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Editorial

Electromagnetic interference shielding and microwave absorption materials: A virtual special issue

The unprecedented developments of electrical and electronic systems during the past decade have brought about serious electromagnetic wave (EMW) pollution interfering with surrounding electronic equipment and military facilities, potentially endangering human health. To address this concern, the development of high performance materials and technologies for electromagnetic interference (EMI) shielding and microwave absorption (MA), is highly desired for civilian and military applications. There are numerous studies worldwide and this special issue perfectly reflects this important trend. This virtual special issue (VSI) in CARBON focuses on absorption and shielding of EMW with a very broad range of materials. In the following paragraphs, we will briefly highlight some materials and results reported in this VSI.

First as it is well known, incident EMW through a material includes three paths that include reflection, absorption and penetration [1]. For the absorption process, the absorbed EMW energy is generally converted into thermal energy or other kinds of energy and then dissipated. To maximize the attenuation capability of EMW absorbents, two main approaches have been applied: tuning an optimization of impedance matching characteristics and strong EMW attenuation ability. The electromagnetic wave absorption ability is often indicated by the reflection loss (RL) [2] which can be expressed as:

$$RL = 20log|(Z_{in} - Z_0) / (Z_{in} + Z_0)|$$

where Z_{in} and Z_0 is the input impedance and free-space impedance, respectively. Dielectric loss and magnetic loss are the main routes for microwave absorption materials (MAMs) to attenuate EMW. Dielectric loss is usually controlled by conduction loss and polarization relaxation. The polarization relaxation loss is split into ionic polarization, electronic polarization, dipoles relaxation polarization and interfacial polarization (spatial polarization). Magnetic loss generally arises from natural resonance, eddy currents, and exchange resonance.

For EMI shielding, when the EMW interacts with lossy materials, the EMW is either reflected from the surface or absorbed by the material. The remaining portion transmits through the material. Therefore, an ideal shielding material should leak negligible or zero energy. The mechanism can be classified into three paths: reflection, absorption and multiple internal reflections of EMW [3]. The shielding effectiveness (SE) can be then described as:

$$SE_T = SE_R + SE_A + SE_M$$

The total shielding effectiveness (SE_T) is the sum of the above three shielding effects, including reflection loss (SE_R), absorption loss (SE_A) and multiple reflection loss (SE_M). In general, the SE_T increases with increasing conductivity, thus indicating that highly conducting materials result in strong SE_T. However, due to the excessive RL, EMW are easy to be reflected to the environment and cause secondary pollution. Therefore, many works have been turning to EMW shielding materials following the absorbing mechanism.

In this context, many efforts have been made to develop: (i) new materials with properly identified mechanisms to enhance the EMW absorption and shielding properties. (ii) Favorable smart structures (e.g., porous foam and layered gradient structures), sometimes involving interface engineering (e.g., core-shell and hierarchical structure), and (iii) a combination of (i) and (ii) [3–9].

It is also noteworthy that MXenes (2D systems) have been newly developed, and they can be used in various applications. However, further studies are still needed to reveal MA and shielding behavior of the MXene family, particularly those exhibiting high electrical conductivity [4,5]. In the cases where “M” exhibits magnetic properties, e.g., Cr or Mn, further enhancement in EMW absorption is expected through magnetic losses [2]. In this context, Che's group prepared a flexible MXene/FeCo film by the electrostatic interaction between negatively charged MXene, and a positively charged FeCo alloy, and demonstrated better MA performance with the maximum RL value of −43.7 dB at 3.76 GHz [6]. In addition, Huang's group reviewed the recent progress of MXene and MXene-based MAMs, describing the advantages and shortcomings of MXene-based composites [2]. Gu's group prepared $Ti_3C_2T_x$/rGO porous EMI shielding composite films by ion-induced self-assembly & vacuum-assisted filtration [7]. Due to the synergy of high electrical conductivity (s) and the porous structure, the EMI shielding effectiveness (SE) of $Ti_3C_2T_x$/rGO porous composite films reached the maximum (59 dB), and the corresponding specific SE (SSE/t) reached 37,619 dB cm^2 g^{-1}.

Carbon-based materials, such as multi-walled carbon nanotubes (MWCNT) [8,9], carbon fibers [10], graphene [11–13], etc., exhibit potential in absorption and shielding due to their light weight, low cost and excellent dielectric properties. Their excellent properties are derived from the conduction loss and the dielectric loss, including dipolar and interfacial polarization loss. However, their MA performance is strongly limited due to the single loss mode and unsatisfactory spatial topography. So these carbon materials are often incorporated with ferromagnetic particles such as CoNi [14–16], $NiCo_2O_4$ [17], Co_3O_4 [8], Fe [18], FeCo and Fe3O4 [19,20], in order to induce magnetic losses. The fascinating electrical and dielectric properties and its controllable assembly makes graphene an outstanding candidate for MAMs. In this regard, Ye's group synthesized the flowerlike Cu9S5/RGO (CSR) composites via a solvothermal method [21]. The CSR-2 sample exhibited the minimum RL value of

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−51.9 dB with thicknesses of 2.8 mm, and the widest effective absorption bandwidth (EAB) is 3.92 GHz in 1.5 mm thick composites. Hu's group carried out a great summary of the recent achievements of carbon-based materials with different microstructures as shielding and absorption materials during the past five years and discussed the remaining challenges for EMI shielding [22].

Metal-organic frameworks (MOFs) derived carbon-based composites also exhibit great potential in the fields of electromagnetic wave (EMW) absorption [11,23–27]. MOFs and their composites are ideal templates to prepare carbon/metal composites by regulating the pyrolysis temperature under the inert atmosphere and post-treatment process. In this context, Hou's group prepared caterpillar-like hierarchically structured Co/MnO/CNTs by pyrolysis of core-shell manganese dioxide and zeolitic imidazolate framework template [23]. The RLmin approaches −58.0 dB and EAB of 4.5 GHz at 1.32 mm thickness. Wu's group also synthesized a series of hierarchical short carbon fibers (SCFs) based composites with in-situ grown cobalt layered double hydroxides (Co-LDHs), via a simple PVP-assisted solvothermal method [10]. These authors reported EAB values of 6.5 GHz at 2.1 mm, and strong RLmin of −40.4 dB at 2.0 mm.

The EMW absorption and shielding properties are not only characterized/governed by the materials, but also by the internal structure of the composite. In this regard, a combination of superior materials and smart structures can be beneficial [28–36]. Zhang's group prepared three different structures: ZnO–C coreshell nanowires, ZnO–C wire-in-tubes and carbon nanotubes [37]. Results indicate that hollow structures are beneficial to the MA performance. The RL_{min} values of wire-in-tube and nanotube structures are much higher than the RL values of core-shell structures. The RL peak of nanotube structures can reach −64.42 dB. The EAB of the wire-in-tube structure with two components is wider than that of the nanotube structure with one component, reaching as wide as 5.76 GHz. The conducting polymer composite (CPCs) with tunable EMW absorption and shielding properties, and relatively facile processability, have been studied as promising candidates [38–40]. CPC foams with a gradient configuration fabricated through incorporating MXene-decorated polymer foam beads revealed a superior EMW attenuation capability. To be more specific, the constructed MXene network in the microcellular foam structure has not only been shown to favor impedance matching, thereby causing more EMW to pass into the absorbent, but it has also improved the attenuation capability of the dielectric loss by prolonging EMW propagating path via multiple scattering [39], which is beneficial for EMW absorption and shielding.

This compilation of papers lay the foundation for a better understanding of the mechanisms governing EMW attenuation by absorbents. Based on that, future studies will investigate the design of all-in-one EMW absorbents, thus meeting all physical and functional requirements for target applications with specific frequency ranges. To use EMW absorbents in commercial applications, in addition to the attenuation capability, their other characteristics such as lightweight [16,41], corrosion resistance [38,42], thermal properties [3,29], and mechanical properties [39,40,43], have also been investigated as essential requirements. Moreover, incorporating these materials with tailored characteristics into modern electronic and electrical designs in various sectors will maintain their performance against EMW pollution. We do hope readers value this VSI, and the journal Carbon will continue publishing papers in the area of microwave absorption and electromagnetic shielding as the number of publications continues to increase.

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