Supplementary Information (SI) for Materials Advances.
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A Cost-Effective Strategy to Design and Fabricate Absorption Dominant Flexible Multilayer Laminates by Rationally Tailoring the Layers

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1. Virtual Waveguide Environment for Multilayer Structures

The designing of rectangular waveguide involves placing the material under test (MUT) between port-1 and port-2 of the waveguide followed by setting boundary condition and waveguide ports, and deciding domain-solver. At first, a solid with dimensions recommended by the general criteria for waveguide dimensions, which are 3 × 1.5 × 5 cm is constructed. As our research aims X-band range, therefore 2.3 × 1 cm is the optimal measurement for each layer of PM/PC, PM/PC/PM, and PC/PM/PC multilayer structure. Moreover, a rectangular waveguide is created by subtracting an additional solid measuring 2.3 × 1 × 1.4 cm. For each of the PM/PC, PM/PC/PM, and PC/PM/PC multilayer structures, Fig.S1 displays the common boundary arrangement. Two waveguide ports are used to energise the electric and magnetic fields, which are set to the X- and Y-boundaries, respectively while Z-axis is open. The mesh size is set to an appropriate number and adjustments are made to the mesh close to the waveguide walls and the component that needs shielding. Finally, simulation is run in frequency domain-solver to calculate S-parameters and the electric and magnetic field distributions inside the waveguide are visualised. The possibility of errors while simulations is mesh convergence which is due to inadequate mesh density that may cause erroneous outcomes, incorrect boundary, and inaccurate material characteristics. Additionally, when the model is oversimplified, it might cause differences in the findings obtained from simulations and experiments.

2. Synthesis of CNF

The synthesis of polycrystalline CNF powder involves employing high quality (≥99%) $CoCO_3$, NiO, and Fe_2O_3, which are obtained from Sigma-Aldrich. This is done by the standard solid-state reaction approach. The reagents were mixed in stoichiometric proportions and subjected to ball milling for a duration of 12 hours in an acetone solvent. The slurry is subsequently dehydrated at a temperature of 70°C for a duration of 24 hours using a hot air oven. The desiccated blend is further pulverized and subjected to calcination at a temperature of 800°C for a duration of 4 hours. The resulting material is then final sintered at a temperature of 1150°C for a duration of 4 hours in a high-temperature furnace to produce CNF.

3. Tau Plot for PC and PM layer

Tauc's method developed in 1966 is used to estimate the band gap energy. In order to establish the Tauc's approach, it is assumed that the energy-dependent absorption coefficient 'α' may be stated using the equation (4) that is presented below:

$$(\alpha h\upsilon)^{1/\gamma} = A(h\upsilon - E_g) \text{.............}(4)$$

where h is the Planck constant, ν is the photon's frequency, E_g is the band gap energy, and A is a constant. The γ factor depends on the nature of the electron transition and is equal to 1/2 or 2 for the direct and indirect transition, respectively

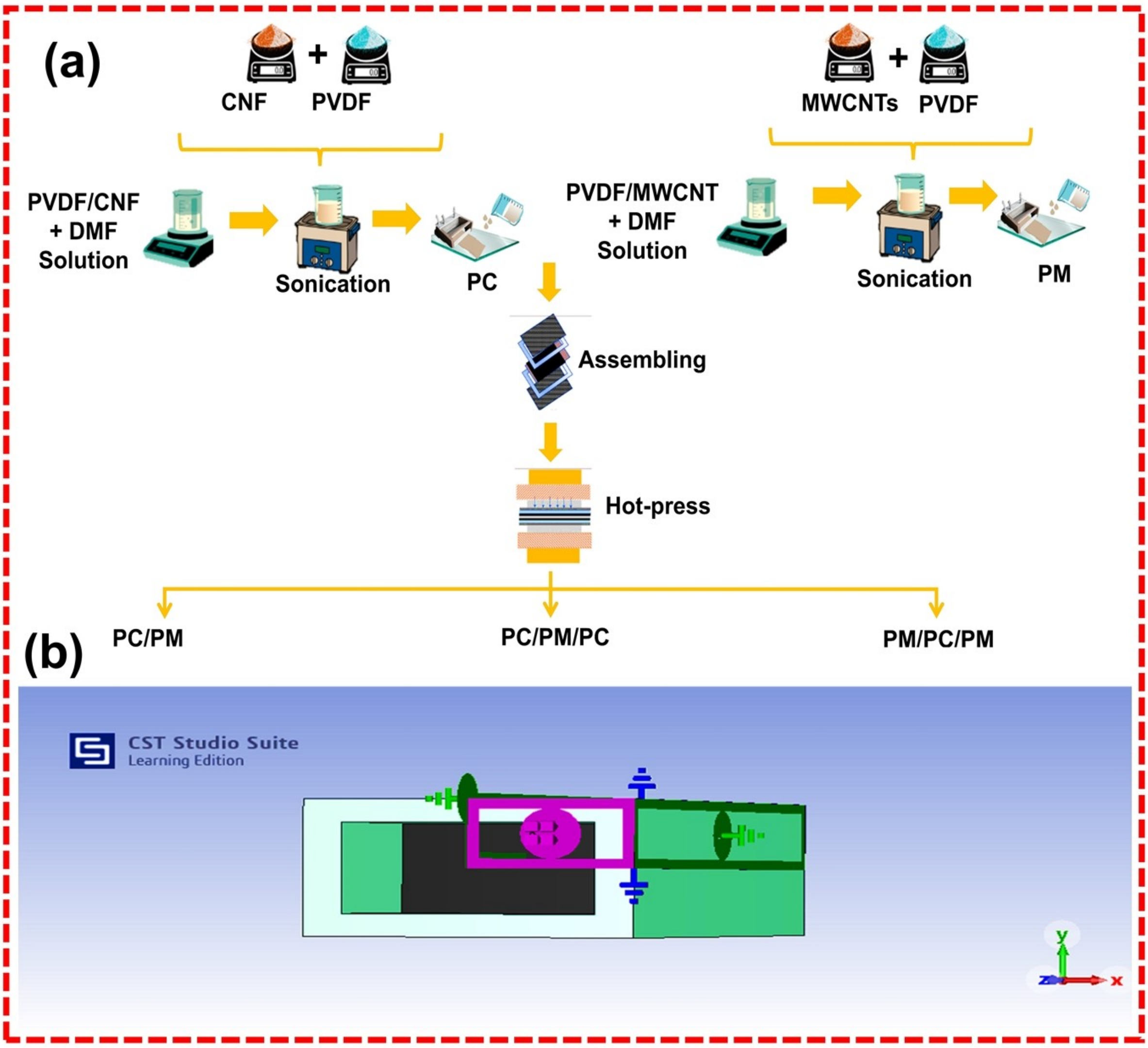


Fig.S1 Boundary set-up for all multilayer structures

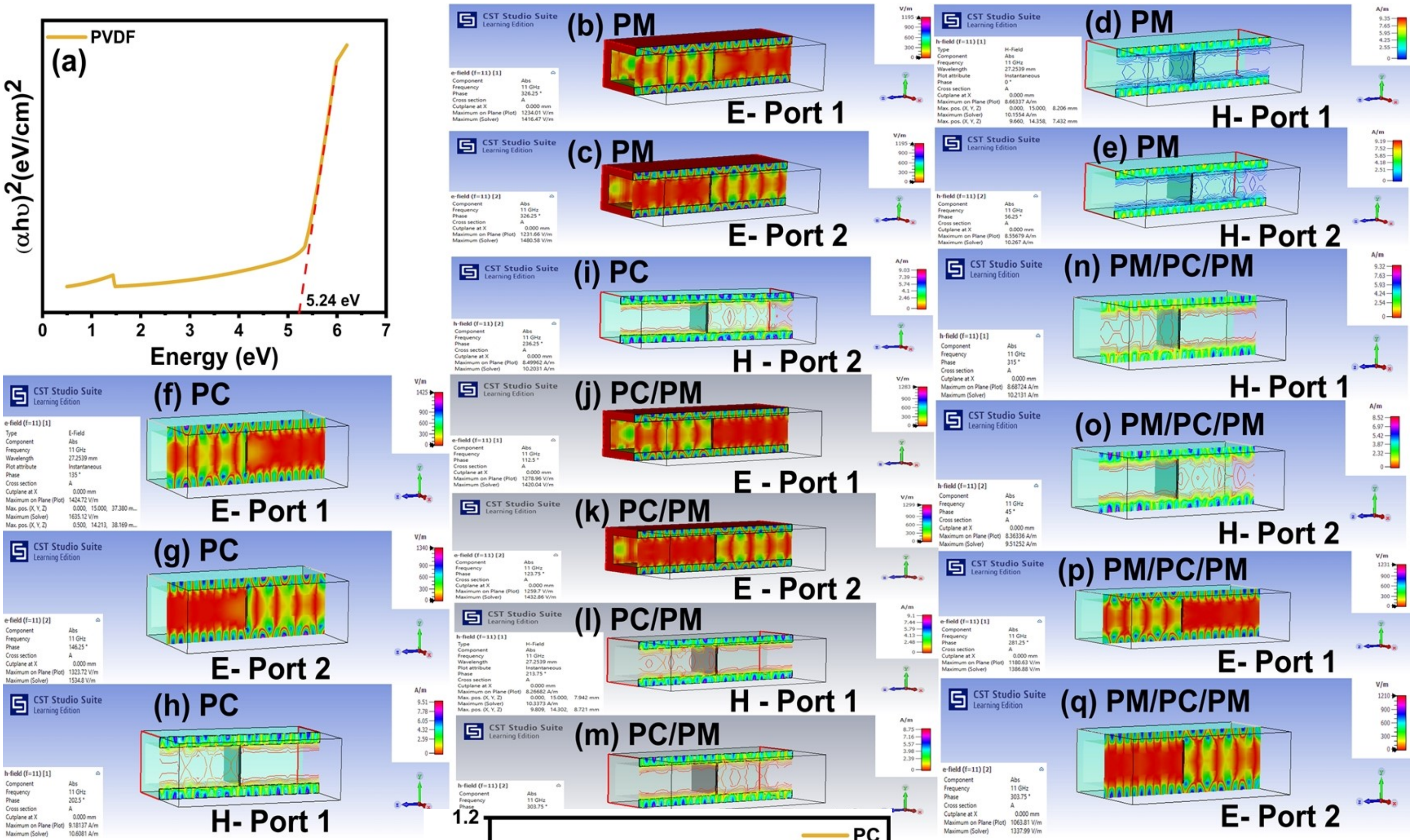
1. Impedance Matching Studies

High loss and impedance matching are the two most important factors that contribute to the efficiency of any microwave absorbing material in terms of shielding against absorption. Thus, taking into consideration the impedance matching degree of the multilayer structures, which aided the passage of microwaves through these multilayer absorbers. As discussed in the section 3.3, of main article, out off all multilayer structures, the three-layer structures PC and PM possessed an exceptional microwave absorption characteristic. Hence, to further support this, impedance maching degree is estimated for the same (see Fig.S3(a)). In order to achieve ideal impedance matching, it is crucial for the material to contain ϵ ′ and μ ′ values that are either equal or equivalent to one another. Therefore, the impedance matching degree (△) may be determined for any material by employing the equation that is presented below:

$|\Delta| = |\sinh^2(Kfd) - M|$ ……………………………………. (1)

where

$$K = \frac{4\pi\sqrt{\varepsilon'\mu'\sin\frac{\delta_\varepsilon+\delta_\mu}{2}}}{c\cos\delta_\varepsilon\cos\delta_\mu} \quad \& \quad M = \frac{4\pi\varepsilon'\mu'\cos\delta_\varepsilon \times \cos\delta_\mu\sqrt{\varepsilon'\mu'} \times \sin\frac{\delta_\varepsilon+\delta_\mu}{2}}{(\mu'\cos\delta_\varepsilon - \varepsilon'\cos\delta_\mu)^2 + \left(\tan\frac{\delta_\varepsilon-\delta_\mu}{2}\right)^2(\mu'\cos\delta_\varepsilon + \cos\delta_\mu)^2}$$



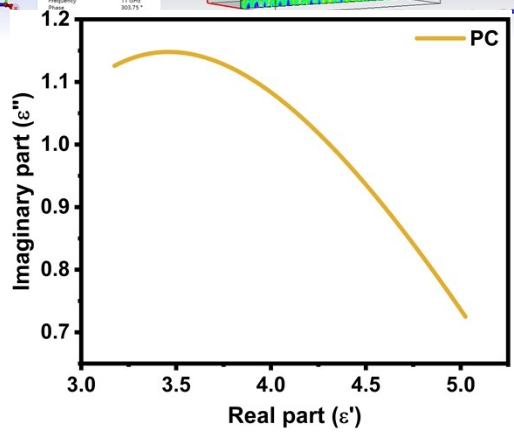


Fig.S3 Cole-Cole Plot for PC

It should be noted that the lower the impedance matching degree, better will be the impedance matching. Fig.S3(a) shows impedance matching for PC and PM layer structures in the frequency range of 8-12 GHz. It is observed that the impedance matching degree of PC is less that PM, which indicates that the PC is impedance-matching layer and thus will have higher shielding due to absorption over the X-band frequency range.

2. Attenuation Constant Studies

The attenuation constant indicates of the electromagnetic (EM) attenuation ability of the absorber. A greater attenuation constant refers to a better capability to transform electromagnetic (EM) energy into other forms of energy. Fig.S3(b) shows the attenuation constant as function of frequency for PC/PM/PC and PM/PC/PM multilayer structures. The fact that the PC/PM/PC have the highest attenuation constant demonstrates possess the strongest EM wave dissipation ability, which agrees well with impedance matching studies and EMI shielding calculations. According to these findings, PC/PM/PC has a greater attenuation constant with the higher RL performance, and excellent absorptions characteristics, surpassing the performance of the vast majority of low-frequency absorbers that have been reported in the past.

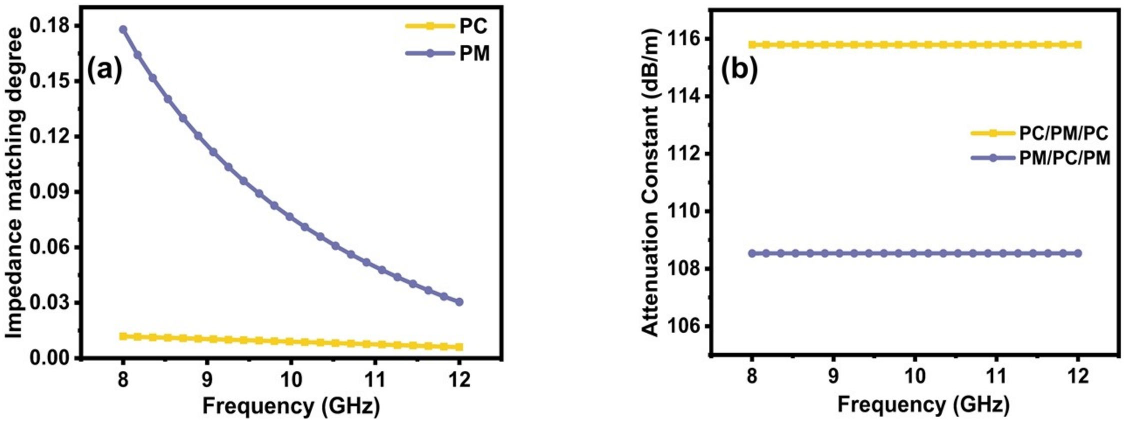


Fig. S4(a) Impedance matching degree studies of PM and PC layer (b) Attenuation constant PC/PM/PC and PM/PC/PM