Effect of SiC layer on microwave absorption properties of novel three-dimensional interconnected SiC foam with double-layer hollow skeleton

Binbin Li¹, Bangxiao Mao¹,², Tao He¹, Xingbang Wang¹ and Haiquan Huang¹

¹ International laboratory for Insulation and Energy Efficiency Materials, College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, 211106, People’s Republic of China
² Jiangsu Collaborative Innovation Center for Advanced Inorganic Function Composites, Nanjing University of Aeronautics and Astronautics, Nanjing, 211106, People’s Republic of China

E-mail: bbli@nuaa.edu.cn

Keywords: SiC foam, double-layer hollow skeleton, microwave absorption, impedance matching ratio, attenuation constant

Abstract
To design a lightweight and high-performance absorber, this work introduced a novel three-dimensional interconnected SiC foam with double-layer hollow skeleton (3D-ISF), which was prepared by depositing SiC, pyrolytic carbon, and SiC layer on interconnected carbon foam, followed by oxidation of carbon. SEM results showed the interconnected hollow structure had been successfully synthesized, which was beneficial for microwave absorbing efficiency, and numerous columnar SiC defects were observed and played a critical role in the microwave absorption properties. The electromagnetic performances of 3D-ISF-I and 3D-ISF-II were investigated in depth. With the increase of thickness of SiC layer, 3D-ISF-II exhibited a better microwave absorption property, which could be ascribed to the higher impedance matching ratio ($Z_r$) and attenuation constant ($\alpha$). The optimum reflection loss value of 3D-ISF-II could reach $-45.649$ dB while that of 3D-ISF-I was just $-32.070$ dB. There is no doubt that the prepared materials have tunable microwave absorbing properties, which can promote the development of SiC-based absorbing materials to a certain extent. Finally, it was confirmed that the $Z_r$ played a dominant role in 3D-ISF, which provided practical guidance for the design of porous materials.

1. Introduction
Wireless communication technology is a double-edged sword, which brings a lot of electromagnetic (EM) pollution while providing convenience to people [1–6]. EM pollution has become one of the most serious environmental pollution that needs to be solved urgently. Therefore, it is very important to develop new high-performance EM wave absorbing materials. Up to now, various EM wave absorbing materials have been developed, such as ferrites [7], metallic oxide [8], metal powders [9], nanoparticles [10], carbon-based materials [11], and SiC-based materials [12]. Among them, metal-based microwave absorbing materials possess high density, easy corrosion, and poor thermal stability, which limit their practical application in harsh environments such as high temperatures. In contrast, SiC-based materials are considered to be promising microwave absorbing materials due to their high temperature resistance, corrosion resistance and excellent mechanical properties. For example, Meng et al developed SiC microtubes by carbothermic process with commercial cotton and tetraethyl orthosilicate solution. The reflection loss values suggested the excellent potential of the material as one microwave absorber. The cotton acted as template and facilitated the formation of microtube that led to the outstanding microwave absorption performance of SiC microtubes [13]. Kuang et al prepared SiC nanowires with different lengths and investigated the microwave absorption behaviors. It was demonstrated that the microwave absorption ability of SiC nanowires improved significantly with the increasing SiC nanowires length. The mechanism behind that was that the longer SiC nanowires were more likely to interconnect with each other,
which contributed to the construction of conduction network [14]. Furthermore, Han et al fabricated SiC$_2$/SiC composites reinforced with 3D four- and five-directional braided SiC fiber preforms via PIP method. In comparison with the 3D four-directional braided SiC$_2$/SiC composites, the 3D five-directional braided SiC$_2$/SiC composites possessed superior microwave absorption properties which resulted from electric dipole polarization, multiple reflections, and conductive networks [15]. Studies have demonstrated that SiC-based materials with different microstructures are extensively applied in the EM wave absorbing field.

In commercial applications, lightweight can increase absorption efficiency and reduce material costs. Therefore, modern microwave absorbers are required to possess both high-performance and lightweight properties. Carbon-based materials have become advanced modern microwave absorbing materials due to their lightweight and excellent EM wave attenuation [16, 17]. In addition, the introduction of porous structures has proven to be a novel approach to improve the microwave absorption properties of absorbers. For instance, Lu et al fabricated porous Co/C nanocomposites by the pyrolysis of Co-based MOF (ZIF-67) precursors under Ar atmosphere. The minimum reflection loss reached $-35.3$ dB. The excellent microwave absorption properties were attributed to the synergistic effects of the multiple components and highly porous structure [18]. Wang et al prepared porous Co-C core–shell nanocomposites via one-step sintering of a cobaltic metal-organic framework (Co-MOF-74). The minimum reflection loss could achieved $-62.12$ dB. The introduction of porous structures enhanced the interfacial polarization and multiple scattering, which was essential to improving microwave absorption properties [19]. As a result, with the open cell structure and high specific surface area, 3D interconnected carbon foam (ICF) has attracted widespread attention. In general, pure ICF could not meet the practical microwave absorbing applications due to the high dielectric loss and high conductivity. However, ICF is an excellent template that other materials can be loaded with to form a porous material. Great researches on this aspect have been explored, such as Ni/carbon foam [20], Ag particles/carbon foam [21], Fe$_3$O$_4$/ZnO-coated CFoam [22], SiC nanowires/carbon foam [23], SiC/Si$_3$N$_4$/carbon foam [24], and MWCNTs/carbon foam [25]. Unfortunately, studies on the preparation of hollow porous SiC absorbers using ICF as templates have not been reported.

In view of the above results, a novel three-dimensional interconnected SiC foam with double-layer hollow skeleton was fabricated by experiment, and applied as a lightweight and high-performance absorber. ICF acted as the primitive template to form the 3D interconnect structure. SiC, pyrolytic carbon (PyC), and SiC layer were sequentially deposited on the ICF skeleton, in which SiC and PyC were deposited via CVD and CVI techniques respectively. The 3D interconnected SiC foam with double-layer hollow skeleton was obtained after removing carbon by oxidation, and it was named 3D-ISF. ICF and PyC can perfectly introduce a double-layer hollow porous structure, which is beneficial for microwave absorbing efficiency. The effect of SiC layer thickness on the microwave absorption properties of 3D-ISF was studied in depth. At last, the microwave absorption mechanism of 3D-ISF was proposed, which provided practical guidance for the design of porous materials.

2. Experimental section

2.1. Synthesis procedures of 3D-ISF

The original ICF interconnect template was first prepared. The melamine foam (density: $\sim 6$ g cm$^{-3}$) purchased from Sichuan Chemical Co., Ltd (Sichuan) was pyrolyzed in a 1100 °C tube furnace where the heating rate was maintained at 1 °C min$^{-1}$ to ensure the stable formation of interconnected skeleton. After 1 h of carbonization, the stable ICF interconnect template was prepared. The detailed preparation process of 3D-ISF is displayed in figure 1. A SiC layer was first deposited on the ICF skeleton by CVD techniques. The ICF was placed horizontally in a CVD furnace and deposited at 1100 °C for 8 h. MTS, H$_2$, and Ar with purities of 99.999% were used as the SiC precursor, reaction gas, and diluent gas, respectively. A certain thickness of PyC layer was then deposited on the SiC layer by CVI process, in which propylene (C$_3$H$_6$) and Ar with purities of 99.999% were used as the carbon precursor and diluent gas, respectively. After 20 h of PyC deposition, a SiC coating was deposited on the PyC layer again using CVD techniques where the details were the same as before. The detailed deposition parameters of all the coatings are shown in table 1. Finally, the prepared sample was placed in a 700 °C muffle furnace and kept for 8 h under air atmosphere to obtain the 3D interconnected SiC foam with double-layer hollow skeleton. Furthermore, in order to reveal the effect of the thickness of SiC layer on the microwave absorption performance of 3D-ISF, two samples with the second CVD-SiC time of 8 h and 16 h were prepared, which were denoted as 3D-ISF-I and 3D-ISF-II, respectively.

2.2. Materials characterization

The porous microstructure and morphological characteristics of ICF and 3D-ISF samples were investigated by using a scanning electron microscopy (SEM; FEI quanta 650). To obtain more structural properties of the
as-prepared samples, XRD patterns and FTIR spectrums were performed on a x-ray diffractometer (XRD, Rigaku D/max-2550) and a Fourier transforms infrared spectrometer (FTIR, Nexus 670), respectively.

2.3. Microwave absorption measurement
A network analyzer (VNA, PNA-N5244A) was employed to collect the electromagnetic parameters of all samples in the frequency range of 2-18GHz. The as-prepared sample was first ground and homogeneously dispersed into soft paraffin wax with the mass ratio of 50%. The mixture was then compressed into toroidal-shaped samples with 3.04 mm in inner diameter, 7.00 mm in outer diameter, and 2.00 mm in thickness.

Table 1. Detailed deposition parameters of all the coatings.

| Parameters of CVD-SiC | Parameters of CVI-PyC |
|----------------------|----------------------|
| MTS (ml/min) | H₂(ml/min) | Ar (ml/min) | Temperature (°C) | Pressure (Pa) | MTS (ml/min) | Ar (ml/min) | Temperature (°C) | Pressure (Pa) |
| 30 | 300 | 300 | 1100 | 505 | 30 | 60 | 1000 | 150 |

Figure 1. Digital photos of preparation process of 3D-ISF (a). SEM images of ICF (b), 3D-ICF/SiC (c), 3D-ICF/SiC/PyC (d), 3D-ICF/SiC/PyC/SiC (e), and 3D-ISF (f).
3. Results and discussions

3.1. Evolution of 3D-ISF

The detailed evolution process of 3D-ISF is shown in figure 1, in which figure 1(a) shows the digital photos, and figures 1(b)–(f) presents the SEM images. After a series of reactions, the color of the 3D-ISF turned brown which was different from the front four black samples. It was the complex porous microstructure that changed the light absorption and reflection of the 3D-ISF [26]. Moreover, it is clear that the five samples did not experience any deformation during the conversion from ICF to 3D-ISF, which means that the 3D-ISF could be made to meet different shape requirements by controlling the shape of the ICF. From figure 1(b), it is obvious that the original ICF possesses interconnected skeleton, but the skeleton were very thin, which tended to cause poor mechanical properties to affect its application. Through the deposition of CVD-SiC and CVI-PyC, the interconnected skeleton were significantly thicker as shown in figures 1(c)–(e), which could effectively improve the mechanical properties of the 3D-ISF. Finally, the carbon component was removed by oxidation process to obtain the double-layered hollow interconnected skeleton (figure 1(f)). In addition, the densities of ICF and 3D-ISF is listed in table 2. Although the densities of 3D-ISF-I and 3D-ISF-II are much larger than that of ICF, they still exhibit the ultra-light properties.

Figure 2(a) shows the XRD patterns of ICF, 3D-ISF-I, and 3D-ISF-II. ICF is an amorphous carbon whose curve appears two broad peaks around 2θ of 22° and 43° corresponding to the (002) and (100) reflection planes of amorphous carbon [26]. In the case of 3D-ISF-I and 3D-ISF-II, curves exhibit three diffraction peaks centered at 2θ of 36°, 60°, and 72°, corresponding to (111), (220), and (311) reflection planes of β-SiC (JCPDS card no. 29-1129), respectively [27]. With increment of the deposition time, the corresponding peak heights also increase. Besides, the FTIR spectrums of ICF, 3D-ISF-I, and 3D-ISF-II are depicted in figure 2(b). Due to the amorphous carbon structure, the ICF curve has no distinct peaks, while results of 3D-ISF show an intense peak at 779 cm$^{-1}$ assigned to the Si-C bond [28]. The peak of 3D-ISF-II is stronger than that of 3D-ISF-I, indicating that the thickness of SiC layer in 3D-ISF-II is thicker than that of 3D-ISF-I. The results of XRD and FTIR indicate the successful preparation of SiC foam.

To further investigate the micro-morphology of the as-prepared 3D-ISF, the high-magnification SEM images of ICF, 3D-ISF-I, and 3D-ISF-II are presented in figures 3(a)–(f). It can be seen in figure 3(a) that the ICF consists of thin interconnected skeleton. From figure 3(c) (3D-ISF-I) and 3e (3D-ISF-II), it is not hard to find that the 3D-ISF perfectly inherits the interconnected skeleton of the initial ICF. Meanwhile, the double-layered hollow porous structure is successfully fabricated, which is considered to be beneficial for microwave absorption. In addition to this, it should be especially noted that the surfaces of 3D-ISF-I (figures 3(d)) and 3D-ISF-II (figure 3(f)) are exceptionally rough compared to the smooth skeleton of ICF (figure 3(b)), where the rough surfaces are composed of columnar SiC defects. It can be explained considering that the proportion of MTS:H$_2$ inside the foam was reduced during the CVD process leading to the longitudinal growth of SiC crystals.
With increment of the deposition time, the SiC defects on the 3D-ISF-II surface were more than 3D-ISF-I. It is worth emphasized that numerous columnar SiC defects introduce a large number of interfaces and particles resulting in a further enhancement of the EM wave absorption properties of 3D-ISF.

3.2. Electromagnetic property

In order to reveal the effect of the thickness of SiC layer on the microwave absorption properties of 3D-ISF, the complex permittivities and permeabilities of the initial ICF, 3D-ISF-I, and 3D-ISF-II in the 2-18 GHz range were investigated in depth, and the detailed parameters are presented in figures 4(a)–(f). In general, the complex
permittivity consists of $\varepsilon'$ (real part) and $\varepsilon''$ (imaginary part), which represent the capacities of electrical storage and dielectric loss, while the permeability is composed of $\mu'$ (real part) and $\mu''$ (imaginary part), which record the energy information of magnetic field [31]. Figures 4(a)–(c) shows the complex permittivities of ICF, 3D-ISF-I, and 3D-ISF-II, respectively. It can be seen that the $\varepsilon'$ of the ICF rises slowly and then remains basically stable, while the $\varepsilon'$ of both 3D-ISF-I and 3D-ISF-II show downturn. It is reported that the decrease of $\varepsilon'$ and the frequency dispersion effect are favorable for the microwave absorption [32]. With increment of the SiC layer thickness, the variation trend of $\varepsilon'$ of 3D-ISF-II is almost the same as that of 3D-ISF-I except a slight decrease. Although the variation in $\varepsilon'$ is slight, its effect on the final microwave absorption properties is still large, which will be discussed in detail later. As for $\varepsilon''$, ICF exhibits a rapid decrease trend, while 3D-ISF-I and 3D-ISF-II slowly decrease. Additionally, the thickness of SiC layer has little effect on $\varepsilon''$. It should be emphasized that the complex permittivities of 3D-ISF-I and 3D-ISF-II show multiple fluctuations, which are usually caused by the dipole and interface polarization [33]. In comparison with ICF, 3D-ISF exhibits complex permittivities due to the special dielectric properties of SiC materials [34]. Figure 4(d) shows the permeabilities of ICF, 3D-ISF-I, and
3D-ISF-II. Both $\mu'$ and $\mu''$ of all samples fluctuate around 1 and 0, respectively, which fully demonstrates that ICF and 3D-ISF are all weakly magnetic or non-magnetic materials. Therefore, we only need to focus on the study of the complex permittivities of ICF, 3D-ISF-I, and 3D-ISF-II. For the comparison of the complex permittivities of ICF, 3D-ISF-I and 3D-ISF-II, figures 4(e)–(f) presents the variation trends of $\varepsilon'$ and $\varepsilon''$ at different frequencies. Clearly, from ICF to 3D-ISF, $\varepsilon'$ and $\varepsilon''$ significantly decrease. With increment of the SiC layer thickness, $\varepsilon''$ decreases further, while $\varepsilon'$ remains stable.

In general, $\varepsilon'$ is closely related to conductivity [35]. $\varepsilon'$ and $\delta$ [33] can be described as follows:

$$\varepsilon'' = 1/2\pi\varepsilon_0\mu f$$
$$\delta = 1/(\pi\mu f\sigma)^{0.5}$$

where $\rho$, $\delta$, and $\sigma$ represent the resistivity, skin depth, and electrical conductivity, respectively. According to equation (1), the higher $\varepsilon'$ means high electrical conductivity. The results indicate that ICF has high conductivity, resulting in better electrical storage and dielectric loss abilities. However, high electrical conductivity tends to increase skin depth effect, which lead to undesired microwave reflection. In contrast, 3D-ISF-I and 3D-ISF-II possess lower $\varepsilon'$, which is favorable for the impedance match.

According to the Debye theory, $\varepsilon'$ can be expressed as follows [36]:

$$\varepsilon' = \varepsilon_\infty + (\varepsilon_\infty - \varepsilon_0)/(1 + \omega^2\tau^2)$$

where $\omega$, $\tau$, $\varepsilon_\infty$ and $\varepsilon_0$ represent the angular frequency, polarization relaxation time, static permittivity, and dielectric permittivity at the high-frequency limit. It can be seen that the decrease in $\varepsilon'$ is resulted from the increase in $\omega$. This is usually attributed to the polarization relaxation [33]. As described above, the $\varepsilon'$ of the 3D-ISF is significantly lower than that of the ICF, indicating that the as-prepared 3D-ISF has a stronger polarization relaxation ability than ICF. Moreover, the polarization relaxation capability is further enhanced with the increase of SiC layer thickness.

The tangent of the dielectric loss can be obtained by dividing $\varepsilon''$ by $\varepsilon'$. This relationship is expressed as follows [37]:

$$\tan \delta \varepsilon = \varepsilon''/\varepsilon'$$

Figure 5 shows the dielectric loss tangent versus frequency for ICF, 3D-ISF-I, and 3D-ISF-II. In figure 5(a), the red and blue curves are much lower than the black curve, indicating that the dielectric loss of the 3D-ISF is much lower than that of the ICF. This also emphasizes that excessive dielectric loss does not necessarily result in better absorbing properties. Figure 5(b) shows the exact dielectric loss values for 3D-ISF-I and 3D-ISF-II. Obviously, there are two relaxation peaks for each curve. Meanwhile, the dielectric loss value of 3D-ISF-II is higher than that of 3D-ISF-I, which means that the absorbing performance of 3D-ISF may increase with increasing SiC layer thickness.

According to Debye theory, $\varepsilon'$ can also be described as equation (5) [38]:

$$\varepsilon'' = (\varepsilon_\infty - \varepsilon_0)\omega\tau/(1 + \omega^2\tau^2) + \sigma_{ac}/\omega\varepsilon_0$$

where $\sigma_{ac}$ and $\varepsilon_0$ represent the alternative conductivity and dielectric constant in vacuum. When the contribution of the second part of equation (5) to $\varepsilon'$ is negligible, $\varepsilon'$ and $\varepsilon''$ can be described with another equation:
Equation (6) shows the Cole-Cole circular relationship between $\varepsilon'$ and $\varepsilon''$, which represents the dielectric relaxation ability of materials. Generally, the dielectric relaxation process can improve the microwave absorption performance. Figures 6(a)–(c) shows the Cole-Cole plots for ICF, 3D-ISF-I, and 3D-ISF-II. It can be seen from figure 6(a) that the Cole-Cole curve is disordered without a semicircle, indicating that the dielectric relaxation ability of the ICF is extremely weak. For 3D-ISF-I and 3D-ISF-II, there are more semicircles in the two curves, which means that the polarization and related relaxation processes of 3D-ISF under oscillating EM fields are abundant. First, the interconnected double-layer hollow structure greatly enhances the interface resulting in multiple reflections and scattering of microwaves inside, which enhances the interface relaxation. In addition, numerous columnar SiC defects introduce a large number of interfaces and particles. The incident EM waves will be captured and get reflected and scatter, which also produces a relaxation process that further improves the absorbing properties of the 3D-ISF. Third, defects and skeleton faults accumulate a large number of dipoles, greatly improving dipole relaxation. Under the synergistic effect of interface relaxation, defect relaxation and dipole relaxation, 3D-ISF will possess stronger microwave absorption performance than ICF. It is worth mentioning that the semicircles in the 3D-ISF-II curve is more regular than that of 3D-ISF-I, which signifies that the dielectric relaxation ability of 3D-ISF may be stronger with the increase of SiC layer thickness.

To evaluate the absorbing properties of 3D-ISF, we conducted in-depth studies on the reflection loss (RL) of all the prepared samples. In general, the most intuitive parameter to measure the absorbing performance is the RL. An excellent absorbing material should absorb more than 90% of EM waves, and its RL value is required to be less than $-10$ dB. Here, the RL can be calculated by several formulas [39, 40]:

$$RL(dB) = 20 \log \left[ \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right]$$

$$Z_{in} = Z_0 \left( \frac{\mu_r}{\varepsilon_r} \right)^{0.5} \tan \left( \frac{j(2\pi f d/c)(\mu_r\varepsilon_r)^{0.5}}{2} \right)$$

$$\mu_r = \mu' - j\mu''$$

$$\varepsilon_r = \varepsilon' - j\varepsilon''$$
where \( c \), \( d \), \( Z_0 \), and \( Z_{in} \) represent the velocity of light, thickness of the absorber, impedance of free space, and input impedance of the absorber in the air, respectively.

Figure 7(a)–(f) presents the plots of \( RL \) versus thickness and frequency for ICF, 3D-ISF-I, and 3D-ISF-II. From figure 7(a), it can be seen that the \( RL \) values for the ICF are all greater than \(-5\) dB, and the minimum \( RL \) value is \(-1.996\) dB as shown in figure 7(b). These results demonstrate that the absorbing properties of ICF are extremely poor. Therefore, ICF cannot be applied as an absorber. In the case of 3D-ISF, the \( RL \) values of 3D-ISF-I have reached \(-20\) dB at the selected thickness range, as shown in figure 7(c). In figure 7(d), the minimum \( RL \) value of 3D-ISF-I can reach \(-32.070\) dB at 8.72 GHz when the absorber thickness is 10 mm. Meanwhile, the corresponding effective absorption bandwidth \( (f_E: \text{frequency bandwidth below } -10 \text{ dB}) \) is 2.38 GHz. For the 3D-ISF-II of figures 7(e) and (f), it can be seen that the \( RL \) values further decrease. The minimum \( RL \) value can reach \(-45.649\) dB at 9.52 GHz when the absorber thickness is 9.5 mm. Moreover, its \( f_E \) with value of 2.74 GHz is also wider than the 3D-ISF-I. It should be stressed that for 3D-ISF-I and 3D-ISF-II, the frequencies corresponding to the minimum \( RL \) are shifted to the low frequency region with increment of the absorber thickness, which can be explained by the 1/4 wavelength formula [41]:
where $c$, $t_m$, and $f_m$ are the light velocity, thickness of absorber, and the matching peak frequency, respectively. As we can see, the higher the $t_m$, the lower the $f_m$.

Furthermore, the minimum $RL$ values of all the samples at various thicknesses are compared as shown in figure 8(a). Obviously, the $RL$ values of the 3D-ISF are much lower than the ICF. Additionally, except for the thickness of 5 mm, the $RL$ values of 3D-ISF-II are all lower than that of 3D-ISF-I. Figure 8(b) shows the effective absorption bandwidth of 3D-ISF-I and 3D-ISF-II at different thicknesses. It can be seen that the $f_E$ values of 3D-ISF-II are significantly improved compared to 3D-ISF-I except for 5mm and 8.5mm. The results show that the prolongation of the deposition time of SiC layer is beneficial to reduce $RL$ and broaden $f_E$.

To show the microwave absorption performance more intuitively, figure 9 shows the 3D plots and 2D plots of frequency- and thickness-dependent $RL$ for ICF, 3D-ISF-I, and 3D-ISF-II. Figure 9(a) shows that all $RL$ values of the ICF are above $-10$ dB. The full red region in figure 9(b) fully demonstrates the very poor absorbing properties of ICF. However, for 3D-ISF, the $RL$ values significantly decrease, as shown in figures 9(c) and (e). The 3D-ISF-I can reach $-10$ dB at the whole thickness when the frequency range from 8 to 18 GHz. By contrast, 3D-ISF-II can achieve $-10$ dB at the whole thickness and $-30$ dB or even $-40$ dB at multiple thicknesses. Compared with figure 9(d), more blue and purple regions are distributed on the yellow strip in figure 9(f), indicating that the absorbing properties of 3D-ISF-II are significantly higher than 3D-ISF-I. Meanwhile, the two yellow strips mean that the 3D-ISF can be well applied to the broadband microwave absorption field. The results prove that the as-prepared 3D-ISF in this study exhibit more excellent absorbing properties than other similar foam materials [42, 43]. There is no doubt that the prepared materials have tunable microwave absorbing properties, which can promote the development of SiC-based absorbing materials to a certain extent.

To explore the absorbing mechanism of 3D-ISF, we studied the impedance matching ratio ($Z_r$) and the attenuation constant ($\alpha$) of the prepared samples, which are the two basic factors that determine the absorbing properties of materials [44]. Generally, $Z_r$ determines the absorption efficiency of the microwave, while $\alpha$ determines the EM waves attenuation ability of materials. The $Z_r$ and $\alpha$ in this work are calculated as follows [45]:

$$Z_r = \frac{Z}{Z_0} = (\mu_r / \varepsilon_r)^{0.5}$$

$$\alpha = 2^{0.5} \pi f_c^{-1} (\mu'' / \varepsilon'') + \mu' \varepsilon'' + \left( (\mu'' / \varepsilon'') - \mu' \varepsilon' \right)^2 + \left( \mu' \varepsilon'' + \mu'' \varepsilon' \right)^2$$

where $\varepsilon_r$, $\mu_r$, $Z$, and $Z_0$ represent the complex permittivity, permeability, impedance value of the absorbent, and impedance of the free space, respectively. As we can see, only when $Z_r = 1$, EM waves will all enter materials without any reflection.

Figure 10(a) presents the plots of $Z_r$ versus frequency for ICF, 3D-ISF-I, and 3D-ISF-II. It can be seen that the maximum $Z_r$ value of the ICF is only 0.147. However, the two curves of the 3D-ISF are much higher than the ICF curve, and the minimum $Z_r$ value of the 3D-ISF is 0.345. This may be ascribed to the SiC material in the 3D-ISF and its special microstructure. The high $Z_r$ means that only a small proportion of the incident EM waves is reflected on the 3D-ISF surface. Additionally, the $Z_r$ values of 3D-ISF-II are always higher than that of 3D-ISF-I.
From figure 10(b), the EM waves attenuation abilities of 3D-ISF-I and 3D-ISF-II are much weaker than that of ICF. The $\alpha$ values of ICF are large and range from 709 to 2070, while the $\alpha$ values of 3D-ISF-I range from 13 to 71. Compared with 3D-ISF-I, the $\alpha$ values of 3D-ISF-II increase slightly but the maximum value is only 74. Although the ICF possesses extremely large $\alpha$, it still exhibits poor absorbing performance, indicating that the attenuation constant is not necessarily proportional to the absorbing performance. It is easy to understand that if the $Z_r$ is extremely low, the high EM waves attenuation ability will be meaningless because most of the microwaves are reflected on the surface. The results show that the high $Z_r$ ensures that a large proportion of microwaves enter the 3D-ISF, making the 3D-ISF exhibit such excellent absorbing properties. The increment of the SiC layer thickness makes the $Z_r$ and $\alpha$ increase, which further improves the absorbing performance of 3D-ISF.

To further investigate the importance of the $Z_r$ and $\alpha$ for 3D-ISF, figure 11 shows the frequency-dependent $Z_r$, $\alpha$, and $RL$ values at thickness of 9.5 mm for 3D-ISF-II. It can be seen that when the $Z_r$ and $\alpha$ are 0.395 and 44.589, respectively, the $RL$ achieves the minimum value of $-45.649$ dB. The $Z_r$ corresponding to the minimum $RL$ is closer to the highest value compared with $\alpha$, which signifies that the impedance matching ratio plays a
dominant role in 3D-ISF. Therefore, in the design of advanced absorbing materials, it is necessary to give priority to impedance matching ratio. Only when the $Z_r$ reaches a certain value, the attenuation constant begins to take effect.

4. Conclusions

In summary, the novel three-dimensional interconnected SiC foam with double-layer hollow skeleton (3D-ISF) was experimentally prepared in this study, and the main conclusions are summarized as follows:

1. The morphological results showed the interconnected hollow structure has been successfully synthesized, which was beneficial to the microwave absorption. Meanwhile, numerous columnar SiC defects were observed and played a critical role in the microwave absorption properties.

2. The thickness of SiC layer has remarkable effects on the final microwave absorption properties of 3D-ISF. Compared to 3D-ISF-I, 3D-ISF-II exhibited a better microwave absorbing property, where the optimum reflection loss value of 3D-ISF-II could reach $-45.649$ dB, while the optimum reflection loss of 3D-ISF-I was $-32.070$ dB.

3. The increment of the SiC thickness thickness made the impedance matching ratio ($Z_r$) and the attenuation constant ($\alpha$) increase, resulting in the more outstanding absorbing properties of 3D-ISF-II. Besides, it was...
confirmed that the Zr played a dominant role in 3D-ISF, which provided practical guidance for the design of porous materials.

Acknowledgments

The work reported here was supported by ‘the Fundamental Research Funds for the Central Universities, NO. NS2019035’. Also, the authors would like to thank Shiyanjia Lab (www.shiyanjia.com) for the support of microwave vector network analyzer system.

ORCID iDs

Binbin Li  https://orcid.org/0000-0001-7905-4340

References

[1] Moitra D 2016 Synthesis of Ni0.4Zn0.6Fe2O4–RGO nanocomposite: an excellent magnetically separable catalyst for dye degradation and microwave absorber RSC Adv. 6 14090–6
[2] Yin X, Kong L, Zhang L, Cheng L, Travitzky N and Grell P 2014 Electromagnetic properties of Si–CN based ceramics and composites Int. Mater. Rev. 59 326–55
[3] Kim D H, Kim Y and Kim J W 2016 Transparent and flexible film for shielding electromagnetic interference Mater. Des. 89 703–7
[4] Chen L, Yin X, Fan X, Chen M, Ma X, Cheng L and Zhang L 2015 Mechanical and electromagnetic shielding properties of carbon fiber reinforced silicon carbide matrix composites Carbon 95 10–9
[5] Zong M, Huang Y, Ding X, Zhang N, Qu C and Wang Y 2014 One-step hydrothermal synthesis and microwave electromagnetic properties of RGO/ NiFe2O4 composite Ceram. Int. 40 6821–8
[6] Cheng Y, Cao J, Lv H, Zhao H, Zhao Y and Ji G 2019 In situ regulating aspect ratio of bamboo-like CNTs via CoN1–x–y catalyzed growth to pursue superior microwave attenuation in X-band Inorg. Chem. Front. 6 309–16
[7] Wei C, Liu Q, Zhu X and Min F 2017 One-step in situ synthesis of strontium ferrites and strontium ferrites/graphene composites as microwave absorbing materials RSC Adv. 7 40650–7
[8] Liu F, Ng V M H, Yao Z, Zhou J, Lei Y, Yang Z, Lv H and Kong L B 2017 Facile synthesis and hierarchical assembly of flowerlike NiO structures with enhanced dielectric and microwave absorption properties ACS Appl. Mater. Interfaces 9 16404–16
[9] Shu R, Xing H, Cao X, Ji X, Tan D and Ying G 2016 Preparation, Microwave absorption and infrared emissivity of Ni-doped ZrO2/Al powders by coprecipitation method in the GEz range Nano 11 1650047
[10] Alam R S, Moradi M, Rostami M, Nikmanesh H, Moayedi R and Bai Y 2015 Structural, magnetic and microwave absorption properties of doped Ba-hexaferrite nanoparticles synthesized by co-precipitation method J. Magn. Magn. Mater. 381 1–9
[11] Singh S K, Adhkar M J and Kar K K 2018 Hierarchical carbon nanotube–coated carbon fiber: ultra lightweight, thin, and highly efficient microwave absorber ACS Appl. Materials Interfaces 10 24816–28
[12] Wei H, Yin X, Hou Z, Jiang F, Xu H, Li M, Zhang L and Cheng L 2018 A novel SiC-based microwave absorption ceramic with Sc2Si2O7 as transparent matrix J. Eur. Ceram. Soc. 38 4189–97
[13] Meng S, Guo X, Jin G, Wang Y and Xie S 2012 Preparation and microwave absorbing properties of SiC nanotubes J. Mater. Sci. 47 2899–902
[14] Xiang J, Jiang P, Hou X, Xiao T, Zheng Q, Wang Q, Liu W and Cao W 2019 Dielectric permittivity and microwave absorption properties of SiC nanowires with different lengths Solid State Sci. 91 73–6
[15] Han T, Luo R, Cui G and Wang L 2019 Effect of fibre directionality on the microwave absorption properties of 3D braided SiC/SiC composites Ceram. Int. 45 7797–803
[16] Sun X, He J, Li G, Tang J, Wang T, Guo Y and Xue H 2013 Laminated magnetic graphene with enhanced electromagnetic wave absorption properties J. Mater. Chem. C 1 765–77
[17] Bo W, Cao M, Lu M, Cao W, Shi H, Jia L, Wang X, Jin H, Fang X and Wang W 2014 Reduced graphene oxides: light-weight and high-efficiency electromagnetic interference shielding at elevated temperatures Adv. Mater. 26 3484–9
[18] Lu Y, Wang Y, Li H, Lin Y, Jiang Z, Xie Z, Kuang Q and Zheng L 2015 MOF-derived porous Co/C nanocomposites with excellent electromagnetic wave absorption properties ACS Appl. Mater. Interfaces 7 13604–11
[19] Wang K, Chen Y, Tian R, Li H, Zhou Y, Duan H and Liu H 2018 Porous Co–C core–shell nanocomposites derived from Co-MOF-74 with enhanced electromagnetic wave absorption performance ACS Appl. Mater. Interfaces 10 11333–42
[20] Zhao H-B, Fu Z-B, Chen H-B, Zhong M-L and Wang C-Y 2016 Excellent electromagnetic absorption capability of Ni/Carbon based conductive and magnetic foams synthesized via a green one pot route ACS Appl. Mater. Interfaces 8 1468–77
[21] Farhan S, Wang R and Li K 2016 Carbon foam decorated with silver particles and in situ grown nanowires for effective electromagnetic interference shielding J. Mater. Sci. 51 7991–8004
[22] Kumar R, Gupta A and Dhakate S 2015 Nanoparticles-decorated coal tar pitch-based carbon foam with enhanced electromagnetic radiation absorption capability RSC Adv. 5 20256–64
[23] Farhan S, Wang R and Li K 2016 Electromagnetic interference shielding effectiveness of carbon foam containing in situ grown silicon carbide nanowires Ceram. Int. 42 11330–40
[24] Dong S, Hu P, Zhang X, Han J, Zhang Y and Luo X 2018 Carbon foams modified with in situ formation of Si3N4 and SiC for enhanced electromagnetic microwave absorption property and thermostability RSC Adv. 4 44714–50
[25] Kumar R, Dhakate S R, Gupta T, Saini P and Singh B P 2013 Effective improvement of the properties of light weight carbon foam by decoration with multi-wall carbon nanotubes J. Mater. Chem. A 1 5727–35
[26] Li B, Mao B, Wang X and Huang H 2019 Effect of SiC nanowires on compression and thermal properties of SiC nanowires/lightweight carbon foam composites Mater. Res. Express 6 085002
[27] Bo Z, Sai T, Long X, Yu Y and Wen G 2017 High-efficient production of SiC/SiO2 core–shell nanowires for effective microwave absorption Mater. Des. 121 185–93
Longkullabutra H, Nhuapeng W and Thamjaree W 2012 Large-scale synthesis, microstructure, and FT-IR property of SiC nanowires Curr. Appl Phys. 12 S112–5

Fu Q-G, Li H-J, Shi X-H, Li K-Z, Wei J and Hu Z-B 2006 Synthesis of silicon carbide nanowires by CVD without using a metallic catalyst Mater. Chem. Phys. 100 108–11

Liang X, Quan B, Sun Y, Ji G, Zhang Y, Ma J, Li D, Zhang B and Du Y 2017 Multiple interfaces structure derived from metal-organic frameworks for excellent electromagnetic wave absorption Part. Part. Syst. Char. 34 1700006

Peng Y, Meng Z, Zhong C, Lu J, Yu W, Yang Z and Qian Y 2001 Hydrothermal synthesis of MoS2 and its pressure-related crystallization J. Solid State Chem. 159 170–3

Quan B, Liang X, Xu G, Cheng Y, Zhang Y, Liu W, Ji G and Du Y 2017 Permittivity regulating strategy to achieve high-performance electromagnetic wave absorbers with compatibility of impedance matching and energy conservation New J. Chem. 41 1259–66

Liang X, Quan B, Ji G, Liu W, Zhao H, Dai S, Lv J and Du Y 2017 Tunable dielectric performance derived from the metal-organic framework/reduced graphene oxide hybrid with broadband absorption ACS Sustainable Chem. Eng. 5 10570–9

Wang P, Cheng L and Zhang L 2017 One-dimensional carbon/SiC nanocomposites with tunable dielectric and broadband electromagnetic wave absorption properties Carbon 125 207–20

Liu P, Yao Z, Zhou J, Yang Z and Kong L B 2016 Small magnetic Co-doped NiZn ferrite/graphene nanocomposites and their dual-region microwave absorption performance J. Mater. Chem. C 4 9734–49

Duan W, Yin X, Li Q, Liu X, Cheng L and Zhang L 2017 Synthesis and microwave absorption properties of SiC nanowires reinforced SiOC ceramic J. Eur. Ceram. Soc. 34 257–66

Liang X, Zhang X, Liu W, Tang D, Zhang B and Ji G 2016 A simple hydrothermal process to grow MoS2 nanosheets with excellent dielectric loss and microwave absorption performance J. Mater. Chem. C 4 6816–21

Li N, Huang G-W, Li Y-Q, Xiao H-M, Feng Q-P, Hu N and Fu S-Y 2017 Enhanced microwave absorption performance of coated carbon nanotubes by optimizing the Fe3O4 nanocoating structure ACS Appl. Mater. Interfaces 9 2973–83

Duan W Y, Yin X W, Ye F., Li Q., Han M K, Liu X F and Cai Y Z 2016 Synthesis and EMW absorbing properties of nano SiC modified PDC–SiOC J. Mater. Chem. C 4 5962–9

Zhao B, Shao G, Fan B B, Zhao W Y, Zhang S H, Guan K K and Zhang R 2015 In situ synthesis of novel urchin-like ZnS/NiS2/γ-Ni composite with a core–shell structure for efficient electromagnetic absorption J. Mater. Chem. C 3 10862–9

Qiu X, Wang L, Zhu H, Guan Y and Zhang Q 2017 Lightweight and efficient microwave absorbing materials based on walnut shell-derived nano-porous carbon Nanoscale 9 7408–18

Li X, Lv D and Chen K 2012 Effects of graphite additive on dielectric properties and microwave absorption properties of zinc-containing foam glass J. Non-Cryst. Solids 358 2917–21

Chen K, Li X, Lv D, Yu F, Yin Z and Wu T 2011 Study on microwave absorption properties of metal-containing foam glass Mater. Sci. Eng. B 176 1239–42

Liang X, Quan B, Ji G, Liu W, Cheng Y, Zhang B and Du Y 2016 Novel nanoporous carbon derived from metal-organic frameworks with tunable electromagnetic wave absorption capabilities Inorg. Chem. Front 3 1516–26

Wang P, Cheng L, Zhang Y, Yuan W, Pan H and Wu H 2018 Electrospinning of graphite/SiC hybrid nanowires with tunable dielectric and microwave absorption characteristics Compos. Part A 104 68–80