Supplementary Information (SI) for Materials Horizons.
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Supporting Information

Bio-based Derived Carbon Materials for Permittivity Metamaterials: Dual Efficacy of Electromagnetic Wave Protection and Joule Heating

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The scattering parameters (S_{11} and S_{21}), complex permittivity (ε′ and ε″), and permeability (μ′ and μ″) of samples (22.86 mm × 10.16 mm × 3.30 mm) were examined through a vector network analyzer (VNA, Agilent N5244A) at X- band (8.2 ~ 12.4 GHz) via the waveguide method. The corresponding reflection coefficient (R), penetration coefficient (T), absorption coefficient (A), reflection loss (SE_R), absorption loss (SE_A), total SE (SE_T), normalized impedance (Z) and attenuation constant (α) was calculated according to S_{11}, S_{21}, ε′, ε″, μ′, and μ″ by the following equations [S1, S2]:

$$R = |S_{11}|^2 \#(S1)$$

$$T = |S_{21}|^2 \#(S2)$$

$$A = 1 - R - T \#(S3)$$

$$SE_R(dB) = 10\log\left(\frac{1}{1-|S_{11}|^2}\right)\#\ (S4)$$

$$SE_A(dB) = 10\log\left(\frac{1-|S_{11}|^2}{|S_{21}|^2}\right)\#(S5)$$

$$SE_T = SE_R + SE_A\#\ (S6)$$

The dielectric loss mainly consists of conductivity loss(ε_c''), interfacial polarization loss(ε_p''), and dipole polarization loss (ε_d''), which are represented as follows [37]:

$$\varepsilon'' = \varepsilon_c'' + \varepsilon_p'' + \varepsilon_d''\#\ (S7)$$

$$\varepsilon_c'' = \frac{\sigma_{dc}}{2\pi f\varepsilon_0}\#(S8)$$

Where σ_{dc} is the direct current conductivity.

The polarization relaxation deduced from CW and CW@PBD composites can be verified by the Cole-Cole diagram derived from Debye theory as follows:

$$\left(\varepsilon' - \frac{\varepsilon_s + \varepsilon_\infty}{2}\right)^2 + (\varepsilon'')^2 = \left(\frac{\varepsilon_s - \varepsilon_\infty}{2}\right)^2\#(S9)$$

Here, ε_s and ε_∞ are the static and optical dielectric constants. According to this theory, the presence of a semicircle implies the presence of some type of polarization relaxation in the material if ε′ is plotted against ε''.

$$\left|\frac{Z_{in}}{Z_0}\right| = \sqrt{\frac{\mu}{\varepsilon}}tanh\left[j\left(\frac{2\pi fd}{c}\right)\sqrt{\mu\varepsilon}\right]\#(S10)$$

where μ and ε are the relative complex permittivity and permeability, *d* is the material thickness, *c* is the velocity of the EMW in free space, and *f* is the frequency. $|Z_{in}/Z_0|$ indicates the degree of matching between the input impedance and air impedance.

$$RL(dB) = 20log\left|\frac{Z_{in} - 1}{Z_{in} + 1}\right| \#(S11)$$

$$Z_{in} = \sqrt{\frac{\mu_r}{\varepsilon_r}}tan\left[j\left(\frac{2\pi}{c}\right)fd\sqrt{\mu_r\varepsilon_r}\right] \#(S12)$$

where Z_{in} represents the normalized input impedance, *c* is the velocity of the EMW in free space, and *d* is the thickness.

The eddy current loss coefficient (Co) can be calculated using the following equations [28]:

$$C_o = \mu''(\mu')^{-2}f^{-1}\#(S13)$$

If magnetic loss arises from eddy current effects, the C_o parameter remains relatively constant across frequency varies.

Theoretical derivation of the conversion of scattering parameters to permittivity and permeability values.

The material is assumed to be uniformly isotropic, of thickness d, and placed in a transmission line of characteristic impedance Z_0. The parameters satisfy the following relationship with the reflection coefficient Γ and transmission coefficient T of the material:

$$S_{11} = \frac{\Gamma(1 - T^2)}{1 - \Gamma^2T^2} \#(S14)$$

$$S_{11} = \frac{T(1 - \Gamma^2)}{1 - \Gamma^2T^2} \#(S15)$$

Reflection coefficients of materials and free space:

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} = K \pm \sqrt{K^2 - 1} \#(S16) \quad K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \#(S17)$$

Transmission coefficients in materials:

$$T = e^{-\gamma d} = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \#(S18)$$

Characteristic impedance of the material:

$$Z = \sqrt{\frac{\mu}{\epsilon}} = Z_0\frac{1+\Gamma}{1-\Gamma}\#(S19)$$

Propagation constant of the material:

$$\gamma = j\omega\sqrt{\mu\epsilon} = -\frac{\ln(T)}{d}\#(S20)$$

Permeability: $\mu = \frac{Z\gamma}{j\omega}\#(S21)$

Permittivity: $\varepsilon = \frac{\gamma}{j\omega Z}\#(S22)$

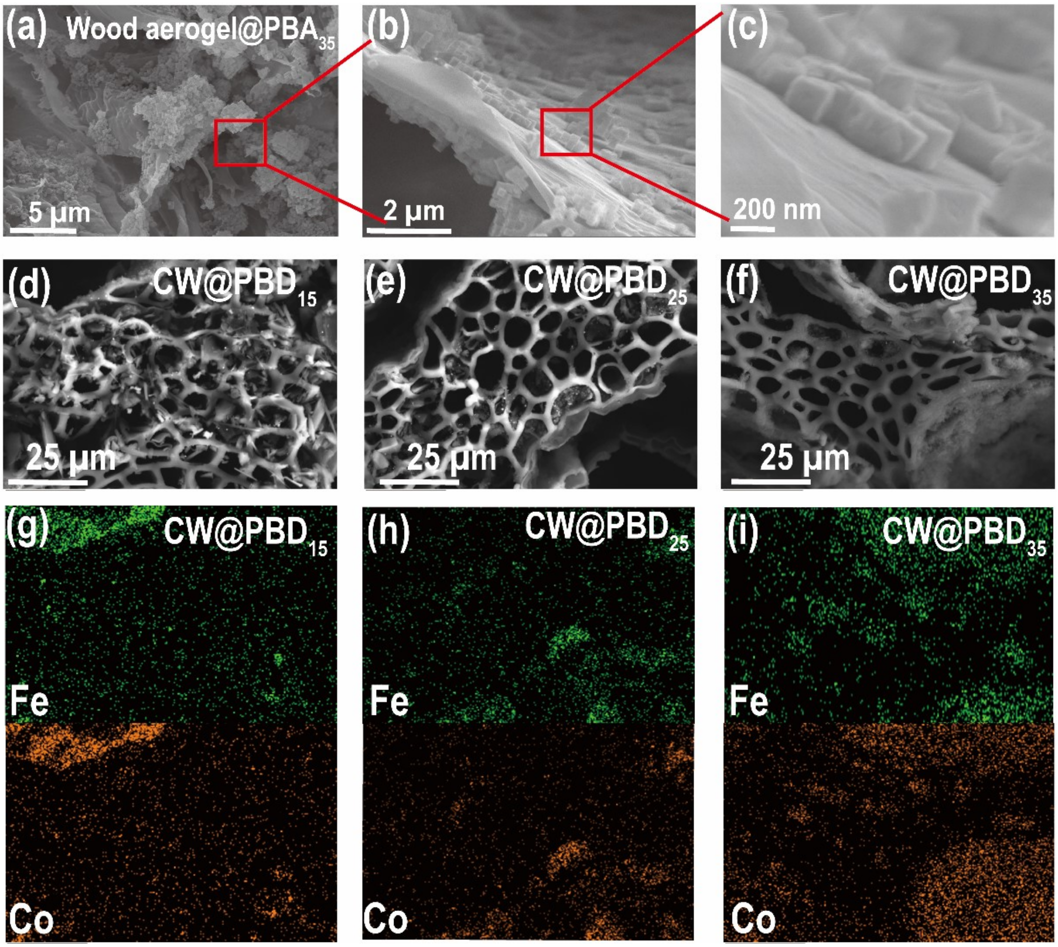

Figure S1. Micro morphology of (a-c) Wood aergoel@PBA_{35}, (d-f) CW@PBD, (g-i) EDS mapping of CW@PBD.

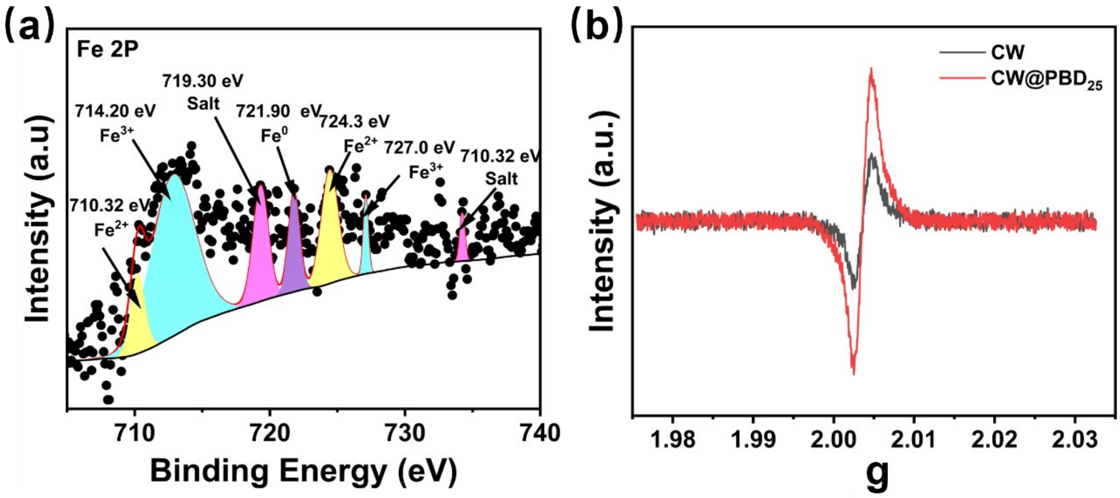

Figure S2. (a) XPS of Fe 2p and EPR of CW@PBD$_{25}$

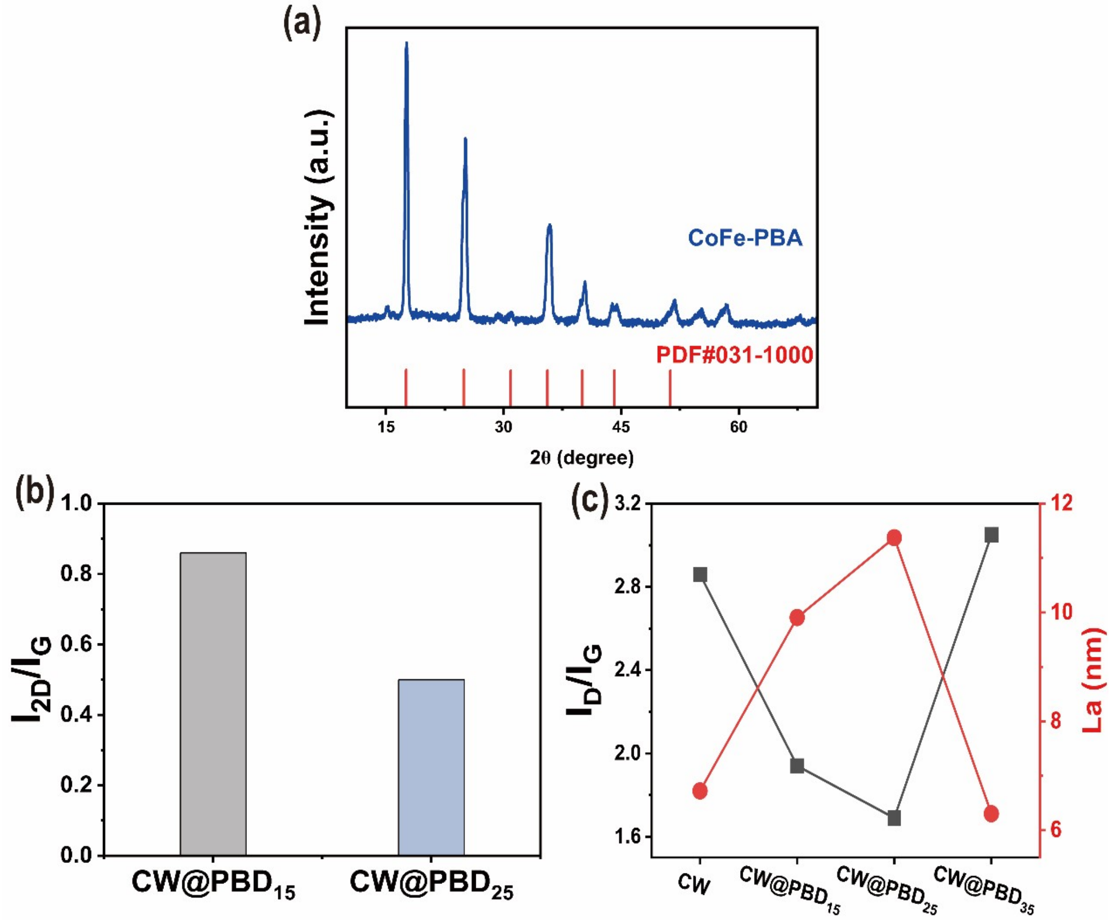

Figure S3. (a) CoFe-PBA XRD spectra, (b) Raman I_{2D} / I_G of CW@PBD, (c) I_D/I_G versus graphite crystal size (La) of CW@PBD.

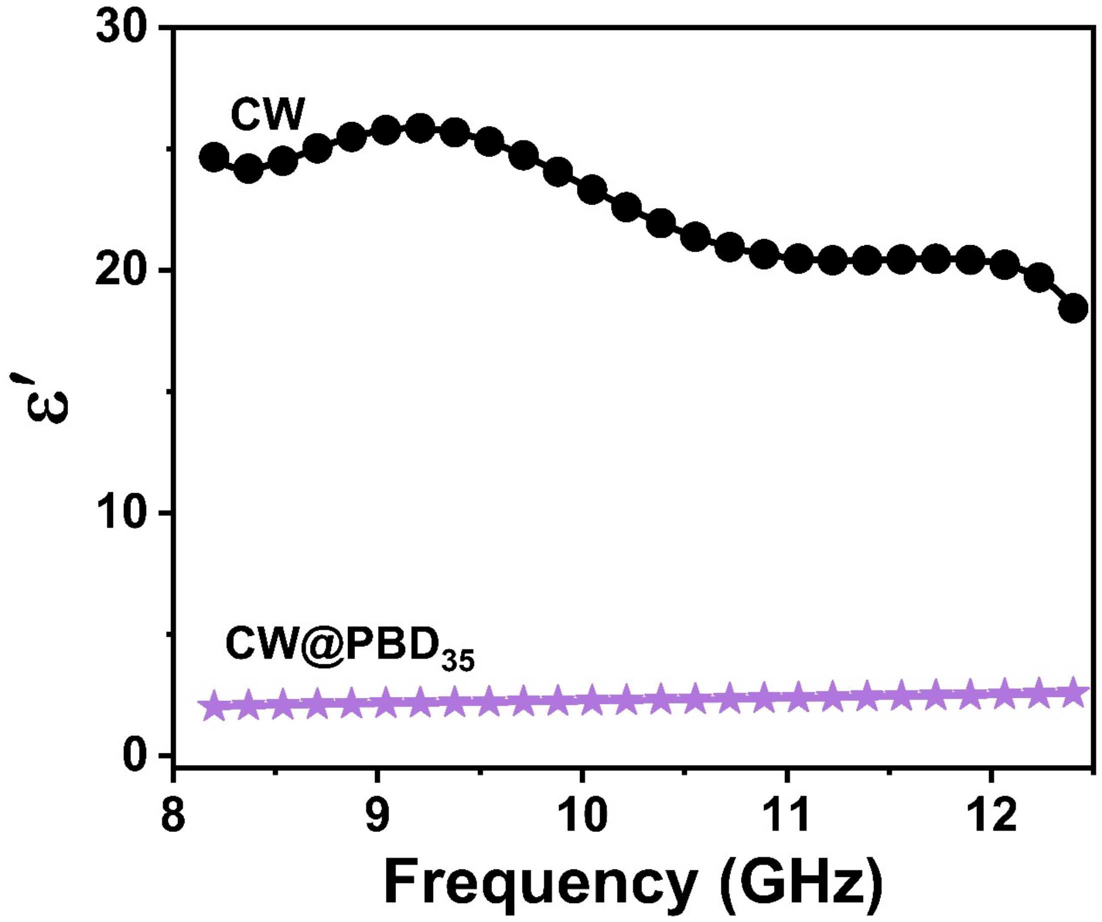

Figure S4. Real permittivity of CW and CW@PBD.

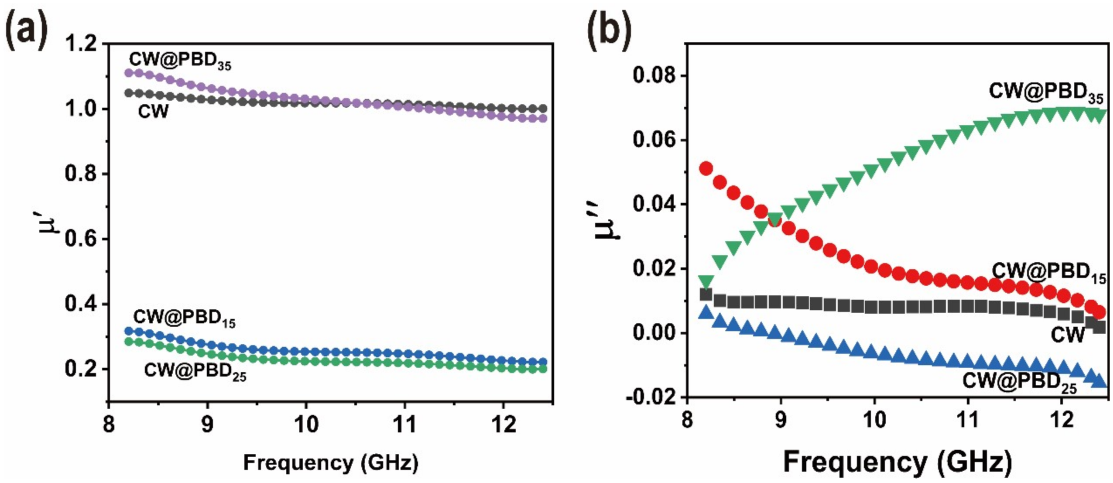

Figure S5. The permeability of CW, CW@PBD. (a) μ′, (b) μ″.

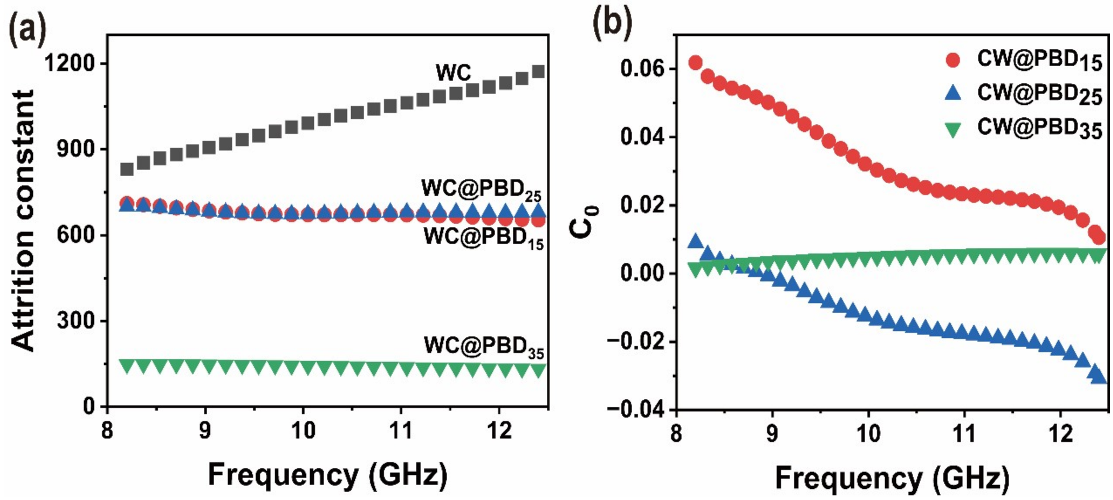

Figure S6 (a) Attenuation constant curves for CW, CW@PBD, (b) Eddy current loss coefficient curves for CW, CW@PBD.

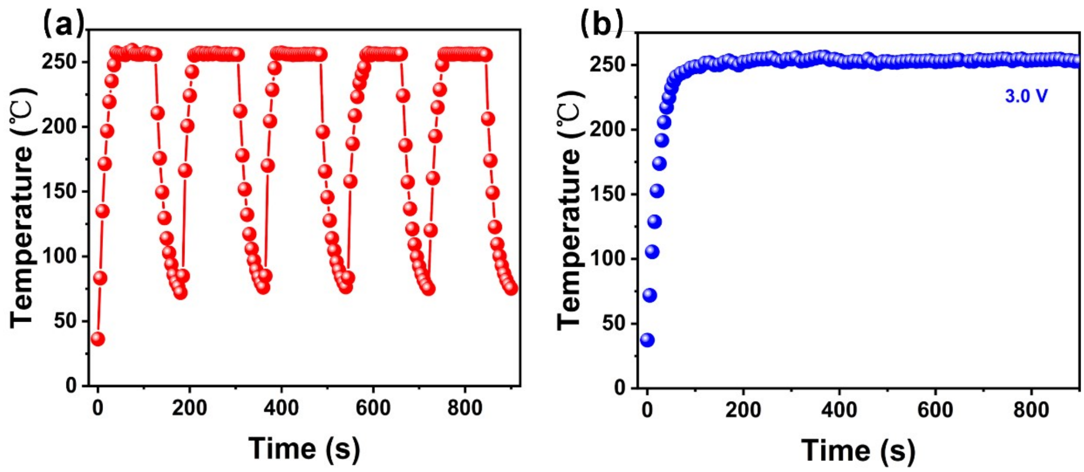

Figure S7 (a) The cyclic stability and (b) long-term stability of Joule heating performance.

Table S1 Comparison of the performance of CW@PBD_{35} microwave absorption with reported materials.

Sample	RL_{min} (dB)	EAB (GHz)	Refs
FeCo/C-3	-35.90	2.58	S3
Fe/Co/C	-47.31	2.72	S4
FeCo-PBA/C	-33.00	3.30	S5
Co-C/MWCNTs	-50.00	3.60	S6
$CoFe_2O_4$/MCHs	-29.70	3.70	S7
CF@$NiCo_2O_4$	-27.80	4.20	S8
HMNCS-2	-39.87	4.00	S9
WPCM/Fe-Co	-48.34	4.20	S10
ZIF-67/SiBCN	-51.60	3.93	S11
Ni/CNT/PI	-56.56	4.20	S12
CW@PBA_{25}	-49.20	4.20	This work

Table S2 Comparison of the performance of $CW@PBD_{25}$ Joule heaters with reported Joule heaters

Sample	Voltage applied (V)	Steady-state temperature (◦C)	Refs
CW/ZIF-8	1.0	70	S1
CW	2.0	83.5	S13
Ni-W-P	2.0	140	S14
AgFe-MF	2.0	53.5	S15
CW	2.0	90.2	S2
Cellulose/MWCNT	2.0	117.1	S16
SEBS@AgNPs@LM	2.0	53.5	S17
Co@CNTs/CW foam	2.5	85.5	S18
WF@GPN	3.0	98	S19
MXene@GO@CNT	4.0	160.5	S20
AgNWs/cellulose	5.0	180	S21
$CW@PBD_{25}$	1.0	56.83	This work
$CW@PBD_{25}$	1.5	96.10	This work
$CW@PBD_{25}$	3.0	255.68	This work

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