have shed some light on improving the comprehensive absorbing capabilities of pure 2D TMDs. By controlling the structural phase of WS₂ by facile hydrothermal method, Ding and co-workers show that the existence of 1T phase WS₂ has obviously improved the microwave absorption ability compared to the 2H phase (figures 4(a)–(e)) \[31\]. An RL value of $-47$ dB with an EAB of 5.2 GHz (figures 4(f)–(i)) was delivered by 1T-phase WS₂ when the filler loading was 35 wt.%. Ning et al have prepared MoS₂ nanosheets by liquid exfoliating the bulk MoS₂ counterpart, and compared the dielectric and microwave absorbing properties of MoS₂ nanosheets and bulk MoS₂. The results show that the $\varepsilon''$ value of the MoS₂ nanosheets is twice of its bulk precursor, and the minimum RL of MoS₂ nanosheets reached $-38.42$ dB with an EAB of 4.1 GHz at a thickness of 2.4 mm, which is four times higher than that of bulk WS₂ \[44\]. They attributed the absorbing capability enhancement of MoS₂ nanosheets over bulk MoS₂ to the improved specific surface area and the defect dipole polarization arising from S and Mo vacancies. However, MoS₂ nanosheets are prone to stack during the mixing process with the matrix material when used as an absorber. The stacking process will reduce the specific area, as well as cover up the S and Mo vacancies. Meanwhile, from the view of dielectric percolation, unary TMD nanosheets are not the ideal candidate to improve the absorber’s dielectric property for its high threshold to achieve percolation. For example, at a relatively high filler loading of 60 wt.%, the optimal absorbing performance is achieved in the case as mentioned above by Ning.

To overcome the stacking disadvantage of bare 2D nanosheets, Liang et al have assembled MoS₂ nanosheet flowers by a hydrothermal method, and the maximum RL can reach $-47.8$ dB at 12.8 GHz at a filler loading of 60 wt.% \[45\]. To further modulate the phase structure of MoS₂-based absorber, Ning and co-workers have prepared MoS₂ flower absorber with a mixed 2H/1T phase and proposed that the mixed phase has structural advantages over pure 2H phase \[46\]. The results show that when the content ratio of 1T phase and 2H phase is 1:1, and the filler loading is 50 wt.%, the microwave absorption performance is the best. When the thickness reaches 3.5 mm, the RL$_{\text{min}}$ value is $-45.5$ dB and the EAB is 3.89 GHz.

The composite material containing more than one kind of TMDs can introduce many phase interfaces, which can improve the multiple reflection and loss of microwaves, thereby improving the absorption capacity.

Xing et al have prepared a three-dimensional (3D) layered MoS₂/FeS₂ composite by a hydrothermal method. The off-axis electron hologram analysis shows the charge density and local electric field distribution in the heterojunction area of MoS₂ and FeS₂ (figures 5(a)–(f)). The existence of the local electric field increases the interface polarization loss capability. When the thickness is only 2 mm (with a filler loading of 50 wt.%), the RL$_{\text{min}}$ value is $-60.2$ dB, and the EAB is 6.48 GHz \[47\].

Zhang et al have successfully synthesized NiS₂@MoS₂ nanospheres with a core–shell structure by a facile hydrothermal method. Due to the synergistic effect and impedance matching properties of the two TMD materials, the RL$_{\text{min}}$ of the absorber can reach $-41.05$ dB at 12.08 GHz, and the EAB is 4.4 GHz at 2.2 mm thickness \[48\]. It is worth noting that the filler loading, in this case, is only 20 wt.%.

As summarized in table 1, it can be concluded that it is challenging for unary TMD to deliver strong RL and wide-band absorption at the same time. Things become better in the case of binary TMD-based absorbers. For example, the MoS₂/FeS₂ absorber has delivered an RL$_{\text{min}}$ of $-60.20$ dB and an EAB of

![Figure 4. (a) Crystal structures of 1T and 2H WS₂, (b)–(e) TEM and HRTEM images of 2H WS₂ and 1T@2H WS₂. (f)–(i) RL at different thicknesses and 3D maps of 1T@2H WS₂ and 2H WS₂. Reprinted from [31], with the permission of AIP Publishing.](image)
6.48 GHz [47]. However, the similar loss mechanism in TMDs still limits the real application of pure TMD-based absorbers.

3.2. 2D TMD/carbon nanomaterials for microwave absorption
Carbon-based nanomaterials have attracted researcher’s attention because of their stable physical and chemical properties, lightweight, and large specific surface area [49, 50]. However, due to the insufficient attenuation and mismatch of characteristic impedance when used as absorbers, the microwave absorbing ability of carbon-based materials is not ideal [51]. Therefore, combining TMDs with carbonaceous materials (hollow spheres, fibers, graphene, and biomass carbon materials, for instance), could utilize the advantages of the two to obtain microwave absorbers with more impressive absorption properties.

3.2.1. WS$_2$/carbon nanomaterials for microwave absorption
As typical carbon materials, graphene and carbon nanotubes (CNTs) are good absorbing or shielding materials due to their stable properties, extremely low density, and large specific surface area [52–55]. However, it is challenging to obtain graphene or CNTs with good dispersibility, which limits their development to a certain extent [56]. Therefore, nano-sized carbonaceous materials (CNTs or graphene, for instance) with good dispersibility tend to perform better in practical applications [57, 58]. WS$_2$ sheet-like structure material has shown excellent performance in EM wave absorption [31, 43]. In situ incorporation of WS$_2$ with carbon-based nanomaterials can improve the dispersibility of the material, creating microwave absorbing material with excellent performances [59].

For example, as shown in figure 6(a), Zhang et al have used a simple hydrothermal method to synthesize WS$_2$-NS/CNTs [60]. The flower-shaped WS$_2$-NS grows uniformly on the surface of CNTs (figure 6(b)). The researchers obtained microwave absorbers with better absorbing properties by tuning the amount of CNTs. The results show that when the filler loading is 60 wt.%, the RL$_{\text{min}}$ value is $-51.6$ dB at 14.8 GHz, and the corresponding EAB has reached 5.4 GHz (figure 6(c)).

As shown in figure 7(a), Piao et al have synthesized WS$_2$ nanosheets with single-walled CNTs by another solvothermal approach (figures 7(b) and (c)) [61]. At a filler loading of 50 wt.%, the minimum RL can reach up to $-66$ dB at a frequency of 8.3 GHz and a corresponding thickness of 2.2 mm. By comparing the aforementioned two cases, it is found that the 1T-WS$_2$/SWCNTs delivered stronger absorbing behavior than that of WS$_2$-NS/CNTs. We suspect that the flower-like 1T-WS$_2$/SWCNTs with a lager diameter ($\sim$1 μm) are prone to form a more robust 3D interconnect network in the wax matrix with a lower percolation threshold to endow its dielectric character on the whole composite. While in the case of WS$_2$-NS/CNTs, WS$_2$ nanosheets with smaller diameters are anchored on the surfaces of CNTs, forming 1D hybrid fiber-like composite with a diameter of $\sim$100 nm. The fiber-like composites are prone to tangle with each other, making the 3D network in the wax matrix not as robust as the case in the larger flower-like model, thus not reaching the full dielectric modulation potential of WS$_2$-NS/CNTs.

Figure 5. (a) TEM imagine of the MoS$_2$/FeS$_2$, (b) off-axis electron holograms of cutting sections, (c) electric potential diagram, (d) charge density distribution, (e) local electric field distribution, (f) the profile of charge density and local electrical field. Reprinted from [47], Copyright (2020), with permission from Elsevier.
| Section | Type | Value (dB) | $f_m$ (GHz) | Thickness (mm) | EAB (<10 dB) (GHz) | Filler loading (wt.%) | References |
|---------|------|-----------|-------------|---------------|-------------------|----------------------|------------|
| § 3.1 2D TMD nanomaterials | WS$_2$ | –15.60 | 5.50 | 5.50 | — | 40% | [43] |
| | MoS$_2$-NS | –38.42 | — | 2.40 | 4.10 | 60% | [44] |
| | MoS$_2$ | –47.80 | 12.80 | 2.20 | 5.20 | 35% | [31] |
| | MoS$_2$-1T-50% | –45.50 | — | 3.50 | 3.89 | 50% | [46] |
| | MoS$_2$/FeS$_2$ | –60.20 | 8.08 | 2.00 | 6.48 | 50% | [47] |
| | NiS$_2$/MoS$_2$ | –41.05 | 12.08 | 2.20 | 4.40 | 20% | [48] |
| | Ni$_3$S$_4$/SnS$_2$/C | –52.97 | 14.92 | 1.57 | 4.80 | 25% | [78] |
| § 3.2 2D TMD/carbon nanomaterials | WS$_2$-NS/CNTs | –51.60 | 14.80 | 1.95 | 5.40 | 60% | [60] |
| | MoS$_2$/CNT | –66.00 | 8.30 | 2.20 | — | 50% | [61] |
| | WS$_2$-rGO | –41.50 | 9.50 | 2.70 | 3.50 | 40% | [62] |
| | WS$_2$/BDC | –51.40 | 5.52 | 4.50 | 3.92 | 40% | [64] |
| | MoS$_2$/C | –44.67 | — | 1.40 | 3.32 | 30% | [2] |
| | MoS$_2$/HCS | –65.00 | — | 2.00 | 5.00 | 60% | [65] |
| | MoS$_2$/graphene | –41.90 | 16.10 | 2.40 | 5.60 | 30% | [71] |
| | MoS$_2$/RGO | –55.00 | — | 2.20 | 6.96 | 20% | [72] |
| | MoS$_2$/RGO | –49.41 | 8.72 | 2.52 | 4.45 | 40% | [29] |
| | MoS$_2$/EG | –25.30 | 15.10 | 1.6 | 4.10 | 7% | [73] |
| | rGO@Ni-MoS$_2$ | –40.00 | 11.00 | 2.00 | 5.00 | 40% | [87] |
| | WSe$_2$/CNTs | –60.10 | 13.92 | 6.61 | 4.24 | 50% | [74] |
| | MoS$_2$/C | –43.10 | — | 1.70 | 6.20 | 60% | [75] |
| | MoS$_2$ | –53.33 | 10.64 | 3.06 | 4.04 | 20% | [77] |
| | MoS$_2$ | –66.84 | 16.96 | 2.13 | — | 20% | [77] |
| | BC/MoS$_2$ | –59.60 | 9.10 | 2.80 | 9.20 | 30% | [76] |
| § 3.3 2D TMD/metal nanomaterials | MoS$_2$/Co | –55.00 | — | 3.00 | 4.00 | 60% | [1] |
| | Ni/MoS$_2$ | –30.39 | 14.72 | 2.00 | 4.72 | 40% | [88] |
| | FeNi$_2$/RGO/MoS$_2$ | –37.02 | — | 2.00 | 4.73 | 60% | [86] |
| | Fe@MoS$_2$ | –64.64 | 14.40 | 2.00 | 7.20 | 55vol.% | [91] |
| | FeCo/MoS$_2$ | –35.83 | 5.83 | 5.00 | 4.56 | 50% | [90] |
| § 3.4 2D TMD/metal oxides nanomaterials | WS$_2$/TiO$_2$ | –43.90 | 5.12 | 2.00 | 4.70 | 40% | [30] |
| | WS$_2$/NiO | –53.31 | 7.12 | 4.30 | 4.88 | 40% | [92] |
| | MoS$_2$/CoO$_x$ | –43.56 | 6.96 | 4.00 | 4.76 | 40% | [95] |
| | Fe$_2$O$_3$/MoS$_2$ | –47.30 | — | 2.70 | 5.80 | — | [79] |
| | MoS$_2$-Fe$_2$O$_3$/C | –64.00 | — | 1.70 | 6.10 | 50% | [89] |
| | MoS$_2$-Fe$_2$O$_3$/graphene | –53.03 | 14.40 | 7.86 | 7.40 | 30% | [103] |
| | MoS$_2$-Fe$_2$O$_3$/CT | –45.80 | 5.90 | 2.50 | 7.40 | — | [104] |
| | MoS$_2$-Fe$_2$O$_3$/Fe$_2$O$_4$/ | –62.00 | — | 2.09 | 6.80 | 8% | [96] |
| | MoS$_2$-Fe$_2$O$_3$/ | –59.27 | — | 1.80 | 5.86 | 50% | [97] |
| | ZnFe$_2$O$_4$/MoS$_2$ | –61.80 | 9.50 | 3.00 | 5.80 | 20% | [105] |
| | CuFe$_2$O$_4$/MoS$_2$ | –49.43 | 10.40 | 2.70 | 8.16 | 30% | [106] |
| | MoS$_2$/Bi$_2$Fe$_3$O$_9$ | –52.30 | 12.40 | 2.80 | 5.00 | 30% | [109] |
| | CoFe$_2$O$_4$/1T/2H-MoS$_2$ | –68.50 | 13.20 | 1.81 | 4.56 | 40% | [110] |
| § 3.5 2D TMD/polymer nanomaterials | Co$_9$Fe$_{24}$O$_4$/MoS$_2$ | –79.90 | 11.20 | 2.73 | 5.92 | 50% | [111] |
| | Co$_9$Fe$_{24}$O$_4$/ | –66.83 | 17.16 | 1.57 | 6.64 | 60% | [112] |
| | MoS$_2$/PANI-NPs | –44.80 | 14.50 | 1.60 | 2.40 | 60% | [116] |
| | PANI@MoS$_2$/Fe$_3$O$_4$ | –49.70 | — | 1.30 | 6.48 | 30% | [117] |
| | PPy@MoS$_2$ | –49.10 | 6.10 | 5.00 | 6.40 | 40% | [118] |
| | rGO@MoS$_2$/PVDF | –43.10 | 14.48 | 2.00 | — | 5% | [119] |
| § 3.6 2D TMD/MXene nanomaterials | Ti$_3$C$_2$T$_x$/MXene/MoS$_2$ | –61.06 | 13.28 | 2.14 | 6.50 | — | [125] |
| | MXene-MoS$_2$ | –46.72 | — | 2.00 | 4.32 | — | [126] |
| | MXene/MoS$_2$ | –51.21 | 10.40 | 2.50 | 4.40 | 30% | [127] |
| | CF@MXene@MoS$_2$ | –61.51 | 7.00 | 3.50 | 7.60 | 20% | [128] |
| | NiS/MoS$_2$/Ti$_3$C$_2$T$_x$ | –58.49 | — | 2.40 | 5.04 | 30% | [129] |
With most of the advantages of carbon-based materials, graphene can be utilized in many application fields as a popular 2D material, and has become one of the most important material in EM wave absorption/shielding fields [63]. Cao et al have synthesized WS$_2$-rGO nanosheet by a facile hydrothermal method (figure 8(a)) [62]. The synergistic effect between the two interfaces after recombination of WS$_2$ with rGO is demonstrated by TEM characterization. At a filler loading of 40 wt.%, the RL$_{\text{min}}$ of the composites is $-41.5$ dB with a matching thickness of 2.7 mm, and the EAB is 3.5 GHz (figures 8(b) and (c)). Motivated by this, Cao's group also proposed to apply WS$_2$-rGO to EM wave shielding field [63].

Using glucose as a precursor, Hou and coworkers obtained a composite material, in which WS$_2$ nanosheets were uniformly coated by biomass-derived carbon (BDC) [64]. This unique cladding structure increases dielectric loss and thus improves the EM wave absorption performance of the hybrid material. The minimum RL of WS$_2$@BDC can reach up to $-51.40$ dB at 5.52 GHz with a thickness of 4.5 mm, and the EAB is 3.92 GHz. This method provides a new idea for improving the EM wave absorption performance of TMDs. Compared to the previous research results associated with pure WS$_2$ nanosheets [31, 43] in section 3.1, the microwave absorption performance of WS$_2$/carbon nanomaterials is significantly improved by the synergetic effect between WS$_2$ and carbon materials.
3.2.2. MoS$_2$/carbon nanomaterials for microwave absorption

Molybdenum disulfide (MoS$_2$) is a typical TMD material, which has exhibited potential microwave absorption performance [45, 46]. For example, Zhang et al. have studied the microwave absorbing ability of MoS$_2$-based materials, including MoS$_2$ and glucose-derived MoS$_2$/C composites with different morphologies. The results showed that MoS$_2$/C has delivered a better absorbing ability than the pure MoS$_2$ counterpart [2]. At 30 wt.% filler loading, the $R_{\text{L}}$ value of MoS$_2$/C could reach −44.67 dB at a matching thickness of 1.4 mm with a corresponding EAB of 3.32 GHz.

Microwave absorbing materials with a larger specific surface area and a hollow structure with sufficient voids usually deliver improved absorption performance [67, 68]. As shown in figure 9(a), Ning et al. have fabricated flower-like MoS$_2$ nanosheets grown inside hollow carbon spheres (MoS$_2$@HCS) by a templating approach (figures 9(b) and (c)) [65]. At 60 wt.% filler loading, an $R_{\text{L}}$ value of −65 dB has been achieved at a matching thickness of 2.0 mm (figure 9(d)). And the EAB of MoS$_2$@HCS is 3.4 GHz. On the contrary, Xu et al. have developed a hybrid material with graphitized-controlled hollow carbon nanosphere decorated with thickness-tuned MoS$_2$ as outer shells (MHCS@MoS$_2$), which delivered an $R_{\text{L}}$ up to 5.95 GHz with a thickness of 2.1 mm. The strongest $R_{\text{L}}$ reached −54.24 dB (at 50 wt.% filler loading) (figures 9(e)–(j)) [66]. Comparing these two cases, we can find that MHCS@MoS$_2$ has delivered wider EAB than MoS$_2$@HCS. This is possibly attributed to the larger diameter, which is beneficial to forming an enhanced electrically conductive network by lower the percolation threshold. Another reason is the outer-shell MoS$_2$ in MHCS@MoS$_2$, which is beneficial for taking full advantage of the excellent electrical property of the outer MoS$_2$.

Mu et al. have synthesized MoS$_2$/CNT composites by a hydrothermal method. Better EM wave absorbing properties were obtained by changing the CNTs content in the MoS$_2$/CNT composites. Studies have shown that the absorption effect is the best when the ratio between MoS$_2$ and CNT is 10:2. The optimal $R_{\text{L}}$ of MoS$_2$/CNT hybrids could reach −46 dB at 6.6 GHz with a thickness of 2.9 mm [69]. In this case, the filler loading is 60 wt.%.

Due to the superior wave-absorbing properties of MoS$_2$, as shown in figure 10(a), Sun et al. compared 2D MoS$_2$ with 0D Ni nanoparticles, 1D CNTs, and 3D carbon layers by constructing heterostructures of different dimensions. They proposed a control interface contact to improve the attenuation of the material [70]. The results show that the materials of type 2 and 3 delivered the best EM wave absorbing performance at a filler loading of 60 wt.%; an $R_{\text{L}}$ of −69.2 dB with an EAB of 4.88 GHz (figure 10(b)).

In Zhang’s report, they obtained MoS$_2$/graphene nanosheets by a facile mechanical exfoliation and solvothermal method [3]. The minimum $R_{\text{L}}$ value of the MoS$_2$/GN absorber reached −55.3 dB with a thickness of only 1.6 mm at only 20 wt.% filler loading. In this case, the EAB is up to 5.6 GHz. Similarly, Wang et al. have constructed a MoS$_2$/graphene 2D heterostructure, which can obtain excellent broadband (5.6 GHz) EM wave absorption performance [71]. At a filler loading of 30 wt.%, MoS$_2$/graphene delivered an $R_{\text{L}}$ value of −41.9 dB at a thickness of 2.4 mm when the frequency of the incident wave is 16.1 GHz.

Jin's group has prepared few-layer MoS$_2$/RGO composites by stirring and mixing MoS$_2$ with RGO (figures 11(a)–(c)) [72]. At only 20 wt.% filler loading, the minimum $R_{\text{L}}$ value of MoS$_2$/RGO is −55 dB under 2.2 mm. The EAB of MoS$_2$/RGO is up to 6.96 GHz. The heterojunction of MoS$_2$/RGO composites leads to more complex and diverse loss mechanisms in MoS$_2$ and RGO. Therefore, compared with pure MoS$_2$ or RGO, MoS$_2$/RGO composites can be used as microwave absorbers with thinner thickness, more significant absorption intensity, and wider absorption bandwidth (figures 11(d)–(f)). In Zhang’s work, they also prepared MoS$_2$/RGO composites by a hydrothermal method, and their MoS$_2$/RGO delivered excellent absorption properties [29]. The results show that the MoS$_2$/RGO absorber with a thickness of 2.52 mm delivered the highest $R_{\text{L}}$ value of −49.41 dB at 8.72 GHz, and the EAB can reach 4.45 GHz. The filler loading...
Figure 9. (a) Schematic synthesis process of MoS$_2$@HCS composites. (b) SEM image of MoS$_2$@HCS. (c) TEM images of MoS$_2$@HCS. (d) RL curves versus frequency for MoS$_2$@HCS at different thicknesses and $l/4$ curve between absorber thickness versus resonant frequency for MoS$_2$@HCS. (a)–(d) Reprinted with permission from [65]. Copyright (2020) American Chemical Society. (e)–(g) TEM images of MHCS@MoS$_2$ composites; (h)–(j) reflection loss curves of MHCS@MoS$_2$ composites at the thickness regions of 1.9–2.4 mm. (e)–(j) Reprinted with permission from [66]. Copyright (2021) American Chemical Society.

Figure 10. (a) Schematic illustration of several samples fabrication processes, (b) Comparison of absorption properties. Reprinted with permission from [70]. Copyright (2017) American Chemical Society.
in their work is 40 wt.%. Liu et al have fabricated a composite combing 3D worm-like expanded graphite (EG) and 2D MoS$_2$ nanosheet by a solvothermal method (figure 11(g)) [73]. At a filler loading of only 7 wt. %, the MoS$_2$/EG composite exhibited an RL of $-52.3$ dB when the frequency of the incident wave is 15.1 GHz. Also, an EAB of 4.1 GHz has been delivered (figure 11(h)).

In addition, these works are expected to become universal routes for the designing of other 2D TMD materials as novel EM wave absorbers (e.g. MoSe$_2$, MoTe$_2$).

3.2.3. Other 2D TMD/carbon nanomaterials for microwave absorption

Studies have shown that the bandgap of layered MSe$_2$ is narrower than that of MS$_2$, and the electrical conductivity is higher, which also illustrates the enormous application potential of MSe$_2$ in microwave absorption [28]. Cao’s group has fabricated hybrid materials containing WSe$_2$ and MWCNTs using a solvothermal method [74]. At a filler loading of 50 wt.%, the RL of WSe$_2$@CNTs can reach $-60.1$ dB, and the EBA can reach 4.24 GHz. Xia et al reported the relationship between MoSe$_2$ with three different morphological structures and investigated the effect of C introduction on the EM wave absorbing performance of MoSe$_2$. It is found that MoSe$_2$ nanoflower has delivered the best EAB, reaching 6.1 GHz. Meanwhile, the RL$_{min}$ value is $-38.5$ dB in the case of MoSe$_2$ nanoflower. When combining with glucose-derived carbon, the minimum RL has been improved to $-43.1$ dB at 1.7 mm. The corresponding EAB of MoSe$_2$ nanoflower has been modulated to 6.2 GHz [75]. In this case, the filler loading is 60 wt. %.

Xu et al have prepared carbonized bacterial cellulose/MoS$_2$ (BCM) nanocomposites [77]. They found that doping BC with phosphorus helps to tune the absorption bands. Bacterial cellulose is like a huge net, and MoSe$_2$ microspheres are evenly distributed on the bacterial cellulose mesh. It greatly increases the number of reflections of EM waves in the absorber, thereby enhancing the RL. At the same time, they also compared P-doped BCMs, and the results show that at filler loading of 20 wt.%, the RL$_{min}$ value of P-doped BC/MoS$_2$ (PBCM) is $-66.84$ dB at 16.96 GHz under a matching thickness of 2.13 mm. Liu et al have obtained C$\mathrm{C@NPC/CoS}_2$ flexible materials by growing Co-MOF precursor on carbon cloth, followed by carbonization and vulcanization (figures 12(a)–(c)) [76]. By studying the effect of carbonization...
temperature on the absorbing properties, it is finally found that when the annealing temperature is 700 °C, the $R_L_{\text{min}}$ is $-59.6$ dB, with the EAB reaching 9.2 GHz (Figures 12(d) and (e)) at a thickness of 2.5 mm. In this case, the filler loading is 30 wt.%.

Tin disulfide (SnS$_2$) is a typical 2D metal sulfide material with a sandwiched structure: two Sn layers encapsulating an Sn atomic layer. SnS$_2$ was seldom studied as an EM wave absorber because of its poor electrical conductivity. Nickel sulfide (NiS$_2$) could be utilized as a dielectric loss type EM wave absorbing material. Dong and co-workers have carbonized popcorn, and then prepared honeycomb-like porous NiS$_2$/SnS$_2$@C composites by a hydrothermal method. Their strategy can combine high conductive NiS$_2$ with poor conductivities SnS$_2$. Due to the unique structure, which enables multiple reflections of EM waves, and the synergistic effect of multiple EM wave attenuation mechanisms, the $R_L$ is as high as $-52.97$ dB at a thickness of 1.57 mm. In this case, the EAB is up to 4.8 GHz [78], and the filler loading is 25 wt.%.

From the above cases, it can be concluded that combining with carbonaceous materials is an effective approach to develop microwave absorbers with satisfactory performances. Some TMDs have showed outstanding performance after compounding with nano-sized carbon materials. For instance, although its $R_L_{\text{min}}$ is only $-21.4$ dB, the EAB of the CF@MoS$_2$ absorber is as large as 10.85 GHz [79]. In another case, the CC@NPC/CoS$_2$ composite has delivered an $R_L_{\text{min}}$ and EAB of 59.6 dB and 9.2 GHz [76], respectively. Thanks for the multiple loss mechanism and impedance matching modulation brought by carbon materials, approaching both strong and wide absorption become possible for TMDs.

3.3. 2D TMD/metal nanomaterials for microwave absorption

Magnetic metals have been utilized in a variety of applications. Due to their high magnetic permeability and good magnetic loss tangent, they have been widely studied in EM wave absorption [80–82]. However, due to the high density and easy oxidation of metals, their real applications are limited [83–85]. Therefore, researchers have adopted various means for modification, one of which is nano-crystallization of metal powders, which uses the movement of free electrons to improve the performance of absorbing materials. Another practical pathway is compounding them with other dielectric loss-type EM wave absorbing materials. When combined with magnetic metallic materials, 2D semiconductive MoS$_2$ with tunable resistivity could regulate the permittivity of metallic materials, and optimize the overall impedance matching degree of the composite.

Zhang et al have synthesized Ni/MoS$_2$ composite by coating magnetic Ni nanoparticles on MoS$_2$ nanosheets. The results show that compared with pure MoS$_2$, the EM wave absorbing performance of Ni/MoS$_2$ composites has been significantly enhanced by introducing magnetic loss mechanism [1]. At a filler loading of 60 wt.%, the $R_L_{\text{min}}$ value could reach $-55$ dB, and the EAB could reach 4.0 GHz. Waqar Uddin
and coworkers have prepared rGO@Ni-doped-MoS₂ composites [87], which delivered a strongest RL of −40 dB at a thickness of 2 mm with an EAB of 5 GHz under a filler loading of 40 wt.%. Similarly, He and his coworkers have prepared a coin-like Fe@MoS₂ nanocomposites with core–shell structures by a solvothermal method. When the filler loading is 60 wt.%, Fe@MoS₂ delivered an EAB of around 4.73 GHz, and an RL_min of around −37.02 dB (figures 13(a)–(e)) [86]. Ding et al have reported FeNi₃@RGO/MoS₂ preparation by a two-step solvothermal reaction [88]. Their experiment results show that the maximum EAB is 4.72 GHz, and the corresponding RL value is −30.39 dB. These two outstanding figures were acquired at a thickness of 2.0 mm and a filler loading of 40 wt.%. Zhou and coworkers have prepared a flower-like FeCo/MoS₂ composite material, in which the FeCo nanoparticles are uniformly dispersed on the surfaces of flower-shaped MoS₂. When the filler loading is 55 vol.%, the FeCo/MoS₂ showed improved wave-absorbing properties with an RL_min of −64.64 dB at a frequency of 14.4 GHz, and the EAB is up to 7.2 GHz (figures 14(a)–(c)) [91]. Yu et al have reported a MOF-derived ZnCo@C hybrid coated by diphasic-MoS₂ nanosheets. This nano-composite with core–shell structure was synthesized by a hydrothermal method. When the filler loading is 50 wt.%, the RL_min value was −35.83 dB at 5.83 GHz with a matching thickness of 5.0 mm. The EAB is up to around 4.56 GHz (figures 14(d)–(f)) [90]. The EM wave absorbing performance of ZnCo@C coated by diphasic-MoS₂ are not as superior as that of Ni/MoS₂, Fe@MoS₂, and FeCo/MoS₂. This is probably because of the sluggishness EM wave absorbing property of Zn.

From the above cases, it can be concluded that it is challenging for unary metal/TMD composite to achieve satisfactory microwave absorbing performance. Some binary alloy/TMD composite has delivered impressive microwave absorbing performances. For example, FeCo/MoS₂ has delivered relatively strong (−64.64 dB) and wide (7.2 GHz) absorption [91]. However, to achieve satisfactory performances, metal/TMD absorbers have to choose relatively high filler loading (>40%). Take into consideration the high density of metals, it is reluctant for metal/TMD absorbers to achieve the goals of ‘thin, lightweight, strong, and wideband absorption’ simultaneously.

### 3.4. 2D TMD/metal oxide nanomaterials for microwave absorption

Zhang and coworkers have fabricated rod-like TiO₂ with different mass ratios on several layers of WS₂ nanosheets by a solvothermal method. Their results show that when TiO₂ content is 10%, and the filler loading is 40 wt.%, the minimum RL at 5.12 GHz is −43.90 dB. And the EAB can reach 4.70 GHz (figures 15(a)–(e)) [30] at a matching thickness of 2.00 mm. Meanwhile, magnetic metal oxide nanoparticles have been utilized as microwave absorber materials by many researchers. This is because of their excellent magnetic loss contribution during the EM wave attenuation process [93, 94]. Cao’s group has obtained WS₂/NiO composites by a similar hydrothermal method (figure 15(f)). The results show that when the introduction of nickel reaches 20%, and the thickness is 4.30 mm, the RL value of the absorbent can reach −53.31 dB, and the EAB could reach 4.88 GHz (figures 15(g)–(j)) [92]. In this case, the filler loading of WS₂/NiO in the wax matrix is 40 wt.%. The author attributed the EM wave absorbing performance...
enhancement of WS₂/NiO to the interfaces between NiO and WS₂, which, to some extent, is responsible for the synergetic dielectric and magnetic loss in WS₂/NiO composite. Chai et al have introduced Co₃O₄ nanoparticles onto MoS₂ sheets by a solvothermal method, which effectively improved the microwave absorption performance of MoS₂ sheets (figure 16(a)) [95]. The results show that when the introduction content of Co₃O₄ is 20 wt.%, the RL₂₃ value of MoS₂/Co₃O₄ composite reaches −43.56 dB (with a thickness of 4.00 mm). Furthermore, in this case, the EAB is up to 4.76 GHz (figures 16(b)–(d)), and the filler loading is only 40 wt.%. As a widely used microwave absorbing material, Fe₃O₄ has attracted much attention because of its good electrical conductivity, constant magnetic moment, and decent permittivity. Wu’s group has synthesized
Fe$_3$O$_4$/MoS$_2$ nanocomposite by a simple hydrothermal method, and the morphology was regulated by changing the ratio of Fe$_3$O$_4$ to MoS$_2$, which also affected the microwave absorption performance of the composite (figure 17(a)) [89]. When the Fe$_3$O$_4$/MoS$_2$ absorber thickness is 1.7 mm, and the filler loading is 50 wt.%, the RL$_{\text{min}}$ value is $-64.0$ dB, and the EAB is 6.1 GHz.

Zhang and coworkers have combined CF with MoS$_2$ nanosheets. In this case, the RL value reached $-21.4$ dB, and the EAB was as high as 10.85 GHz (figures 18(e) and (f)) [79]. The authors also found that when the Fe$_3$O$_4$ nanoparticles were introduced into CF@MoS$_2$, the RL of CF@MoS$_2$@Fe$_3$O$_4$ could reach $-47.3$ dB at a thickness of 2.7 mm, and the EAB could reach 5.8 GHz (figures 18(a)–(d)). The comparison of these two materials clearly elucidates the interaction between magnetic and conductive losses [98–102].

Zhang and coworkers have successfully synthesized a heterostructure hybrid material, which was referred to as MoS$_2$@Fe$_3$O$_4$/CT. MoS$_2$@Fe$_3$O$_4$/CT was synthesized by immobilizing MoS$_2$@Fe$_3$O$_4$ on the surfaces of one-dimensional carbon microtubes via a simple mechanical stirring method (figure 17(b)) [96]. The
Figure 18. (a)–(d) The EM wave absorbing mechanisms of CF@MoS$_2$ and CF@MoS$_2$@Fe$_3$O$_4$ composites, (e),(f) SEM and TEM images of CF@MoS$_2$. Reprinted from [79], Copyright (2021), with permission from Elsevier.

Research result shows that the $RL_{\text{min}}$ value of the composite material reaches $-62$ dB at 2.09 mm, and the EAB is 6.8 GHz with a filler ratio of only 8 wt.% Yang et al have synthesized Fe$_3$O$_4$ nanoparticles with MoS$_2$ nanosheets (MoS$_2$–Fe$_3$O$_4$) by a solvothermal method, and then synthesized MoS$_2$–Fe$_3$O$_4$–C by a chemical vapor deposition (CVD) method using acetylene as a carbon precursor [103]. When the mass loading is 30 wt.%, the $RL_{\text{min}}$ of the MoS$_2$–Fe$_3$O$_4$–C hybrid can reach $-53.03$ dB at 14.4 GHz. Similarly, Wang et al have prepared flower-structured MoS$_2$–graphene hybrid by a solvothermal method, and then composited Fe$_3$O$_4$ particles with MoS$_2$/graphene by mechanical stirring to obtain the MoS$_2$/Fe$_3$O$_4$/graphene as an EM wave absorber [104]. The minimum RL is $-45.8$ dB when the frequency of the incident EM wave is 5.9 GHz, and the matching thickness is 2.5 mm. In this case, the maximal EAB is up to 7.4 GHz.

Liu et al controlled the morphology of their product by using different sulfur sources, resulting in different microwave absorption properties. It was found that Fe$_3$O$_4$/FeS$_2$ composites prepared using thiocetamide exhibited excellent absorption properties due to their cubic polyhedral structure and appropriate amount of sulfur vacancies (figure 17(c)). When the filling ratio is 50 wt.% vs. paraffin, the Fe$_3$O$_4$/FeS$_2$ composite delivered an $RL_{\text{min}}$ value of $-59.27$ dB, and an EAB of 5.86 GHz at a thickness of only 1.8 mm [97].

Ferrites have attracted the attention of many researchers’ due to their high magnetic loss [107, 108]. Wang et al have successfully prepared a flower-like core–shell ZnFe$_2$O$_4$@MoS$_2$ nanocomposite by a hydrothermal method (figures 19(a) and (b)). The study result shows that with a filler loading of 20 wt.%, the ZnFe$_2$O$_4$@MoS$_2$ composite could deliver an $RL_{\text{min}}$ value of $-61.8$ dB at a thickness of 3.0 mm. Also, the optimal EAB of ZnFe$_2$O$_4$@MoS$_2$ could reach 5.8 GHz (figure 19(c)) [105].

Liu et al have encapsulated CuFe$_2$O$_4$ particles in 2D MoS$_2$ nanosheets to form a CuFe$_2$O$_4$/MoS$_2$ composite with a flower-like structure (figures 19(d) and (e)). When the filling loading is 30 wt.%, the absorber achieves an EAB of 8.16 GHz at 2.3 mm. Also an $RL_{\text{min}}$ value of $-40.33$ dB could be delivered by the CuFe$_2$O$_4$/MoS$_2$ composite (figure 19(f)) [106].

Dai et al have prepared MoS$_2$@Bi$_2$Fe$_5$O$_9$ microspheres with MoS$_2$ nanosheets tightly anchored on the Bi$_2$Fe$_5$O$_9$ micro-platelets by a hydrothermal method (figures 20(a) and (b)). When the thickness is 2.8 mm, and the filling loading is 30 wt.%, an $RL_{\text{min}}$ of $-52.3$ dB is obtained by the MoS$_2$@Bi$_2$Fe$_5$O$_9$ composite, and the EAB reaches 5.0 GHz (figures 20(c) and (d)) [109].

Wang et al have synthesized a core–shell structured CoFe$_2$O$_4$@1T/2H-MoS$_2$ nanocomposite by a simple solvothermal method. The microwave absorption performance of the CoFe$_2$O$_4$@1T/2H-MoS$_2$ could be improved by modulating the content of MoS$_2$ (figures 20(e) and (f)). Their results show that at a thickness of 1.81 mm, the $RL_{\text{min}}$ value is $-68.5$ dB at a filler loading of 40 wt.%. Meanwhile, the EAB is 4.56 GHz in this case (figures 20(g) and (h)) [110].
Many researchers usually prepare ferrites with different morphologies and crystal structures by adjusting the synthesis processes, so as to regulate the corresponding microwave absorbing properties. Long et al have prepared Co$_{0.6}$Fe$_{2.4}$O$_4$@MoS$_2$ nanocomposites with a core–shell structure by a solvothermal method. The optimal RL value could reach $-79.9$ dB when the frequency of the incident EM wave is 11.2 GHz. The optimal EAB of the Co$_{0.6}$Fe$_{2.4}$O$_4$@MoS$_2$ is 5.92 GHz [111]. On this basis, they have synthesized Co$_x$Fe$_{3-x}$O$_4$/MoS$_2$ nanocomposites with positive/inverse core–shell structures. When the $x$ value is 0.5, and the mass loading ratio is 60 wt.%, the optimal RL could reach $-66.83$ dB at a thickness of 1.57 mm. Also, an EAB of 6.64 GHz could be achieved by Co$_{0.5}$Fe$_{2.5}$O$_4$/MoS$_2$ [112].

From the above cases, it can be concluded that 2D TMD/metal oxide nanomaterials have delivered better microwave absorbing performance than 2D TMD/metal nanomaterials. For example, an EAB of 8.16 GHz and an RL$_{\text{min}}$ of $-49.43$ dB have been obtained by the CuFe$_2$O$_4$/MoS$_2$ absorber [92]. Introducing ferrites into 2D TMD-based absorbers could further improve the absorption intensity. For instance, the Co$_{0.6}$Fe$_{2.4}$O$_4$@MoS$_2$ absorber has delivered an RL of $-79.9$ dB [111]. However, the high RL value might be the result of sacrificing EAB. Taking the relatively high filler loadings in the cases of 2D TMD/metal oxide nanomaterials into account, metal oxide is still not as efficient as carbon material in adjusting 2D TMD’s microwave absorbing performances.
3.5.2DTMD/polymernanomaterialsformicrowaveabsorption

Conductive polymers have the advantages of low density, diverse structures, and tunable electrical conductivity [113]. In the field of microwave absorption, conductive polymers could generate current under the stimulation of EM waves, and the conduction of current in the material will generate heat, thereby attenuating the energy of EM waves [114, 115].

As shown in figure 21(a), Zhang et al have grafted polyaniline nanoneedles (PANI-NDs) on the surfaces of MoS\(_2\) nanosheets by an in-situ reaction. The researchers explored different reaction times to obtain different growth heights for PANI-NDs (figure 21(b)). When the filling ratio is 60 wt.\%, the RL\(_{\text{min}}\) value of the MoS\(_2\)/PANI-NDs at a thickness of 1.6 mm is −44.8 dB, which is attributed to the synergistic effect between MoS\(_2\) and PANI-NDs (figure 21(c)) [116]. Qi’s group has grafted PANI onto the surfaces of MoS\(_2\) nanowires by an in-situ polymerization method; and then introduced Fe\(_3\)O\(_4\) onto the surfaces of PANI by a hydrothermal method, so as to synthesize PANI@MoS\(_2@Fe_3O_4\) composite. The introduction of Fe\(_3\)O\(_4\) is beneficial for optimizing impedance matching. When used as an absorber (figures 21(d) and (e)), the RL value of PANI@MoS\(_2@Fe_3O_4\) reaches −49.7 dB at a thickness of 1.3 mm, and the EAB is 6.48 GHz (figure 21(f)) [117]. In this case, the filler loading is 30 wt.\%.

Gai and coworkers have prepared PPy@MoS\(_2\) core–shell structure composites by a solvothermal method, and their results show that the optimal RL of the absorber was −49.1 dB at 5.0 mm, and the EAB can reach 6.4 GHz at 2.5 mm [118]. Guo’s group has prepared rGO@MoS\(_2\) nanocomposites by a simple physical method. After introducing polyvinylidene fluoride (PVDF), the RL\(_{\text{min}}\) of the rGO@MoS\(_2@PVDF\) nanocomposite could reach −43.1 dB at 14.48 GHz. At the same time, the rGO@MoS\(_2@PVDF\) composite also delivered satisfactory EM wave shielding performance [119].

The microwave absorption improving effects of polymer materials on 2D TMDs are similar to that of carbonaceous materials we discussed in section 3.2. Unfortunately, limited research data were found in this field. Concluded from the existing data, it is challenging for 2D TMD/polymer composites to achieve RL values better than −50 dB.

3.6.2DTMD/MXenenanomaterialsformicrowaveabsorption

In general, 2D transition metal carbides/carbon nitrides are referred to as MXenes [120]. Among them, the most widely studied is Ti\(_3\)C\(_2\)Tx, which has a large specific surface area, good mechanical properties, and tunable surface. Generally speaking, Ti\(_3\)C\(_2\)Tx is conducive to multiple reflections of EM waves, thus attracting widespread attention in the field of microwave absorption [121–124]. Ren and coworkers have prepared Ti\(_3\)C\(_2\)Tx MXene/W\(_\text{S}_2\) composites by a hydrothermal method. Due to the existence of an immense amount of 2D heterostructures, the RL\(_{\text{min}}\) reached −61.06 dB at 13.28 GHz. In addition, the EAB of Ti\(_3\)C\(_2\)Tx MXene/W\(_\text{S}_2\) is up to 6.5 GHz [125].

Che’s group has prepared MXene-MoS\(_2\) composites by a hydrothermal reaction (figure 22(a)). The 3D conductive interconnection network constructed by the 2D/2D heterostructures makes the MXene-MoS\(_2\)
composites deliver excellent absorption properties (figures 22(d)–(f)). In the charge density images derived from the off-axis electron holograms of MXene-MoS$_2$, the area where the color changes correspond to the overlapping of MoS$_2$, where plenty of charges are accumulated. The accumulated charges induced in a strong interface polarization, which greatly consumes the incident EM wave and improves the microwave absorption performance (figures 22(g)–(i)). As a result, the $R_{\text{Lmin}}$ of the MXene-MoS$_2$ composite reaches $-46.72$ dB at a thickness of 2 mm, and an EAB of 4.32 GHz could be obtained (figures 22(b) and (c)) [126].

Liu et al have successfully prepared 2D MXene and MoS$_2$ into a 3D spherical MXene/MoS$_2$ structure by ultrasonic atomization (figure 23(a)). Due to its unique hierarchical structure, when the filling ratio in paraffin is 30 wt.%, the $R_{\text{Lmin}}$ value could reach $-51.21$ dB at 10.4 GHz, and the EAB reaches 4.4 GHz at a thickness of 1.6 mm (figures 23(b) and (c)) [127]. Wang and coauthors have introduced MXene and MoS$_2$ onto the surfaces of carbon fiber (CF), and fabricated a CF@MXene@MoS$_2$ layered structure by a hydrothermal method. The synergistic effect of MXene and MoS$_2$ enables the composite to deliver efficient microwave absorption performance. When the absorber thickness is 3.5 mm, and the filling ratio is 20 wt.%, the optimal RL is $-61.51$ dB. In addition, the optimal EAB of the CF@MXene@MoS$_2$ is 7.6 GHz [128].

Chang et al have introduced NiS particles and 2D MoS$_2$ on Ti$_3$C$_2$T$_x$ by a two-step solvothermal method, and synthesized a ternary NiS/MoS$_2$/Ti$_3$C$_2$T$_x$ structure with a multilayer interface (figures 24(a) and (b)). The spherical NiS particles are dispersed on the surfaces of 2D Ti$_3$C$_2$T$_x$ and MoS$_2$ sheets. Under the synergetic effect of dielectric loss and multiple reflections between the interfaces, the $R_{\text{Lmin}}$ at 2.4 mm is $-58.48$ dB and the EAB is 5.04 GHz (figure 24(c)) [129]. In this case, the filler loading is 30 wt.%.

From the above cases, it can be concluded that MXene is a promising 2D material in microwave absorption field. When combined with TMDs, synergistic effect could be achieved by MXenes and TMDs.
For example, the CF@MXene@MoS₂ absorber has delivered an impressive $R_{\text{L,min}}$ value of $-61.51$ dB and an EAB of $7.6$ GHz at a filler loading of only $20$ wt.% [128]. The author attributed the excellent performance of the CF@MXene@MoS₂ to the enhanced dielectric loss by the MXene sheath and the improved impedance matching by the edge-on MoS₂ nanosheets. However, we believe that the CF is the dominant reason for the improved impedance matching and reduced filler loading, compared with other composites that only contain TMDs and MXenes. The improved performance of the CF@MXene@MoS₂ also has a lot to do with the 3D CF skeleton, which could prominently lower the percolation threshold. 2D MXenes and TMDs tend to stack on each other, which will lower the surface area and reduce the microwave absorption performance. Future study on 2D MXene/TMD shall pay attention on this intractable problem.

4. Conclusion and perspectives

With the intensive study of 2D layered materials in the post-graphene era, TMD has emerged as one of the most promising candidates for electrochemical energy-related applications. This paper reviews the structural design and the corresponding microwave absorption properties of typical 2D TMD-based composites in recent years. By combining 2D TMDs with other absorbers, various composite microstructures, such as core–shell structures, stacked structures, and 3D network structures, are designed. Due to the intricate overlap between interfaces, the multiple reflections of microwaves are facilitated. In synergy with various loss mechanisms, the 2D TMD-based composites show excellent wave absorption properties. Table 1 summarizes the absorbing capabilities of different types of 2D TMDs nanomaterials in the order of the article sections. The first conclusion drew from table 1 is that it is difficult for TMDs to achieve the goals of ‘thin, wide, light, and strong’ by itself. Secondly, from reviewing sections 3.1 to 3.6 it is obvious that combining with carbonaceous materials is the most widely studied approach. This is because of the low density and high electrical conductivity of carbon-based materials. Actually, by enhancing the conductive loss and balancing the impedance matching, 2D TMD/carbon nanomaterial could give more impressive RL and EAB values simultaneously. Thirdly, among TMD-based composites, the microwave absorbing performance of fiber-shaped absorbers are always at the forefront (e.g. CF@MoS₂ [79] and CC@NPC/CoS₂ [76] in section 3.2, PANI@MoS₂@Fe₃O₄ [117] in section 3.5, and CF@MXene@MoS₂ [128] in section 3.6). This is probably because that the micro-length fibers with high aspect ratio tend to form 3D percolation network more easily, which is beneficial for improve the conduction loss and reduce the filler loading.

Apart from the experimental results we discussed above, most of the experimental studies are still in the research stage and far from practical application. Notably, ‘thin, wide, light, and strong’ is the goal of microwave absorber development. However, the majority of current research has concentrated on the EAB and maximal RL, ignoring the thickness and weight of the absorber. Therefore, it is even more necessary to rationally design the preparation process conditions to achieve better performance of TMDs matrix composites that can be used in real practical applications. In addition, the relationship between materials’ micro-structure and their absorption ability is of vital importance in developing high-performance absorbers. However, most of our research results only described the structure-performance relationship in self-justification and case-by-case way, lacking theoretical models. For instance, the percolation threshold to
achieve the strongest absorption and the widest bandwidth for a micro-flower-shaped absorbing material shall be different from a flake-shaped one. A mathematical model capable of predicting a material’s absorbing ability (e.g. optimal filler loading) based on the material’s powder size, structure feature, and dielectric data as input parameters shall be beneficial for achieving high-performance absorbers with reduced experimental cost. In conclusion, 2D TMD-based composites are a promising research topic, and continuing devotion to them is beneficial for the development of other novel microwave absorption materials.

Data availability statement

No new data were created or analysed in this study.

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