Supporting Information

MOFs-Derived CNFs@Co/C Fibers with Adjustable Cavity Size for Efficient Electromagnetic Wave Absorption

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Radar cross section (RCS) simulation

In order to study the actual response of hollow CNFs@Co/C fibers samples to electromagnetic wave (EMW), ANSYS Electronics Desktop 2024 (HFSS) software was used to simulate the RCS of EMW absorbers. The model is a double-layer rectangular body composed of an absorbing sample and a perfect electrical conductor (PEC). The thickness of the sample and PEC are 2.4 mm and 2 mm, respectively, and their side lengths are 180 mm. The model is placed on the *XOY* plane, and the EMW are emitted in the negative direction of the *Z*-axis, while the polarization direction propagates along the *X*-axis. The boundary condition on the *X* and *Y* axis is 200 mm. The scattering direction is determined by θ and *phi* in spherical coordinates. The monitoring frequency is 12.72 GHz. It is generally accepted that the scattering directions of RCS value (σ) can be determined by theta and phi in spherical coordinates, which can be described as:

$$\sigma\left(\mathrm{dBm}^2\right)=10\log\left(\left(4\pi S/\lambda^2\right)\left|E_s/E_i\right|\right)^2 \quad \text{(S1)}$$

where S, λ, E_s, and E_i denote the area of the simulated absorbing model, wavelength, electric field intensity of transmitting wave, and receiving wave, respectively:

EMW absorption performance analysis

The reflection loss is generally used to represent the absorption intensity of EMW by materials, which is the most important indicator to measure the electromagnetic wave absorption performance of materials. The reflection loss (RL) of absorption materials can be calculated by the following formula:

$$Z_{in}=Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left[j\left(\frac{2\pi fd}{c}\right)\sqrt{\varepsilon_r\mu_r}\right] \quad \text{(S2)}$$

$$RL = 20\lg\left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right| \tag{S3}$$

where Z_{in} represents the normalized input impedance, Z_0 is the impedance of free space, c, f and d are the light speed, microwave frequency, and thickness, respectively, ε_r and μ_r refer to the complex permittivity and complex permeability.

The loss factor can be calculated by the following formula:

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon')^2 + (\mu''\varepsilon'' + \mu'\varepsilon')}} \tag{S4}$$

Impedance matching of samples can be represented by the following formula:

$$\frac{Z_{in}}{Z_0} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left[j\left(\frac{2\pi fd}{c}\right)\sqrt{\varepsilon_r\mu_r} \right] \tag{S5}$$

where Z_0 is the wave impedance of the material, and Z_{in} is the wave impedance of free space, μ_r and ε_r are the complex permeability and complex permittivity of the material, c, f and d are the speed of light, frequency, and sample thickness, respectively.

Debye relaxation correction formula (S6, S7):

$$\varepsilon_r - \varepsilon_\infty = \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (\iota\omega\tau)^{1-\alpha}} (0 < \alpha < 1) \tag{S6}$$

$$\varepsilon_r' = \varepsilon_{r\infty} + (\varepsilon_{rs} - \varepsilon_{r\infty}) \frac{1 + (\omega\tau)^{(1-\alpha)} sin\frac{\pi\alpha}{2}}{1 + 2(\omega\tau)^{(1-\alpha)} sin\frac{\pi\alpha}{2} + (\omega\tau)^{2(1-\alpha)}} \tag{S7}$$

in this equation, ε_r is the complex permittivity, ε_0 and ε_∞ are the ‘‘static’’ and ‘‘infinite frequency’’ permittivity, ω=2πf, and τ is a generalized relaxation time.

ε_p'' and ε_c'' are the dielectric loss contributed by polarization relaxation and charge transport, respectively, which can be obtained according to Debye theory (S8-10):

$$\varepsilon'' = \frac{\varepsilon_s - \varepsilon_\infty}{1 + (2\pi f)^2 \tau^2} \omega\tau + \frac{\sigma}{2\pi f \varepsilon_0} = \varepsilon_p'' + \varepsilon_c'' \tag{S8}$$

$$\varepsilon_c'' = \frac{\sigma}{2\pi f \varepsilon_0} \quad \text{(S9)}$$

$$\varepsilon_p'' = \frac{\varepsilon_s - \varepsilon_\infty}{1 + (2\pi f)^2 \tau^2} \omega\tau = \varepsilon'' - \varepsilon_c'' \quad \text{(S10)}$$

where ε_s is the relative permittivity at static, and ε_∞ is the "infinite" high frequency, σ is the conductivity

It is generally recognized that the Cole-Cole semicircle can be explained by the relaxation process, and the relationship between ε′ and ε″ can be expressed as (S11):

$$\left(\varepsilon' - \frac{\varepsilon_s + \varepsilon_\infty}{2}\right)^2 + \left(\varepsilon''\right)^2 = \left(\frac{\varepsilon_s - \varepsilon_\infty}{2}\right)^2 \quad \text{(S11)}$$

each semicircle in the ε'-ε'' curve stands for a polarization relaxation process. The ε_s and ε_∞ represent the static permittivity, the permittivity at infinite frequency, respectively. The large number of semicircles means the strong dipole polarization process.

The eddy current effect factor (C_0), which were calculated by the following formula (S12)

$$C_0 = \mu'' \left(\mu'\right)^{-2} f^{-1} = 2\pi\mu_0 d^2 \sigma \quad \text{(S12)}$$

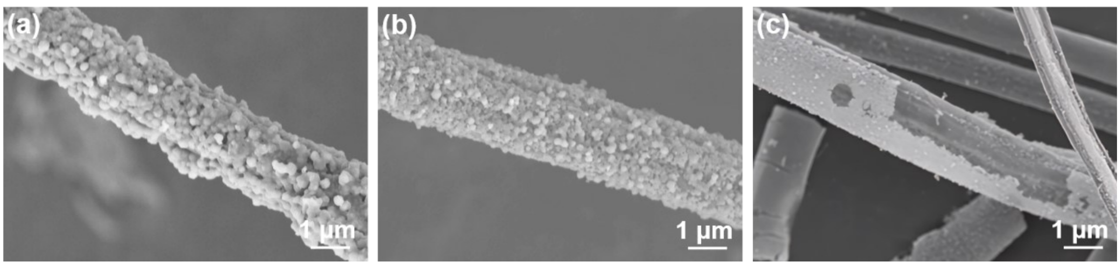

Fig. S1. SEM images of (a) CNFs@Co/C-1, (b) CNFs@Co/C-2, (c) CNFs@Co/C-3.

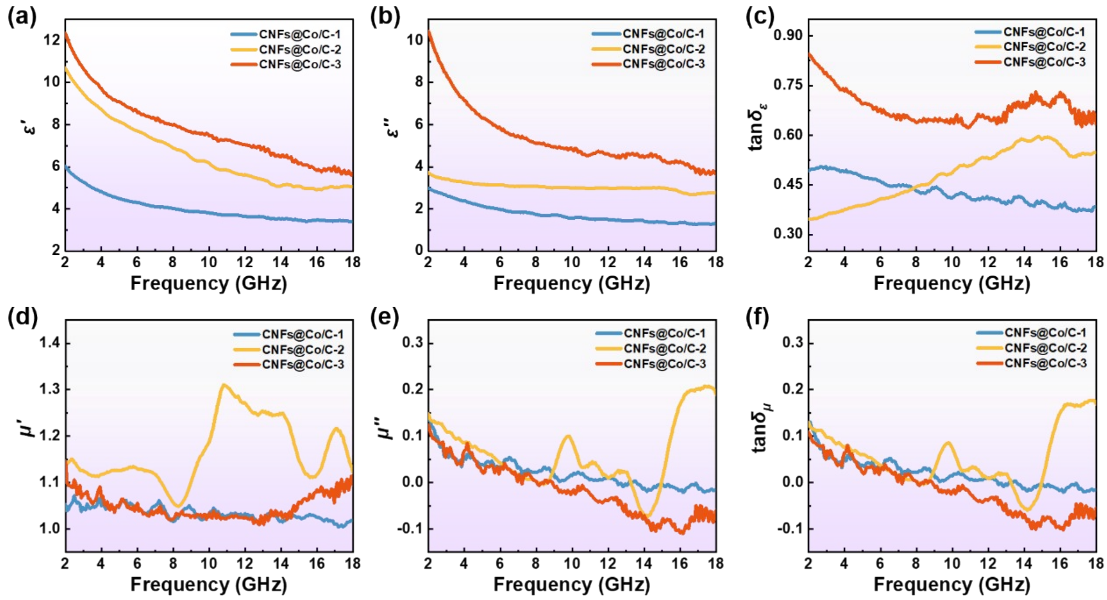

Fig. S2. (a) ε', (b) ε'' and (c) tanδ_{ε}, (d) μ', (e) μ'' and (f) tanδ_{μ} of CNFs@Co/C-1, CNFs@Co/C-2 and CNFs@Co/C-3.

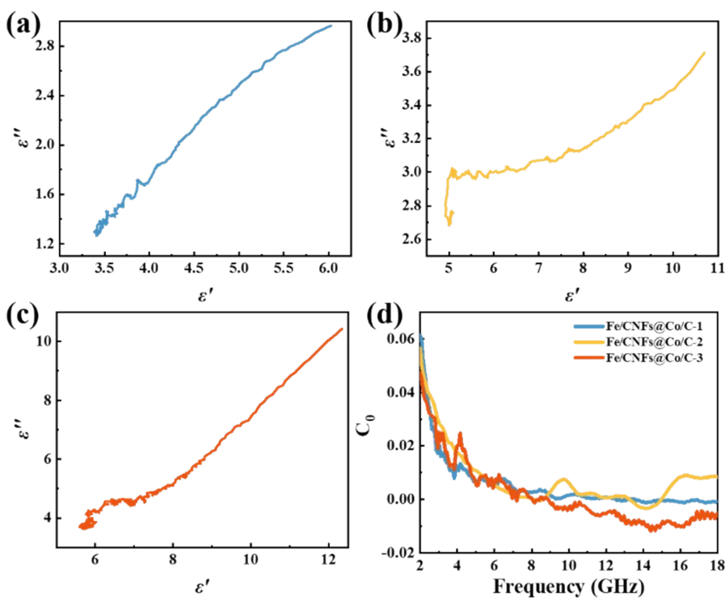

Fig. S3. Cole-Cole curves of (a) CNFs@Co/C-1, (b) CNFs@Co/C-2, (c) CNFs@Co/C-3; (d) C0 curves of hollow CNFs@Co/C fibers.

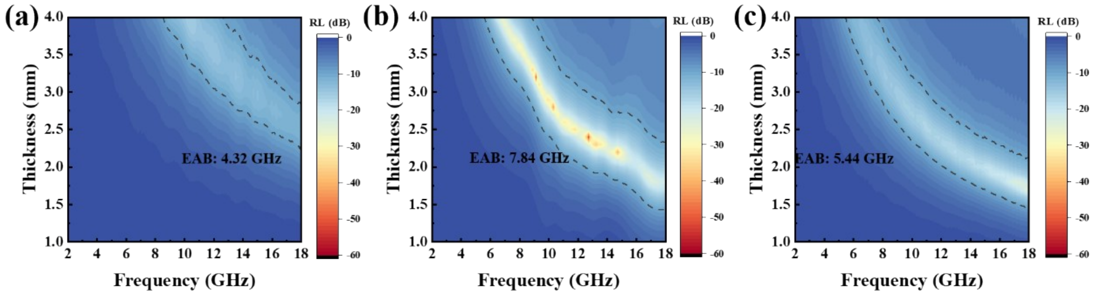

Fig. S4. 2D projection images of (a) CNFs@Co/C-1, (b) CNFs@Co/C-2, (c) CNFs@Co/C-3.

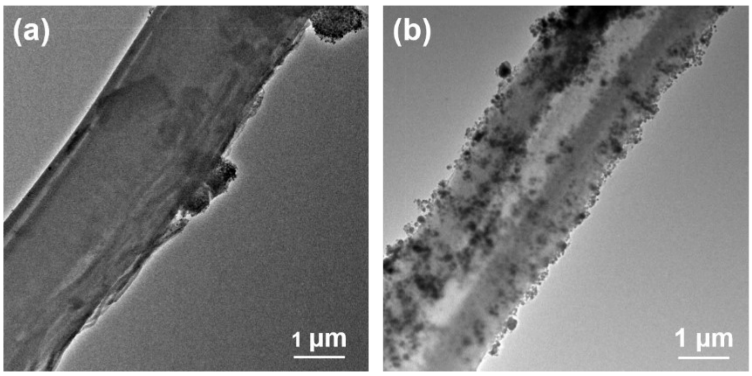

Fig. S5. TEM images of CNFs@Co/C-0, CNFs@Co/C-2.

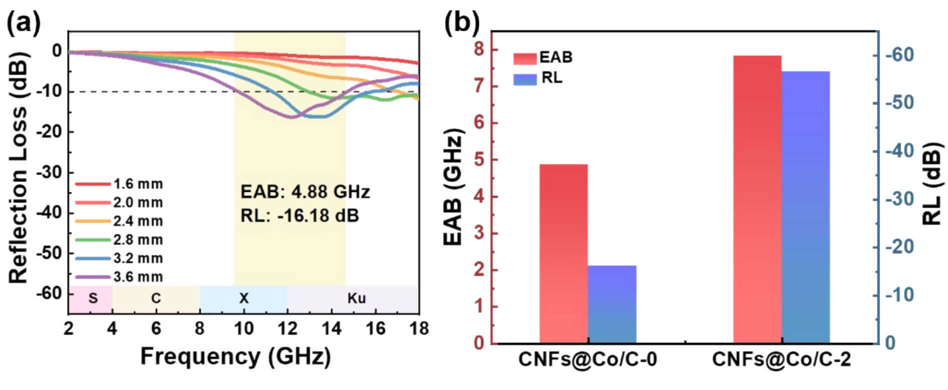

Fig. S6. (a) 2D reflection loss curves of CNFs@Co/C-0, (b) Comparison chart of EAB and RL for CNFs@Co/C-0 and CNFs@Co/C-2.

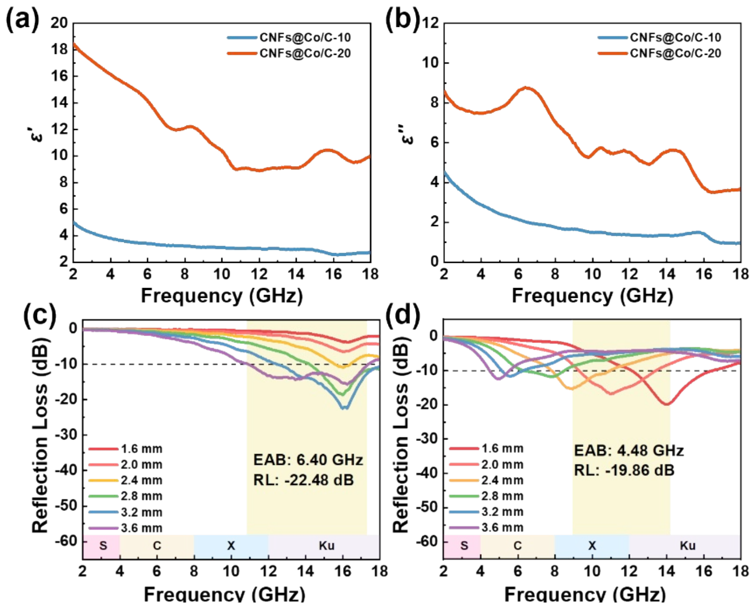

Fig. S7. (a) ε', (b) ε'' of CNFs@Co/C-10 and CNFs@Co/C-20; 2D reflection loss curves of (c) CNFs@Co/C-10 and (d) CNFs@Co/C-20.

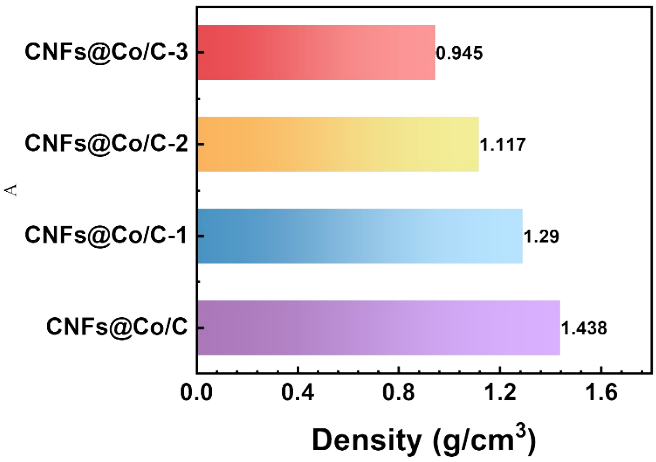

Fig. S8. Density of CNFs@Co/C fibers.

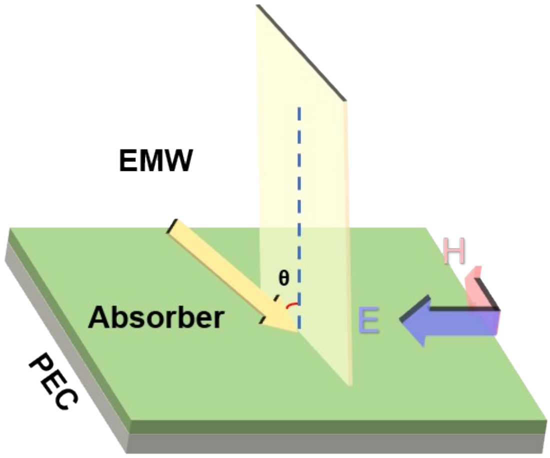

Fig. S9. RCS simulation model.

Table S1 EMW absorption performances of some representative carbon-based materials

EMW absorption materials	EAB (GHz)	t (mm)	RL_{min} (dB)
Fe_3O_4@PANI/EUG	4.01	4.0	-48.98
SiCnws/SiOC	2.73	2.4	-52.66
FeCo@SiO_2@LAS	7.52	2.9	-50.90
CoO/Co_9S_8/NC	5.76	2.93	-50.40
8EMG/MZF	4.70	1.6	-56.90
Ag/Fe_3O_4/SBA-15	3.52	5.0	-43.99
Sb_2S_3@MoS_2	4.00	2.0	-48.09
graphene/g-C_3N_4	4.60	4.5	-34.69
GaIn-4Mn-magnetic field	5.82	2.2	-45.65
This work	7.84	2.4	-56.63

Table S2 EMW absorption performances of other lightweight absorption materials[s1-s3]

EMW absorption materials	EAB (GHz)	RL_{min} (dB)	Density (g/cm^3)	t (mm)
Carbon fiber (CF)	11.10	-21.50	1.75	20
Polypropylene fiber (PF)	10.30	-26.40	0.9	20
FG6	2.98	-17.50	0.9	20
CFCM-2	6.50	-62.70	2.592	3.2
This work	7.84	-56.63	1.117	2.4

Table S3 "Cavity size-Fiber volume-Filler loading" among CNFs@Co/C fibers

Samples	Cavity size	Density	Fiber volume	Filling ratio	Filler loading
CNFs@Co/C-1	0.32 µm	1.290 g/cm^3	0.014 cm^3	15 %	0.018 g
CNFs@Co/C-2	0.5 µm	1.117 g/cm^3	0.016 cm^3	15 %	0.018 g
CNFs@Co/C-3	1.05 µm	0.945 g/cm^3	0.019 cm^3	15 %	0.018 g

References

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