

# Terahertz Wave Shielding of Carbon Nanotube-Organic Silicone

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**ABSTRACT:** We have developed a carbon nanotube organic silicone rubber (CNT-OSR) composite medium, composed of methyl trifluoropropyl silicone rubber as the matrix, with different mass fractions of carbon nanotubes added and formed through vulcanization using a bis (cyclopentadiene) vulcanizing agent. The CNT-OSR composite media with carbon nanotube contents of 2 wt%, 5 wt%, and 8 wt% were tested, and the maximum absorption and shielding efficiencies of the media for terahertz waves in the 0.5–1.0 THz frequency range were found to be 69.77 dB, 76.28 dB, and 63.69 dB, respectively. Through impedance matching theory analysis, the absorption and shielding effectiveness of the medium for terahertz waves were confirmed. Additionally, the composite medium exhibits excellent hydrophobic properties. It provides a simple and feasible approach for developing lightweight, efficient, and multifunctional terahertz wave absorbing and shielding materials for the next generation of terahertz wireless communication.

## 1. INTRODUCTION

Terahertz technology has shown great potential for applications in biomedical, high-speed wireless communication, spectral analysis, and other fields [1, 2]. The new future communication technologies represented by 6G communication will not only promote social progress, but also exacerbate electromagnetic pollution. Electromagnetic interference (EMI) or radiation can harm human health and disrupt the normal operation of electronic devices [3, 4]. Therefore, it is crucial to develop thin and lightweight high-efficiency terahertz wave shielding materials [5]. However, traditional electromagnetic shielding materials mainly improve their electromagnetic shielding effectiveness by enhancing the reflection of electromagnetic waves, which can cause secondary electromagnetic pollution problems. In order to reduce reflection and control secondary electromagnetic pollution, researchers have started designing some high-absorption electromagnetic shielding materials in recent years. For example, in 2022, Xie et al. [6] studied layered MXene-based hybrid aerogels, and M-120 aerogels achieved the highest absorption and shielding efficiency of 58 dB for terahertz waves in the frequency band of 0.5~3 THz. In 2023, Ji et al. [7] proposed porous graphene and titanium nitride nanoparticles (LIG/TiCN) composites, and achieved the absorption and shielding efficiency of 33 dB in the frequency band of 0.1~3 THz. In 2024, Su et al. [8] prepared sandwich shaped MXene/SiC (MSiOC) composite materials with a terahertz wave absorption shielding efficiency of 30 dB in the frequency range of 0.2–1.6 THz. In 2025, Hassan et al. [9] studied carbon-doped hexagonal boron nitride (hBN) thin film materials, achieving an absorption shielding efficiency of 55 dB in the frequency range of 0.3–1.8 THz. In 2025, Zhang et al. [10] developed a core-shell structure  $\text{Fe}_3\text{O}_4@/\text{VO}_2/\text{Ti}_3\text{C}_2\text{T}_x$  film achieved the highest absorption shielding efficiency of 35.67 dB in the frequency range of 0.1–3 THz. Developing

environmentally friendly, efficient, and low reflection electromagnetic shielding materials has become a research focus in this field.

In this article, we used methyl trifluoropropyl silicone rubber and carbon nanotubes to composite carbon nanotube organic silicone rubber materials with nanotube mass fractions of 2 wt%, 5 wt%, and 8 wt%, and studied their electromagnetic shielding effectiveness in the terahertz band. The test results show that the carbon nanotube organic silicone rubber composite material with a carbon nanotube content of 5 wt% has an absorption rate of 99.9% for terahertz waves in the frequency range of 0.5–1.0 THz, and the highest shielding efficiency is 76.29 dB. The characteristic impedance analysis shows that the developed composite material exhibits excellent absorption and shielding characteristics.

## 2. SAMPLE PREPARATION

Using methyl trifluoropropyl silicone rubber (FVMQ) as the matrix, carbon nanotubes with mass fractions of 2 wt%, 5 wt%, and 8 wt% were added, and disulfide (2,5-dimethyl-2,5-dihexane, dBPH) was used for vulcanization molding. Firstly, the filler dispersion process is implemented through a double roll open mill, and carbon nanotubes are gradually added into the raw rubber system in batches. After multiple passes of mixing and refining, the uniform distribution of fillers is achieved. Subsequently, sulfurizing agent was added at a ratio of 1.5 phr and continued to mix to ensure system homogenization. Finally, a flat vulcanizing machine was used for hot pressing and shaping. The process parameters were set to a temperature of 185° and a pressure of 10 MPa. After injecting the premixed rubber material into a specific height mold, three rounds of air extraction and defoaming were completed within 10 seconds, followed by another one-minute interval for exhaust. Finally, hot pressing was maintained for 10 minutes to complete the vulcanization process. This

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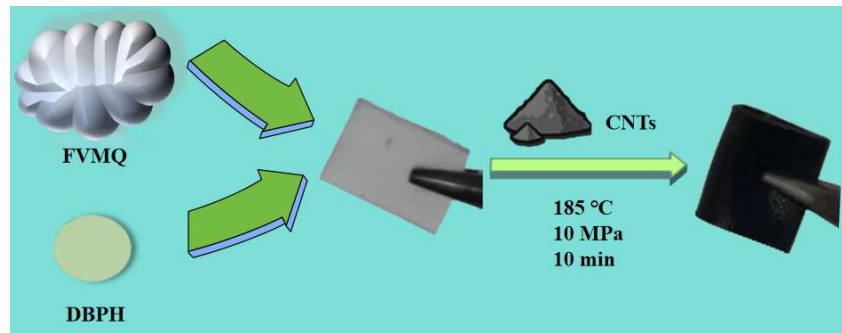


FIGURE 1. Fabrication of CNT-OSR composite medium.

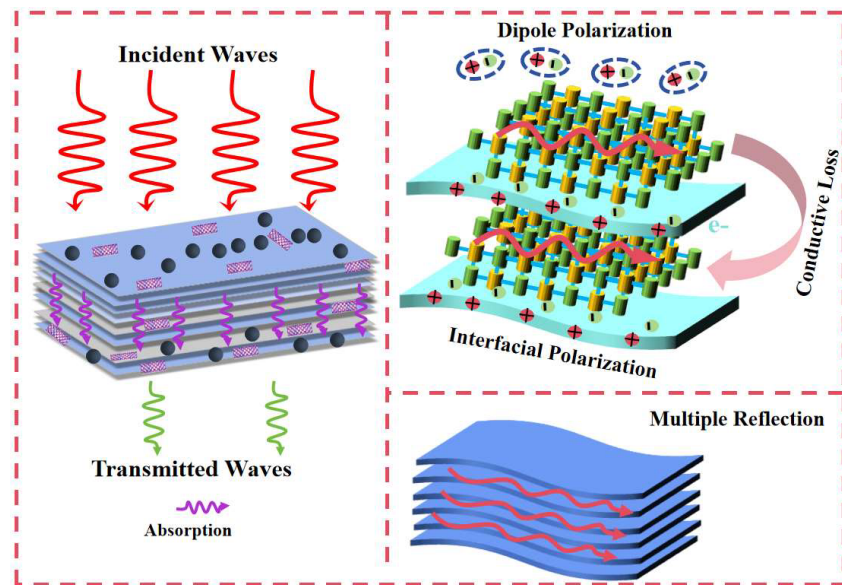


FIGURE 2. Terahertz electromagnetic shielding mechanism of CNT-OSR composite material.

preparation method is also applicable to organic silicone rubber matrices with different filling materials. The filling materials can be prepared by changing from carbon nanotubes to carbon black or graphene. The preparation process of the CNT-OSR composite material is shown in Figure 1. The disulfide used in the preparation process of the composite medium is from Aladdin, with a purity of 93%. The carbon nanotubes are purchased from Chengdu Organic Chemical Co., Ltd. The methyl trifluoropropyl silicone rubber raw rubber is from Aladdin, with a purity of over 95%. All chemicals are of analytical grade and do not require further purification before use. Figure 2 illustrates the terahertz electromagnetic shielding mechanism of CNT-OSR composite material. The high absorption of terahertz waves by CNT-OSR is caused by interface polarization, dipole polarization, conduction loss, and multiple internal reflections. The scanning electron microscope (SEM) images of carbon nanotube organic silicone rubber with different carbon nanotube contents at a magnification of 10 k are shown in Figures 3(a)–3(c). The X-ray diffraction (XRD) characterization curve of the composite material is shown in Figure 3(d). The four composite media produce diffraction peaks at  $2\theta = 11.5^\circ \sim 12.5^\circ$ , which

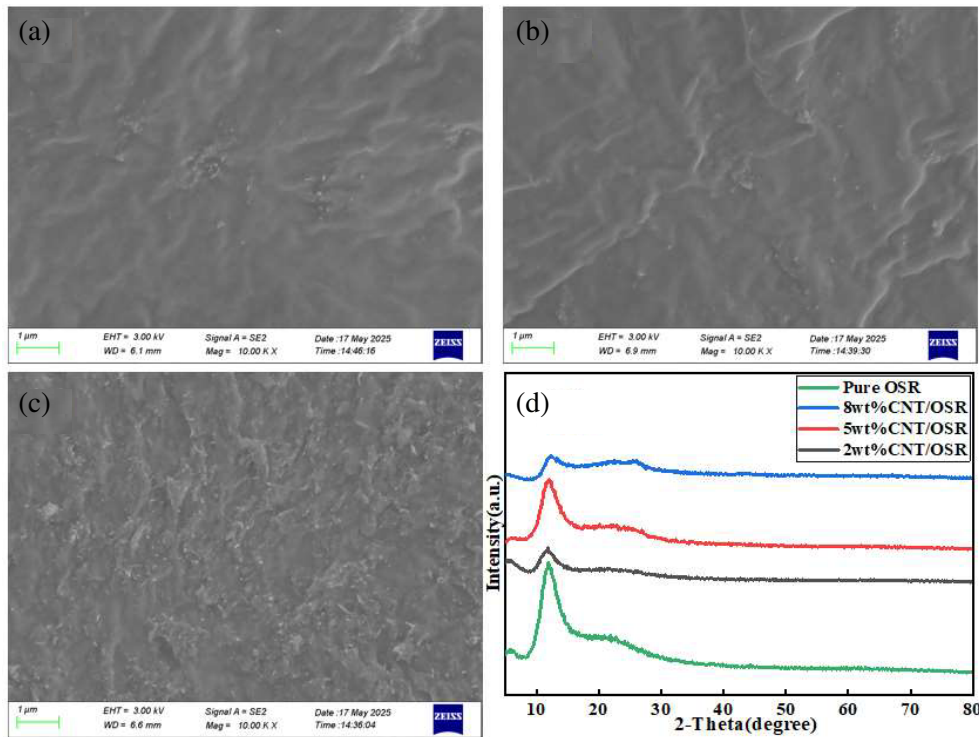
represent the amorphous structure of the silicone rubber. As the concentration of carbon nanotubes increases, the composite material produces diffraction peaks, representing the CNT002 peak plane at around  $2\theta = 26^\circ$ .

### 3. EXPERIMENTAL RESULTS ANALYSIS

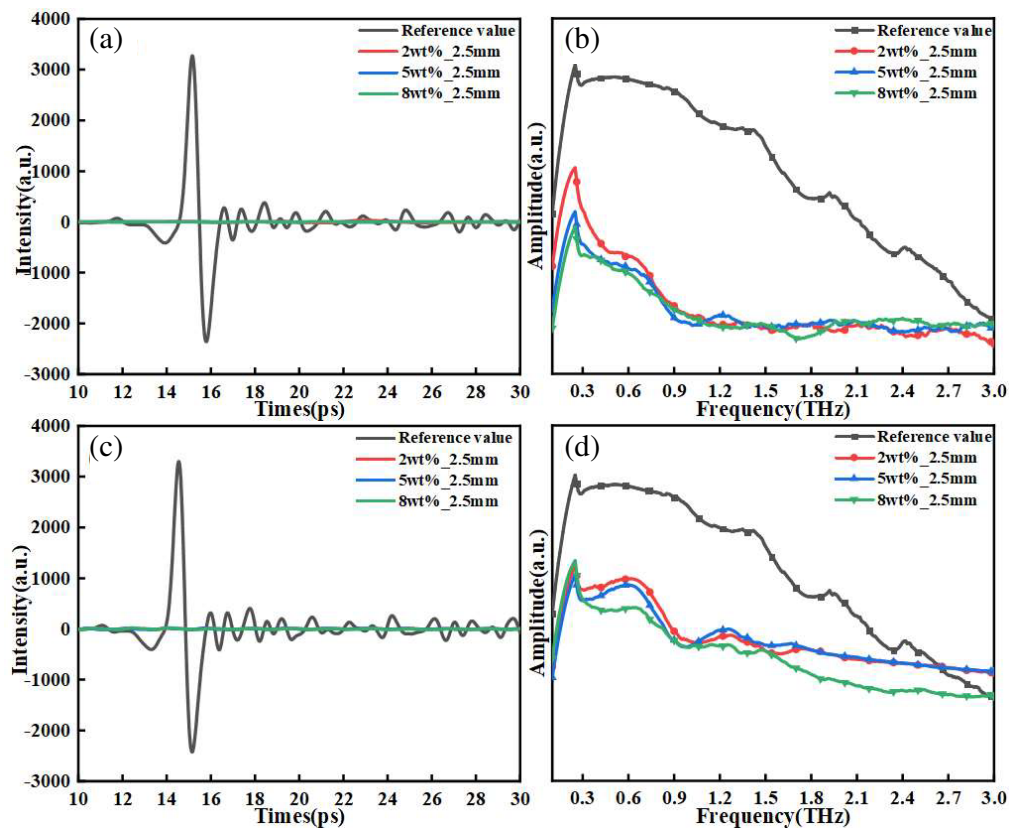
The terahertz transmission and reflection time-domain spectra of CNT-OSR composite media with different carbon nanotube contents were tested using a terahertz time-domain spectroscopy system (THz-TDS) at room temperature, as shown in Figures 4(a) and 4(c). The transmission and reflection frequency-domain spectra obtained by fast Fourier transform of the time-domain spectra are shown in Figures 4(b) and 4(d). The transmittance ( $T$ ), reflectance ( $R$ ), and absorption ( $A$ ) of CNT-OSR composite media can be calculated by

$$T(\%) = \left[ \frac{E_s^{(T)}(\omega)}{E_r^{(T)}(\omega)} \right]^2 \times 100\% \quad (1)$$

$$R(\%) = \left[ \frac{E_s^{(R)}(\omega)}{E_r^{(R)}(\omega)} \right]^2 \times 100\% \quad (2)$$



**FIGURE 3.** Scanning electron microscopy (SEM) images and XRD pattern of CNT-OSR, (a) CNT-OSR with carbon nanotubes mass fractions of 2 wt% at  $\times 10$  k, (b) CNT-OSR with carbon nanotubes mass fractions of 5 wt% at  $\times 10$  k, (c) CNT-OSR with carbon nanotubes mass fractions of 8 wt% at  $\times 10$  k, (d) XRD pattern of the CNT-OSR.



**FIGURE 4.** Terahertz spectra of CNT-OSR composite materials: (a) Transmission time-domain spectrum, (b) Transmission frequency-domain spectrum, (c) Reflection time-domain spectrum, (d) Reflection frequency-domain spectrum.

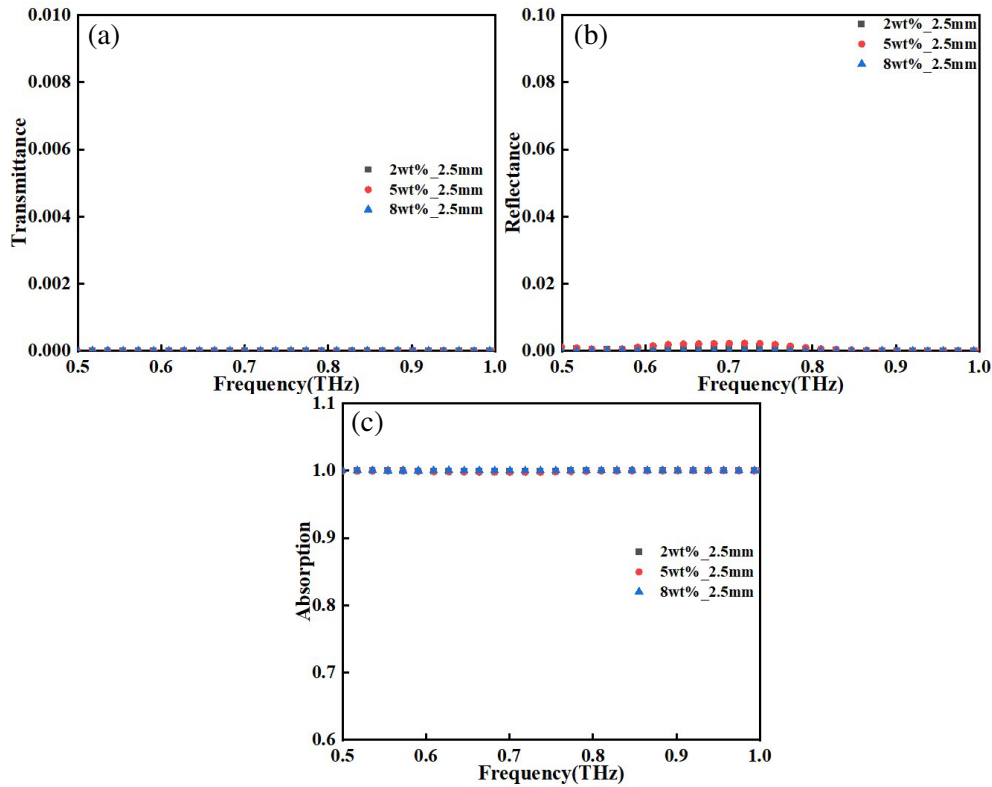


FIGURE 5. Terahertz performance of the CNT-OSR composite material, (a) Transmittance, (b) Reflectivity, (c) Absorption.

$$A(\%) = 100\% - T(\%) - R(\%) \quad (3)$$

According to the above equations, the terahertz spectra of CNT-OSR composite media were calculated, as shown in Figure 5. All three composite media achieved a 99.9% absorption rate of terahertz waves in the 0.5–1.0 THz frequency range, with a transmittance of less than 0.1% and a reflectance of less than 0.1%.

The total shielding effectiveness ( $SE_T$ ), absorption shielding effectiveness ( $SE_A$ ), and reflection shielding effectiveness ( $SE_R$ ) of composite media can be calculated by:

$$SE_T = -20\lg \frac{E_s^T(\omega)}{E_r^T(\omega)} \quad (4)$$

$$SE_A = -10\lg \frac{T}{1-R} \quad (5)$$

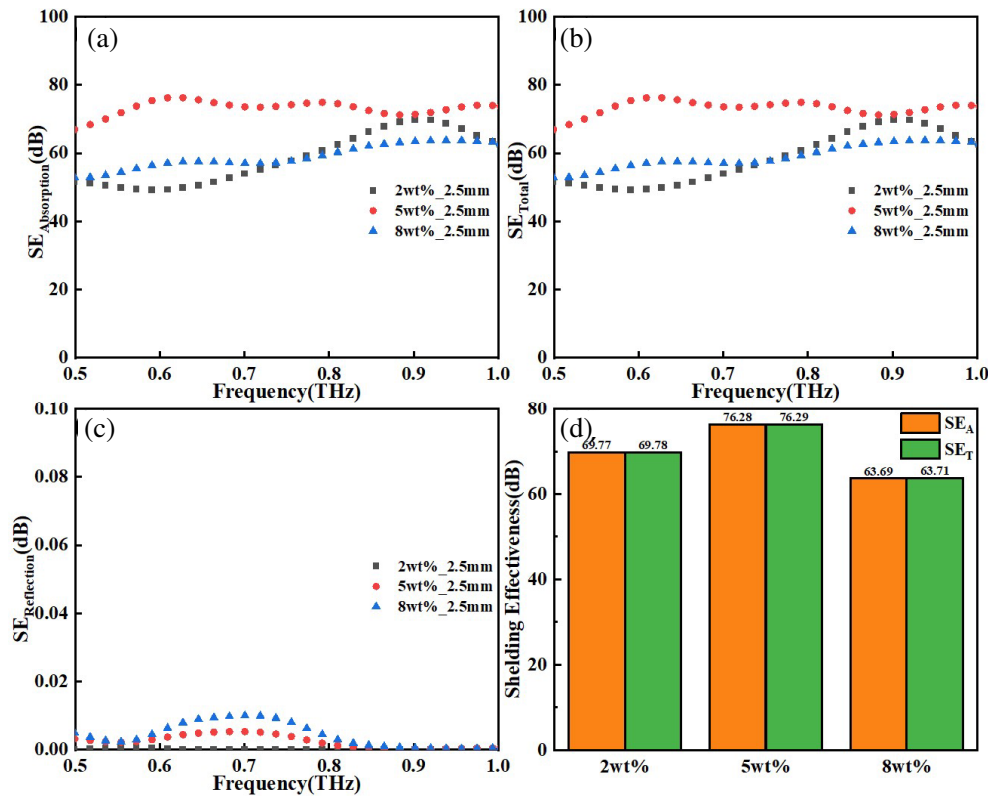
$$SE_R = -10\lg(1-R) \quad (6)$$

$$SE_T = SE_A + SE_R + SE_M \quad (7)$$

The calculated terahertz shielding effectiveness (EMI SE) of the composite material is shown in Figure 6. From Figure 6(a), it can be seen that the CNT-OSR composite material with a CNT content of 2 wt% has a maximum  $SE_A$  of 69.77 dB in the frequency range of 0.5–1.0 THz, the composite material with a CNT content of 5 wt% has a maximum  $SE_A$  of 76.28 dB, and the composite material with a CNT content of 8 wt% has a maximum  $SE_A$  of 63.69 dB. From Figure 6(b), it can also be found that the CNT-OSR composite material with a CNT content of 2 wt% has a maximum  $SE_T$  of 69.78 dB in the frequency range of 0.5–1.0 THz; the composite material with a CNT content of

5 wt% has a maximum  $SE_T$  of 76.29 dB; and the composite material with a CNT content of 8 wt% has a maximum  $SE_T$  of 63.71 dB. From Figure 6(c), it can be noted that the  $SE_R$  of all three composite materials is lower than 0.1 dB. Comparing the  $SE_A$  and  $SE_T$  of composite materials with different carbon nanotube contents, the composite material achieves terahertz wave shielding with electromagnetic absorption as the main component, and the high overall shielding efficiency  $SE_T$  is mainly attributed to the high  $SE_A$  of the composite medium, as shown in Figure 6(d). When the content of carbon nanotubes in the composite medium is 5 wt%, CNTs are uniformly dispersed to form a continuous conductive network, which promotes the synergistic enhancement of interface polarization, dipole polarization, and conduction loss. The impedance and free space matching are optimal, and the shielding effectiveness reaches the highest value. When the carbon nanotube content is 8 wt%, local aggregation occurs when the carbon nanotube exceeds the dispersion threshold, interrupting the conductive path and reducing the polarization active sites, resulting in a decrease in the dissipation ability of terahertz waves and a decrease in shielding effectiveness.

Carbon nanotubes and sulfurizing agents were weighed using an analytical balance with an accuracy of  $\pm 0.1$  mg, ensuring that the mass fraction deviation of CNTs was controlled within  $\pm 0.05$  wt%. Each sample was measured at five random locations with a micrometer, yielding an average thickness of  $2.50 \pm 0.03$  mm (relative deviation 1.2%). The composite dielectric material was repeatedly measured three times using THz-TDS during testing, SET calculation error within 0.1 dB, and dielectric constant real and imaginary parts cal-



**FIGURE 6.** Terahertz shielding properties of the CNT-OSR composite material, (a)  $SE_A$ , (b)  $SE_T$ , (c)  $SE_R$ , (d) Comparison between  $SE_A$  and  $SE_T$ .

culation errors below 0.001. Analysis of the composite material with 5 wt% CNT content showed a positive correlation between the total shielding effectiveness and thickness according to transmission line theory. With a thickness relative deviation of 1.2%, the total shielding effectiveness absolute error was approximately  $76.29 \text{ dB} \times 1.2\% \approx 0.92 \text{ dB}$ . Assuming independent errors in repeatability measurements and thickness, the total uncertainty was calculated by  $\sqrt{0.92^2 + 0.1^2} \approx 0.925 \text{ dB}$ . With a coverage factor  $k = 2$  corresponding to a 95% confidence level, the expanded uncertainty was  $2 \times 0.925 = 1.85 \text{ dB}$ . Therefore, the total shielding effectiveness of the composite material with 5 wt% CNT content in the 0.5~1.0 THz frequency band was  $76.29 \pm 1.85 \text{ dB}$ .

The absorption of a composite medium is usually related to the complex permittivity, with the real part and imaginary part corresponding to the storage and dissipation capacity of the composite medium for terahertz waves, respectively. Figures 7(a)–7(c) show the complex permittivity versus loss angle tangent ( $\tan\delta$ ) curves for the proposed composite media with different carbon nanotube contents. When the carbon nanotube content increases from 2 wt% to 8 wt%, the dielectric loss tangent of the composite dielectric constant gradually increases. The normalized impedance and attenuation coefficient of the CNT-OSR composite material with air are calculated by

$$Z = \text{Sqrt}[(\mu_0/\epsilon')/(1 - j \tan \delta)] \quad (8)$$

$$\alpha = \frac{\sqrt{2\pi}f}{c} \sqrt{\mu''\epsilon'' - \mu'\epsilon' + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\mu'\epsilon'' + \mu''\epsilon')^2}} \quad (9)$$

where  $\mu = 4\pi \times 10^{-7}$ ,  $\tan\delta = \epsilon''/\epsilon'$ ,  $\epsilon'$  is the real part of the dielectric constant,  $\epsilon''$  the imaginary part of the dielectric constant,  $c$  the speed of light in vacuum, and  $f$  the frequency,  $\mu' = 1$ ,  $\mu'' = 0$ . Taking the CNT-OSR composite material with a CNT content of 5 wt% as an example, the normalized impedance and attenuation constant curve of the CNT-OSR composite material were calculated using Equations (8)–(9), as shown in Figure 8. From Figure 8(a), it can be seen that in the frequency range of 0.5–1.0 THz, the real part of the normalized impedance is 1.01–1.10, and the imaginary part is close to 0, indicating that the impedance of the composite material matches the impedance in free space, further confirming that the composite material has very little reflection of terahertz waves. From Figure 8(b), it can be seen that in the frequency range of 0.5–1.0 THz, the attenuation coefficient  $\alpha$  of the composite material increases from 8031.8 to 10474.7 with the increase of frequency, indicating excellent terahertz wave dissipation ability in the prepared CNT-OSR composite material. In addition, the CNT-OSR composite material has excellent superhydrophobic properties, as shown in Figure 9, enhancing the application scenarios of the composite material. Table 1 compares the total terahertz shielding effectiveness of CNT-OSR composite material with some reported studies and shows that CNT-OSR composite material has advantages in shielding effectiveness.

We constructed an empirical model to fit the relationship between the dielectric constant and shielding effectiveness of composite media. Taking the CNT content  $p$  (2 wt%, 5 wt%, 8 wt%) as the variable, the fitted equations are  $\epsilon'(p) = 2.5 + 0.14p$  and  $\epsilon''(p) = 0.4 + 0.041p$ . The SET can then be obtained

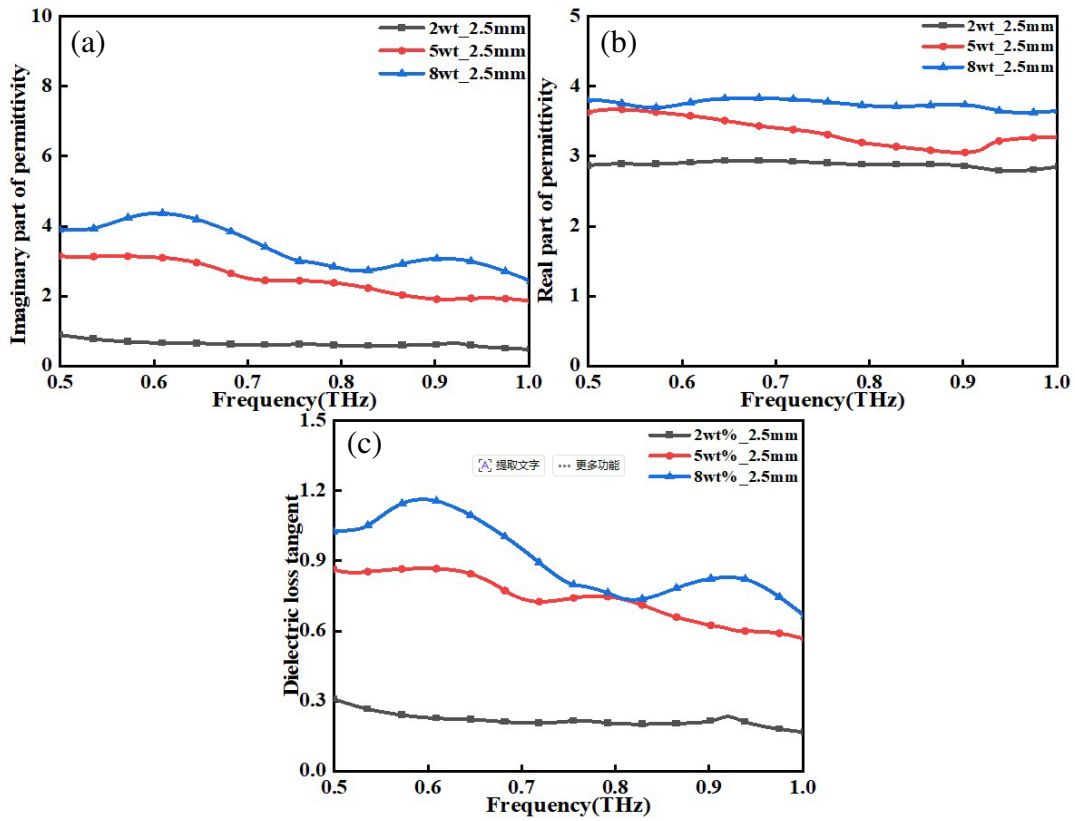


FIGURE 7. Dielectric properties of the composite medium: (a)Imaginary part of permittivity, (b) Real part of permittivity, (c) Dielectric loss tangent.

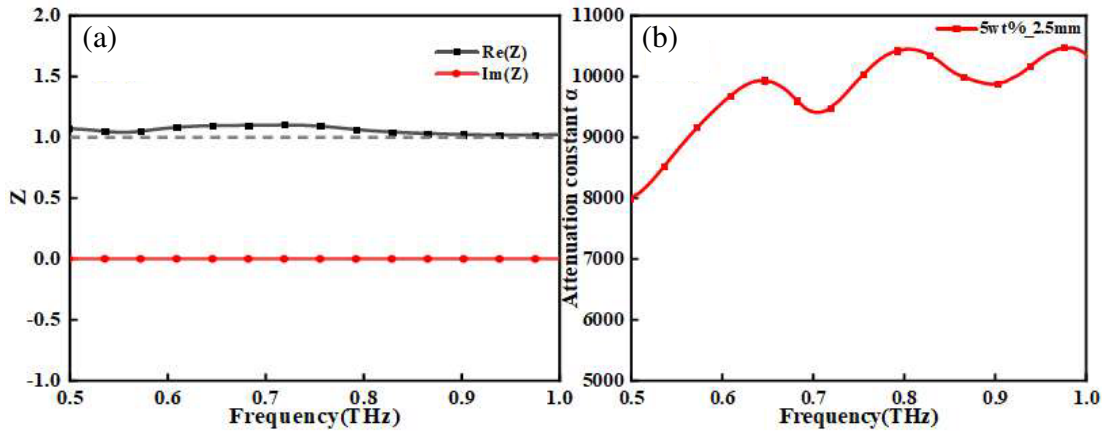


FIGURE 8. (a) Normalized impedance (Z) of the CNT-OSR with carbon nanotubes mass fractions of 5 wt%, (b) Attenuation constant ( $\alpha$ ) of the CNT-OSR with carbon nanotubes mass fractions of 5 wt%.

by

$$SE_T(p, f, d) = 8.686d \times \frac{\pi f}{c} \times \sqrt{2\epsilon'p \times (\sqrt{1 + \tan^2 \delta(p)} - 1)} \quad (10)$$

By substituting the carbon nanotube content  $p = 5 \text{ wt\%}$ , composite dielectric thickness  $d = 2.5 \text{ mm}$ , and frequency  $f = 1.0 \text{ THz}$  into the equation, the SET predicted result is calculated to be 76.5 dB, which is highly consistent with the experimental value of 76.29 dB.

When the content of carbon nanotubes is 5 wt%, and the thickness of CNT-OSR changes from 1 mm to 2.5 mm, the changes in the absorption rate and absorption shielding effectiveness of the composite medium for terahertz waves are shown in Figure 10. When the thickness is increased from 1 mm to 2 mm, the absorption rate and shielding effectiveness of the composite medium for terahertz waves steadily improve. When the thickness is 2.5 mm, the shielding effectiveness of the composite medium for terahertz waves reaches its optimal value. The optimized size obtained in this article is 2.5 mm, as shown

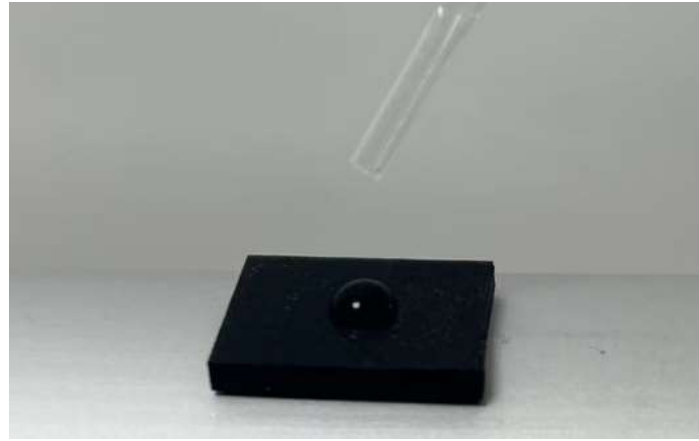


FIGURE 9. Hydrophobic properties of CNT-OSR composite material.

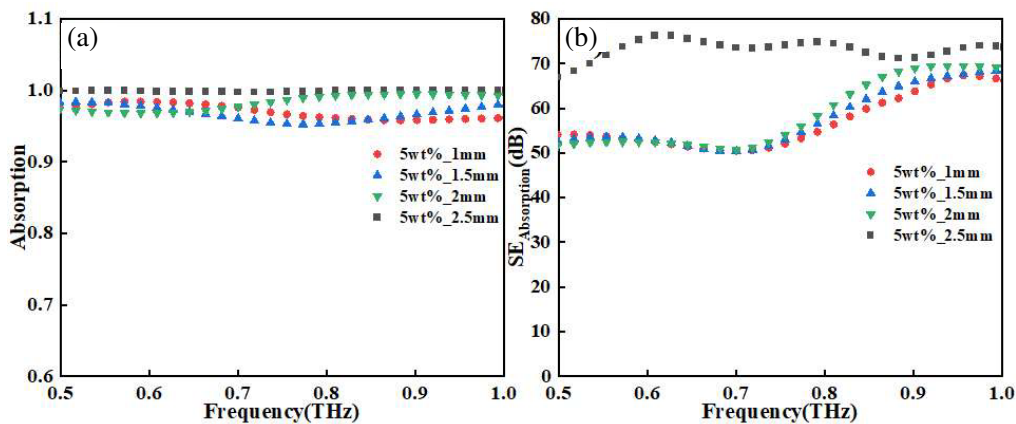


FIGURE 10. Terahertz wave absorption and absorption shielding effectiveness of composite media with different thicknesses.

TABLE 1. Terahertz shielding performance of this work compared with reported studies.

Ref	Materials	Thickness (mm)	Band (THz)	$SE_T$ (dB)
11	CNF/SBC	3	0.4–2	70
12	ATO/PAAm-CSDN	2	0.4–1.0	60.2
13	PVA/I-P-rGO	1	0.2–2.0	22.4
14	TiO-TiO <sub>2-<math>\delta</math></sub>	0.00051	0.2–1.3	13
15	$\beta_{12}$ -Br/PDMS	2	0.5–2	70
This work	CNT-OSR	2.5	0.5–1.0	76.29

in Figure 10. Thin cutting thickness can be achieved using micro milling technology, with an accuracy of up to 0.01 mm.

#### 4. CONCLUSION

We prepared carbon nanotube-organic silicone rubber (CNT-OSR) composite materials and tested their shielding properties against terahertz waves. The results show that when the carbon nanotube content increases from 2 wt% to 5 wt%, the nanotubes are uniformly dispersed in the silicone rubber matrix and form a continuous conductive network. This synergistically enhances interfacial polarization, dipole polarization, and conduction loss effects, aligning the composite dielectric with

free-space impedance. It achieves a 99.9% terahertz absorption rate in the 0.5–1.0 THz frequency band, with a maximum total shielding effectiveness of 76.29 dB. When the content further increases to 8 wt%, the carbon nanotubes exceed the dispersion threshold, leading to local agglomeration, which disrupts the continuous conductive pathways, reduces polarization-active sites, and weakens the composite's dissipation capability for terahertz waves, resulting in a decline in absorption shielding effectiveness to 63.69 dB. Through impedance analysis and attenuation constant calculation, it is further confirmed that the CNT-OSR composite material has low reflection for terahertz waves and an absorption-dominant terahertz shielding effec-

tiveness. In addition, the material shows excellent superhydrophobic properties, which can be used in extreme rainstorm weather. The prepared CNT-OSR composite material has important application value in the fields of high-precision electronic device protection, information leakage prevention, and terahertz stealth technology in the future due to its advantages of low reflection and strong shielding effectiveness.

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