

Supplementary Information

Resonance-Engineered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene Metasurface for Ultra-Broadband Absorption-Dominated Green Electromagnetic Interference Shielding

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1. Ti₃C₂T_x MXene film Conductivity

$$\text{Conductivity, } \sigma = \frac{1}{R_S \times t} = 1.62 \times 10^5 \text{ S/m}$$

Where, Sheet resistance, $R_S = 4.532 \times \frac{V}{I}$, t = Ti₃C₂T_x MXene film thickness, and $\frac{V}{I}$ = Slope of the I-V curve, as shown in Figure S2.

2. EMI shielding relations

The shielding effectiveness (SE) of a material is the sum of the contributions from reflection (SE_R) and absorption (SE_A).

$$SE = SE_R + SE_A \quad (S1)$$

Reflectance (R), transmittance (T), and absorbance (A) are calculated from the measured Scattering parameters, S_{11} and S_{21} using the following relations,

$$R = |S_{11}|^2 \quad (S2)$$

$$T = |S_{21}|^2 \quad (S3)$$

$$A = 1 - T - R \quad (S4)$$

Where S_{11} stands for the reflection coefficient of the input, and S_{21} represents the forward transmission coefficient from the input to the output. The total EMI SE is calculated as,

$$SE = 10 \times \log_{10} \frac{1}{T} \quad (S5)$$

While the reflection (SE_R) and absorption (SE_A) components are determined by

$$SE_R = 10 \times \log_{10} \frac{1}{1-R} \quad (S6)$$

$$SE_A = 10 \times \log_{10} \frac{1-R}{T} \quad (S7)$$

To further evaluate the sustainability of the shielding mechanism, g_s is introduced to quantify the absorption-dominated contribution to EMI attenuation, is defined as the following equation¹,

$$g_s = \frac{1}{|S_{11}|^2} - \frac{|S_{21}|^2}{|S_{11}|^2} - 1 \quad (\text{S8})$$

3. Transmission-Line Equivalent-Circuit theory for the Scaled MXJC metasurface

The MXJC metasurface is modeled at normal incidence by an effective surface impedance Z seen by a normally incident EM plane wave in free space. The MXJC pattern printed on a grounded dielectric slab is represented by a lumped grid impedance Z_s , while the Ag grounded PET and PDMS substrate is represented by an equivalent dielectric slab impedance Z_d .

Transfer matrix formulation of the MXJC metasurface

For normal incidence, each layer of the metasurface-substrate-ground system can be represented as a two-port weakly lossy network with an ABCD matrix M . Cascading layers corresponds to multiplying their transfer matrices in the correct order, and the overall reflection coefficient is obtained from the resulting ABCD matrix. We modelled the structure: Free space as port 1, MXJC grid as lumped RLC, grounded PET-PDMS slab as short-circuited transmission line, and Ag ground as port 2. Only the MXJC grid and PET-PDMS substrate sections require explicit ABCD representation^{2,3}.

The $\text{Ti}_3\text{C}_2\text{T}_x$ MXene film is characterized by a DC conductivity σ and thickness t , giving a sheet resistance,

$$R_s = \frac{1}{\sigma \times t}$$

For a quasi-uniform current path of length “ L_y ” and width “ w ”, the corresponding series resistance is approximated as

$$R_1 \approx R_s \frac{L_y}{w}$$

Here, R_1 captures the ohmic losses in the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene tracks⁴.

The MXJC pattern is modelled at each scale factor s , by a series RLC branch describing the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene grid and its interaction with the gaps by Z_s . For scaling the MXJC meta-atom, a larger geometry produces a lower resonance, consistent with the full-wave simulation.

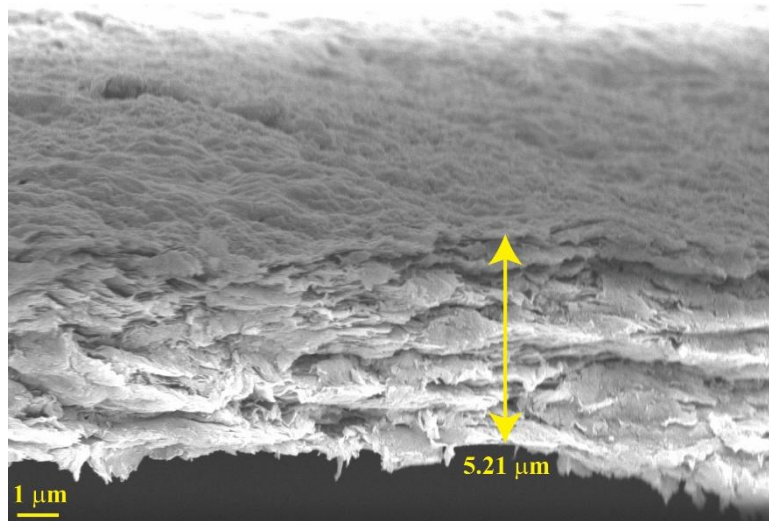


Figure S1: Cross-sectional FESEM image of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene thin film having a thickness of 5.32 μm .

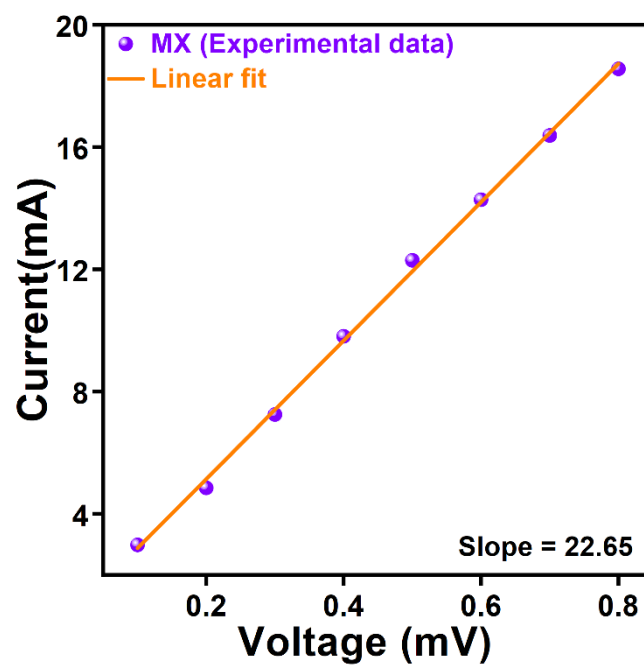


Figure S2: I-V characteristics of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene thin film.

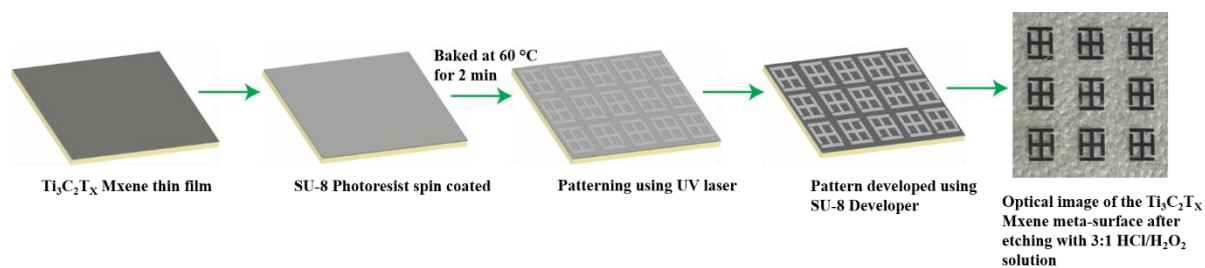


Figure S3: Patterning of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene thin film using photolithography.

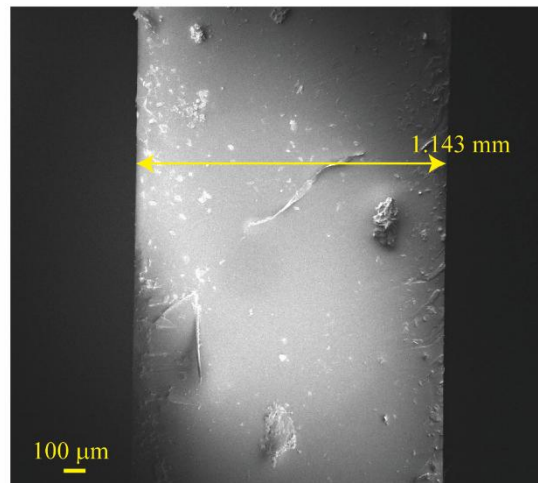


Figure S4: Cross-sectional FESEM image of Ag back layer deposited on PDMS spacer having a thickness of 1.19 μm .

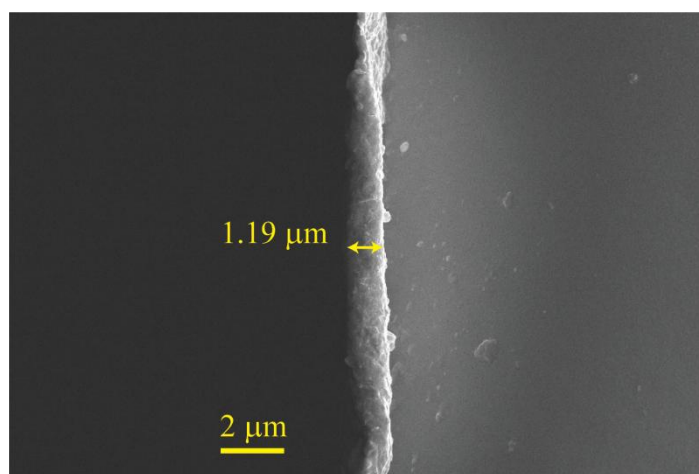


Figure S5: Cross-sectional FESEM image of PDMS spacer layer having a thickness of 1.143 mm.

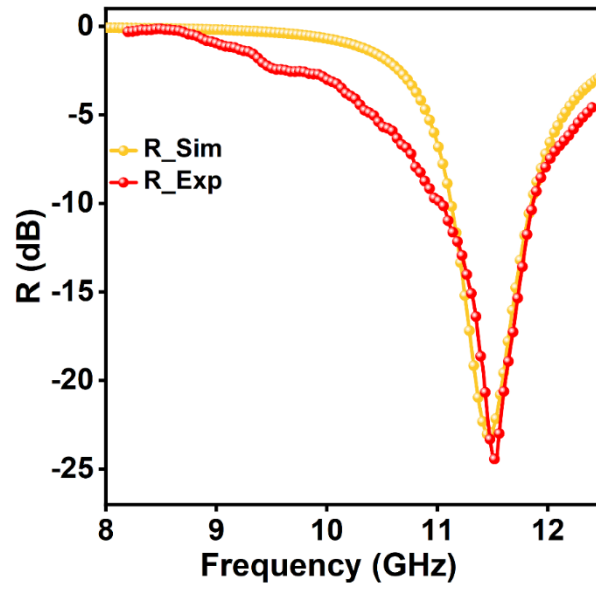


Figure S6: Simulated and experimental Frequency-dependent R (dB).

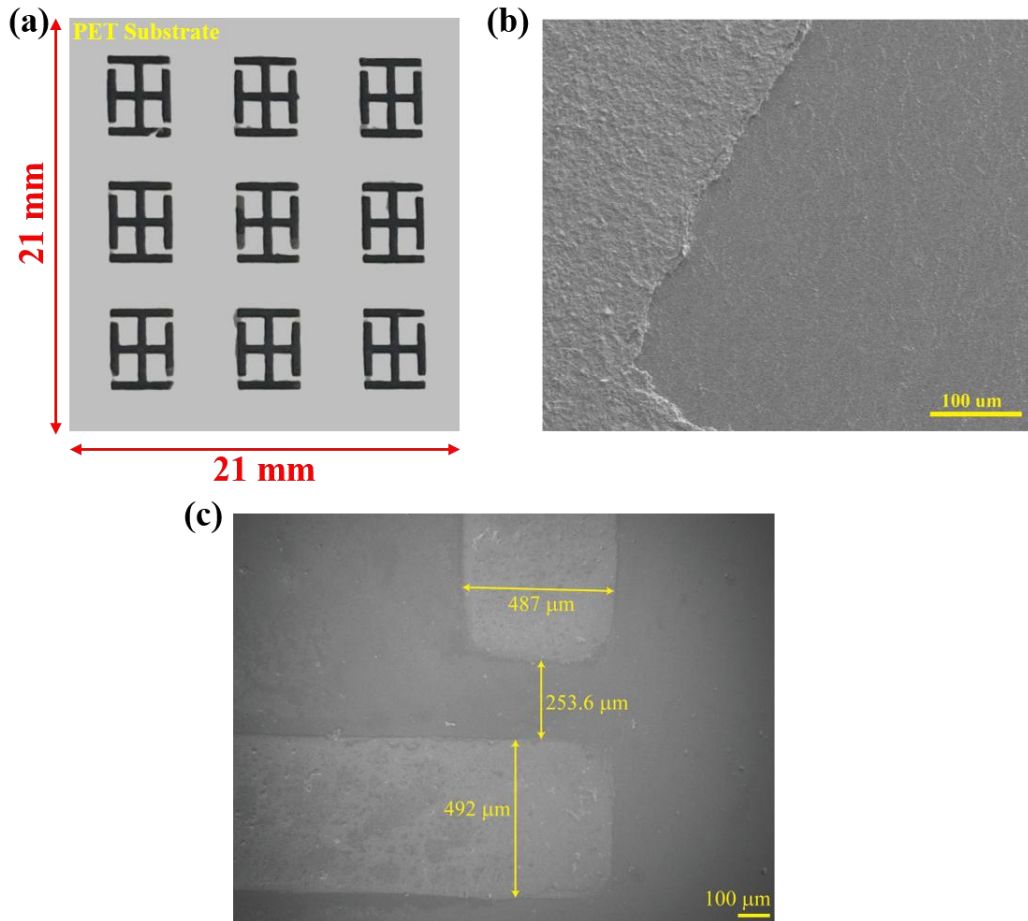


Figure S7: (a) Optical image of the MXJC metasurface. (b) and (c) Top-view FESEM image of the MXJC meta-atom showing well-defined sharp edges and geometrical parameters closely matching the Simulated parameters.

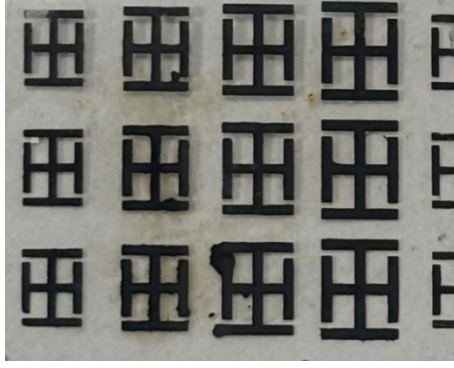


Figure S8: Optical image of the S-MXJC metasurface.

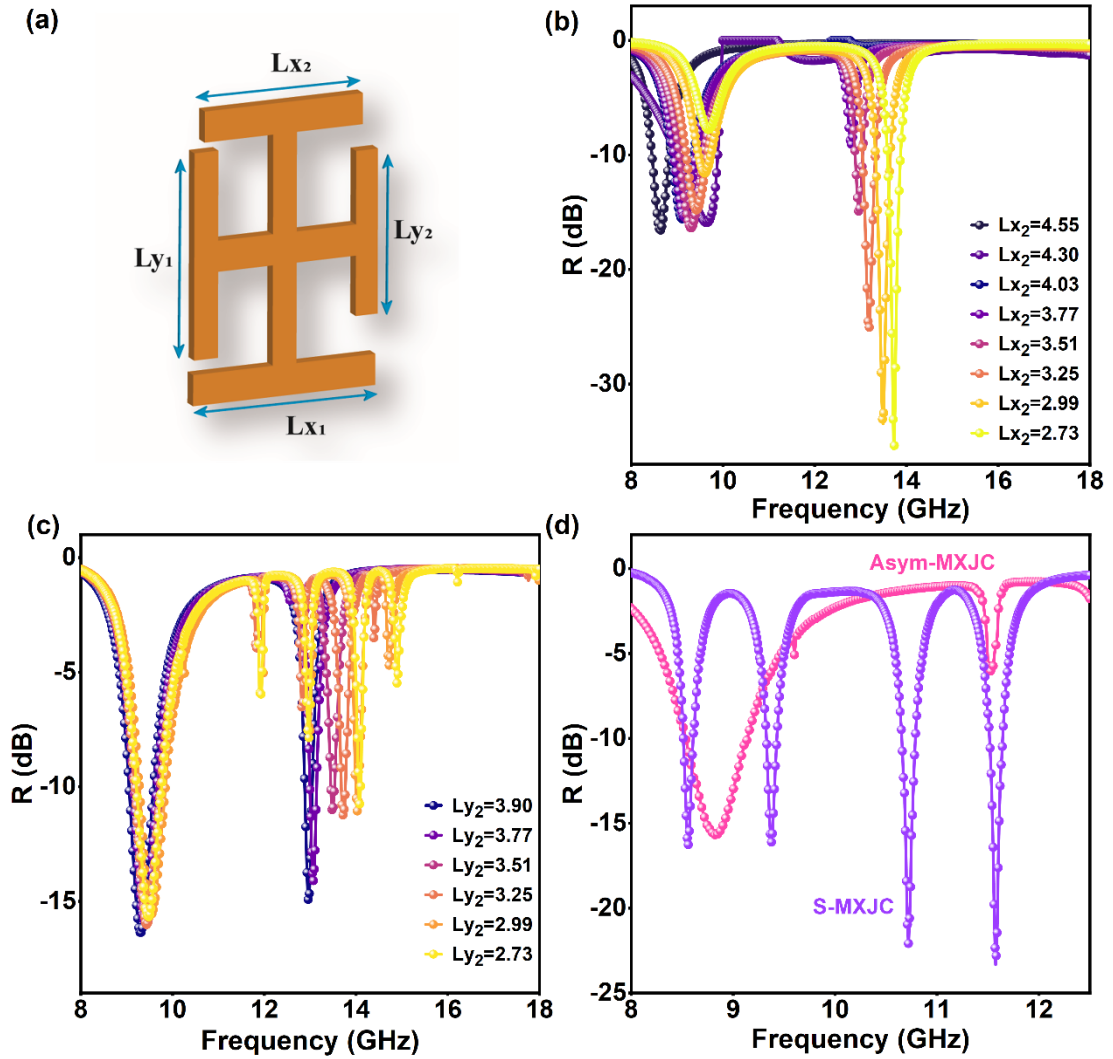


Figure S9: (a) Schematic representation of the asymmetric MXJC (Asym-MXJC, for $s = 1.3x$) meta-atom. The four arm lengths are $L_{x1} = 4.55$ mm, $L_{x2} = 3.51$ mm, $L_{y1} = 3.90$ mm, and $L_{y2} = 2.73$ mm, respectively, with other geometrical parameters identical to the S-MXJC meta-atom. Reflection Coefficient (R , dB) spectra of the Asym-MXJC meta-structure for variations in (b) L_{x2} , (c) L_{y2} , and (d) comparison of the optimized Asym-MXJC and S-MXJC meta-structures.

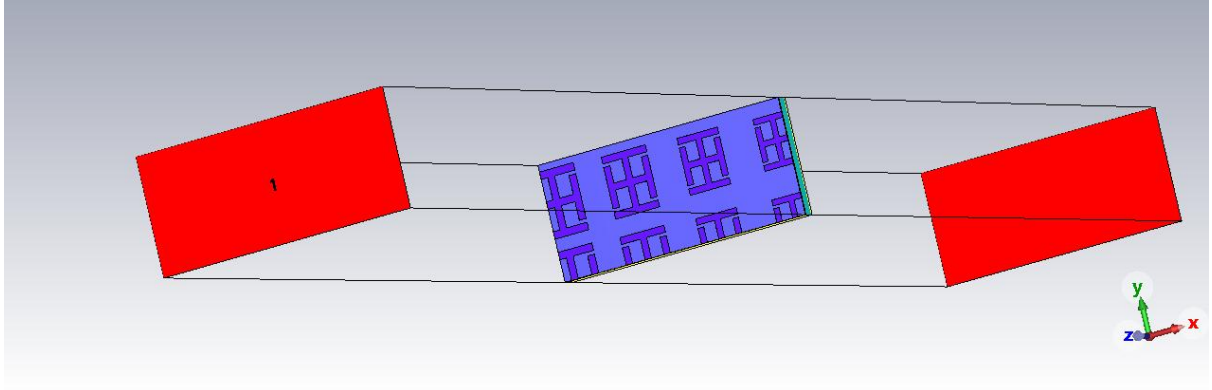


Figure S10: Actual tested geometry of S-MXJC under finite size waveguide condition for simulations (dimension: 22.9×10.2 mm²).

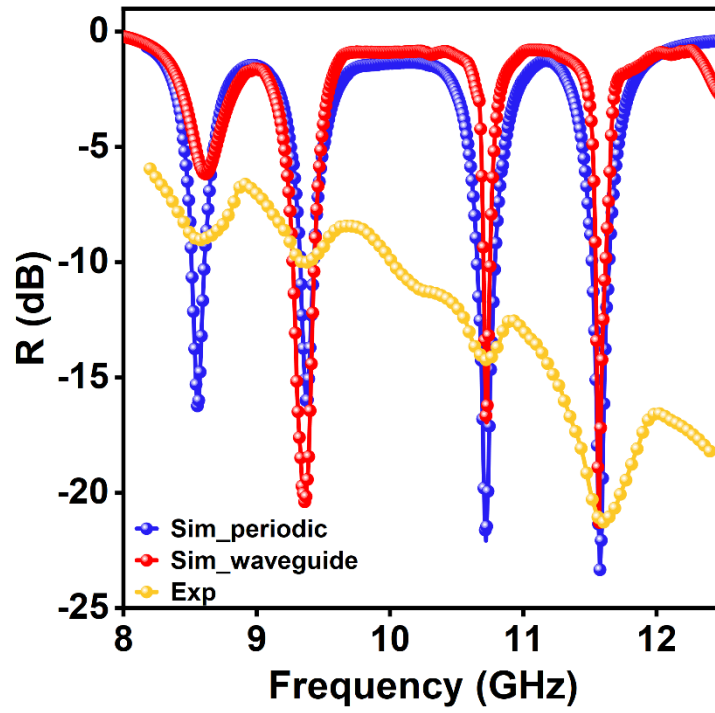


Figure S11: Simulated and experimental R (dB) of the S-MXJC meta-structure. Here, Sim_periodic represents the simulated response obtained under periodic conditions and Sim_waveguide represents the simulated response obtained using finite-size waveguide measurement configuration.

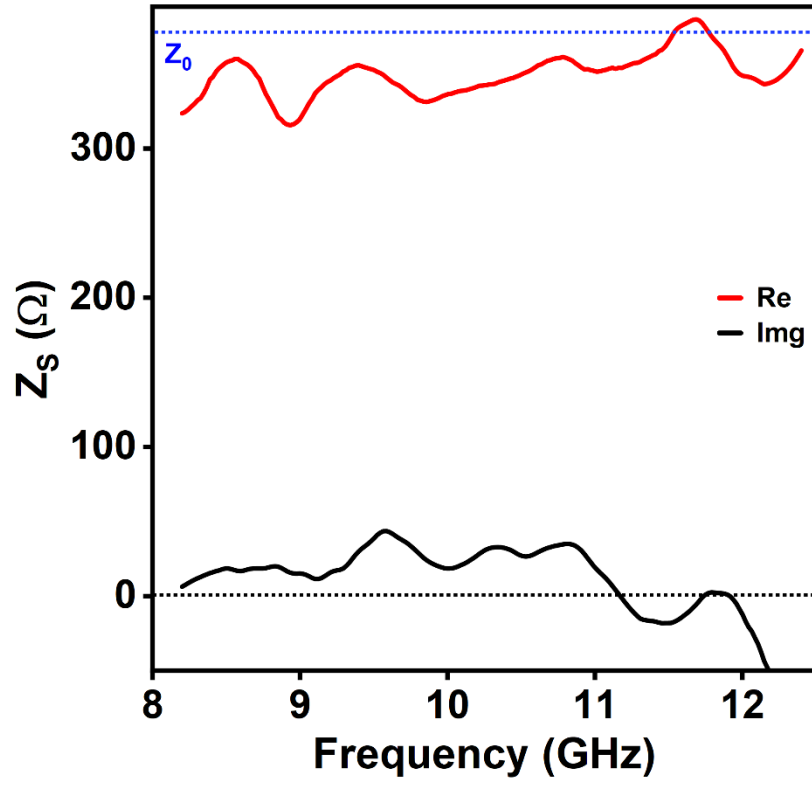


Figure S12: Impedance matching of the S-MXJC supercell over the entire X-band.

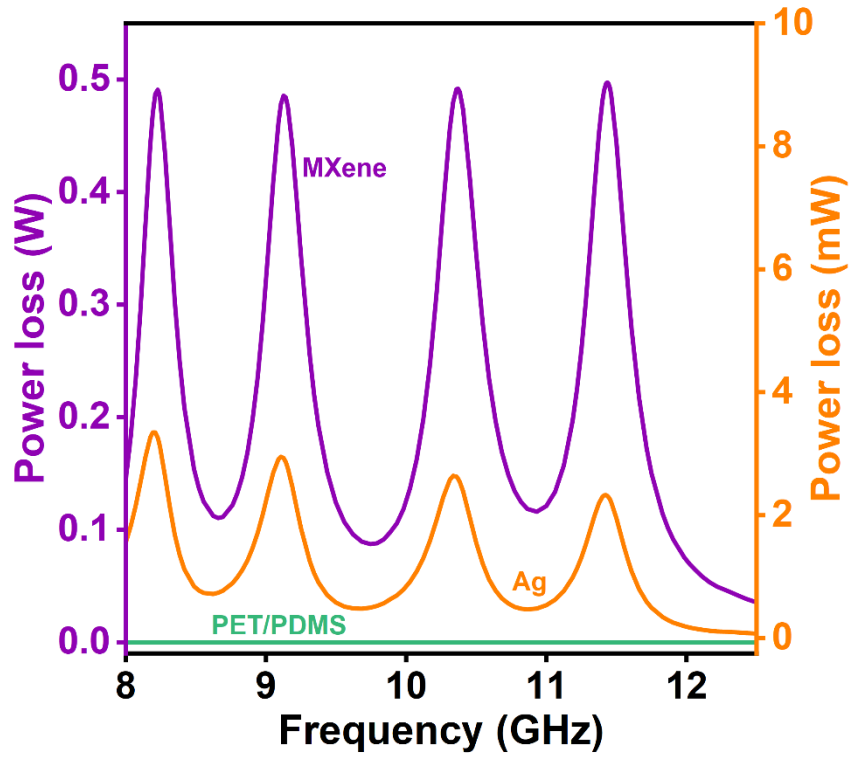


Figure S13: Layer-resolved power loss of the S-MXJC meta-structure.

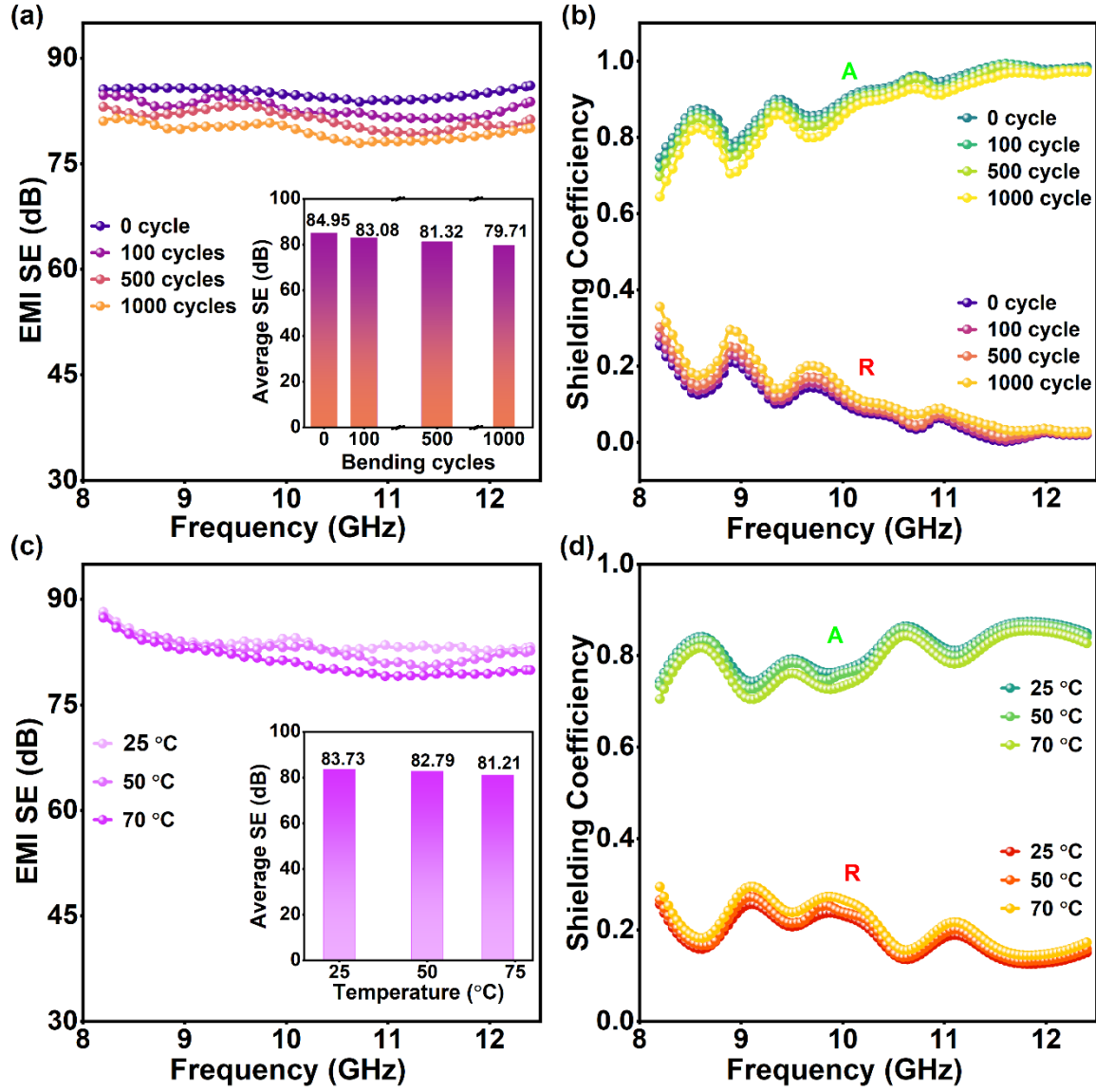


Figure S14: (a) EMI SE (inset: Average SE), and (b) R, A of the MXJC shield under different bending cycles. (c) EMI SE (inset: Average SE), and (d) R, A of the MXJC shield at different temperatures.

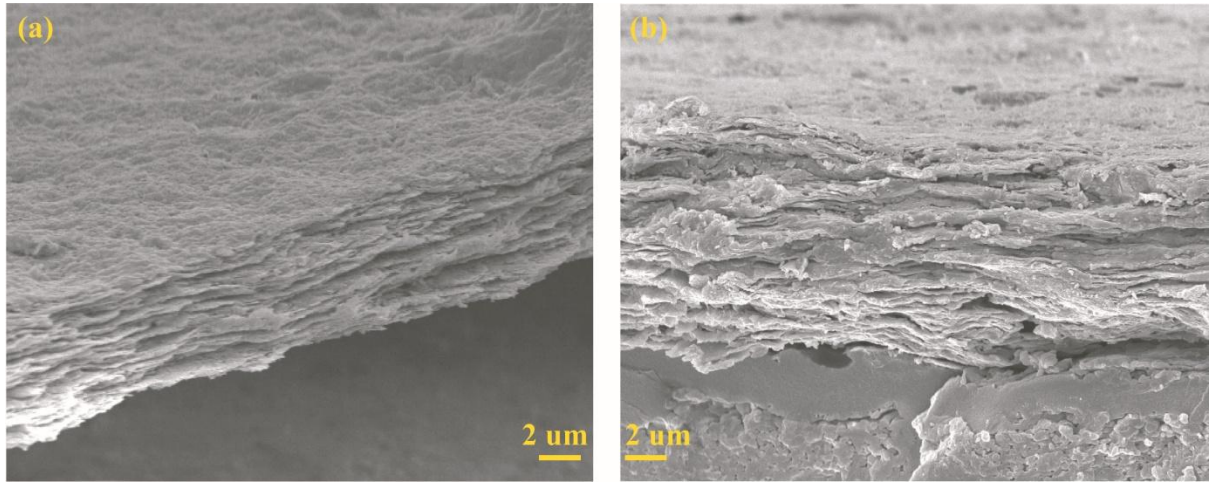


Figure S15: FESEM image (a) before and (b) after 1000 bending cycles.

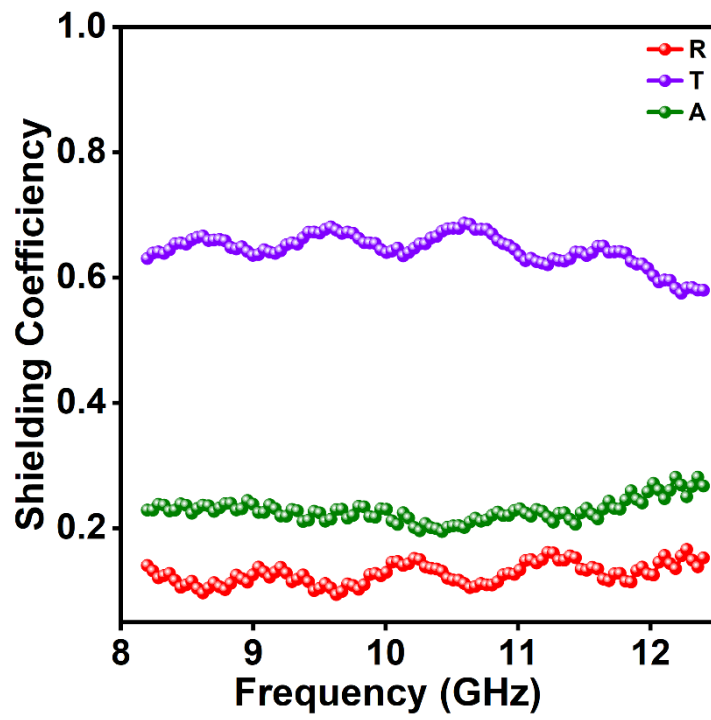


Figure S16: R, T, A of the S-MXJC meta-structure without Ag back layer.

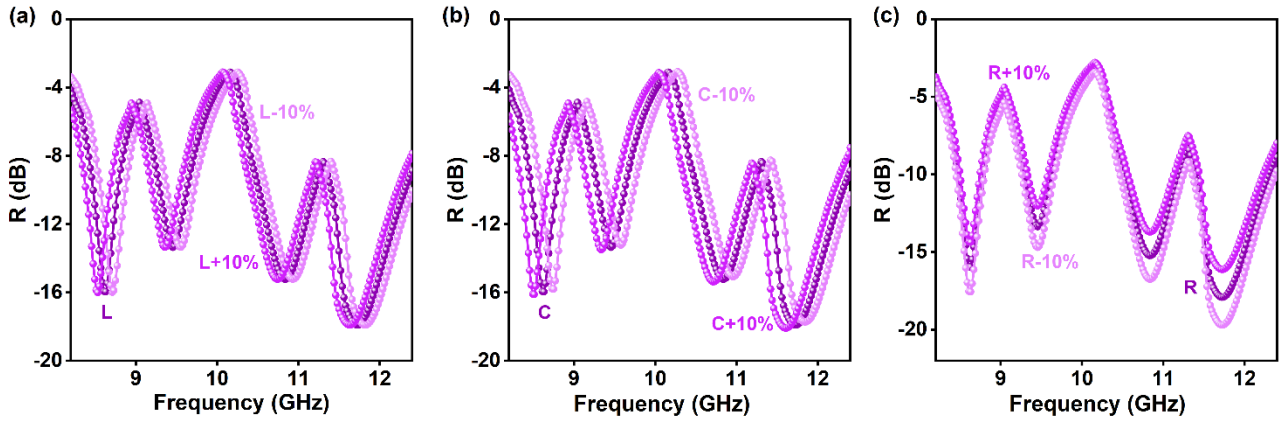


Figure S17: Parameter sensitivity analysis by independently varying the dominant circuit elements (a) L, (b) C, and (c) R by -10% and +10% around their optimized values.

Table S1: Comparison of the proposed meta-structure in terms of resonator type, overall structure thickness, fractional bandwidth (> 90% absorption), maximum SE, and green index over the operational bandwidth, with other metasurface-based absorbers that achieve comparable bandwidth and absorption levels using simpler geometries or different material systems.

Material	Resonator	Thickness (mm)	Fractional bandwidth (>90% absorption) (GHz)	Maximum SE (dB)	Green index (g_s)	Ref.
AgNWs/GO	Thin film	-	-	30.3	<i>0.074</i>	⁵
Ti ₃ C ₂ T _x /Sodium alginate	mesh	2.01	-	64.2	<i>0.064</i>	⁶
ITO	Slot type cross dipole	5.35	4.2	25	-	⁷
Ti ₃ C ₂ T _x /PEDOT:PSS	mesh	0.295	-	51.7	-	⁸
Ti ₃ C ₂ T _x /RGO	Scaffold	2.7	-	62.5	<i>0.051</i>	⁹
Ti ₃ C ₂ T _x /AgNWs	Crackle grid	-	-	24.6	-	¹⁰
PDMS/AgNWs	Fence	-	-	32.2	<i>~ 0.11</i>	¹¹
Graphene	Strips	<i>~ 0.001</i>	-	26.6	<i>~ 1.6</i>	¹²
Graphene/Carbon fiber	Rectangular slots	-	-	54.33	-	¹³
Ti ₃ C ₂ T _x	Multi-arm Jointed - cross	<i>1.231</i>	4.2	83.78	<i>64.55</i>	This work

Notes: Values in italics were not provided in the cited reference and instead calculated from other relevant parameters provided therein. Abbreviations: AgNWs (Silver nanowires), GO (Graphene oxide), ITO (Indium tin oxide), PEDOT:PSS (poly(3,4-ethylenedioxythiophene):polystyrene sulfonate), RGO (Reduced graphene oxide), PDMS (polydimethylsiloxane).

References:

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