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Tailorable microwave absorption characteristics of bio-waste based composites through macroscopic design

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Abstract

Biologically sourced filler such as dried cow dung (dielectric) loaded polydimethyl siloxane (PDMS) composite for broadband microwave absorption is explored in this work. PDMS is well known elastomer for electromagnetic (EM) applications due to the many advantages such as lightweight, flexible, corrosion protective, facile preparation and large area fabrication. Optimally prepared, 8 mm thicker PDMS-cow dung (PC) composite shows minimum reflection loss (RL) value - 6 dB in the Ku-band (12.4-18 GHz), and it does not meet the percolation limit (RL ≤ -10 dB). In order to enhance the microwave absorption and absorption bandwidth (RL ≤ -10 dB), various macroscopic design such as pyramidal and multi-layered pyramidal PC composite design was carried out for same thickness. Optimized multi-layered pyramidal PC composite exhibit more effective absorption, and obtained minimum RL value was -43 dB having two specific absorption bandwidth in the frequency range 8.2-18 GHz (both X-band and Ku-band). Mechanistically, the edge scattering and combined one fourth resonances as well as high dielectric loss which leads to more storage of electromagnetic energy are the major contribution factors. Further electromagnetic power loss is more prominent in multi-layered pyramidal PC composite due to inhomogeneous energy losses. The simulated result was compared with the experimental data and shows the suitability of this composite for real time application especially for defence. This work also indicates that the low dielectric composites can be used for real time microwave absorption through different macroscopic design.
• INTRODUCTION

In the recent time, the military uses modern warship/unmanned air vehicles for defence which has advanced electronic systems. Generally, all advanced electronic systems are mounted on a large metal superstructure consisting of navigational and target-acquisition radar. However, this arrangement can create major problems such as false images from self-reflections, indirect radar return, loss of radar energy, and system-to-system interference etc. due to the electromagnetic interference (EMI). In order to avoid these problems, need of tuned-frequency elastomeric absorbers are increasingly felt. The conventional radar absorption materials are mainly ferrites based, carbon based, graphene/CNT based, conducting polymer and hollow microsphere based. However, recent advances in fabrication technology of carbonaceous composites for microwave absorption especially in the X-band (8.2-12.4 GHz) and Ku-band (12.4-18 GHz) have demonstrated the use of biomass as a filler or coating. Studies regarding fabrication of inexpensive, lightweight microwave absorbers using organic wastes, biomass and porous carbon materials from biomass waste has appealed the scientific community owing to its rich material sources, simple preparation process and environmental friendliness. Cow dung is such an environmental friendly biomass and well known manure. Recently, cow dung has been used for a variety of electronic applications like electrodes for biochemical sensors and fuel cells. However, reports on cow dung for EM application is limited. The key interest on cow dung for radar absorption is that it is naturally abundant porous carbonized lightweight dielectric material (density of dried cow dung lies 1-1.5 gcm$^{-3}$). In addition, cow dung contains mainly cellulose and therefore it can be carbonized easily. Various, porous carbonized materials such as spinach, cabbage etc. have been studied for microwave absorption. However, to the best of our knowledge, cow dung loaded flexible elastomer for broad band microwave absorption is not explored.
The real challenge is to achieve radar absorption bandwidth (reflection loss (RL) $\leq -10$ dB, corresponds to 90 % absorption) for single layer. To overcome this multilayer structure is promising due to multiple resonances.\textsuperscript{17} To the best of our knowledge, work on cow dung containing flexible elastomer and its macroscopic design for electromagnetic wave absorption is very limited. In this study, dried powdered cow dung was used as a filler material in polydimethyl siloxane (PDMS) to fabricate a radar absorbing elastomer and designed various structure for tuning the absorption bandwidth. The objective of this work is the investigation of the microwave absorption characteristics of biologically sourced carbonaceous wastes such as reduced cow dung (low dielectrics) loaded polymer (PDMS) composite at macroscopic design (mm size).

- EXPERIMENTAL
  - Composite preparation

Wet cow dung was collected from a local dairy farm and dried completely under sunlight (8 h), and further dried at 200±2 °C for 2 h. After that, it was crushed into a fine powder. This powder was added very slowly to the PDMS (Sylgrad 250, Germany) under mechanical stirring and kept for stirring for another 10 min. Finally, it was poured to X-band and Ku-band sample holder and kept for drying at 60±2 °C for 6 h. Various weight percentages, viz., 15 %, 50 % and 80 % was added and composites were respectively named as PC1, PC2 and PC3.

The multi-layered pyramidal sample was also fabricated using same procedure for PC3 composite. First, unit cells were fabricated as shown in Schematic 1. The specific PET mould sizes (unit cell) are as mentioned in the discussion part (based on simulation) starting with 10 mm×10 mm×1 mm and gradually decreasing by length and breath, viz., 9 mm×9 mm×1 mm and so on. Once the unit cells are fabricated, six-unit cells are pasted without any gap on
aluminium tape (conductor) and measurement sample effective area was covered by four such rows.

**Schematic 1.** Schematic representation of multi-layered pyramidal PC3 composite sample preparation.

- **Characterization**

The surface morphology of PC composite was carried out using a field emission scanning electron microscope (FESEM, Carl Zeiss). The dielectric properties of both the PDMS and the PC composites were measured in the X-band (8.2-12.4 GHz) and Ku-band (12.4-18 GHz) by using Agilent vector network analyser (Agilent N5201). The thru-reflect-line (TRL) calibration is the standard calibration method (also industrial standard) to obtain the complex $S$-parameters ($S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$). A complete two port TRL calibration was performed in both the bands, before commencement of the measurements. Using the obtained $S$-parameters, relative permittivity ($\varepsilon_r = \varepsilon' - i\varepsilon''$) values were determined using the standard Nicholsion-Ross-Weir (NRW) method. The RL of a perfect electric conductor (PEC) backed material is given by,
Reflection loss (RL) = 20log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| (dB) \quad (1)

\( Z_{in} \) is the input impedance and can be written as,

\[ Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh \left( \frac{2\pi f d \sqrt{\mu_r \varepsilon_r}}{c} \right) \quad (2) \]

\( Z_0 \) is the characteristic impedance of free space (= 377 Ω), \( d \) is the thickness of the absorber and \( c \) is the velocity of light. The \( \varepsilon_r \) and \( \mu_r \) is the relative permittivity \( (\varepsilon_r = \varepsilon' - i\varepsilon'') \) and permeability \( (\mu_r = \mu' - i\mu'') \), respectively.

- **Macroscopic pattern designs and simulations**

The artificial pattern designs of the composites and RL simulations were carried out using the CST microwave studio (2015). It is one of the most powerful electromagnetic computational tools and it solves Maxwell equations by resorting to the finite integration technique (FIT) in time domain and to a finite element method (FEM) in the frequency domain. In the designed structure, the unit cell with PEC substrate was constructed with same area (10 mm × 10 mm) in a periodic array. The boundary conditions, viz., electric and magnetic respectively were applied at the X- and Y-direction, so that microwave propagates along the Z-axis.

- **RESULTS AND DISCUSSION**

Recorded FESEM images of sunlight dried and thermally reduced (200±2 °C) cow dung was shown in the Figure 1(a) and Figure 1(b) respectively. The reduced cow dung observed to be irregular porous in nature. Because of irregular shape and porous nature, it can create the linkage in polymer matrix easily and a better heterogeneous composite system can be expected.
as compared to the non-reduced cow dung. In our experiment, thermally reduced cow dung was used for composite preparation (PC). The recorded EDX spectra of reduced cow dung was shown in Figure 1(c). The presence of C, O, Na, K and Ca in the reduced cow dung was confirmed by the EDX. The EDX data also suggest that presence of O (~ 50 weight %) is maximum in the reduced cow dung (Figure 1(c)). It is believed to be due to the porous nature of the reduced cow dung where oxygens are trapped. The C was found to be the second highest element (~ 30 weight %) in the reduced cow dung.

![SEM images of (a) sunlight dried cow dung and (b) thermally reduced cow dung and (c) EDX spectra and results of reduced cow dung.](image)

**Figure 1.** SEM images of (a) sunlight dried cow dung and (b) thermally reduced cow dung and (c) EDX spectra and results of reduced cow dung.
As shown in Figure 2(a), the reduced cow dung has the porous structure with pore size ranging from 2 to 50 nm. The nanoporous reduced cow dung was further explored by N\textsubscript{2} adsorption/desorption experiment performed at 77 K. Figure 2(b) shows the isotherm curve (adsorption–desorption hysteresis loop), indicating a rapid N\textsubscript{2} uptake at a very low-pressure region (P/P\textsubscript{0} < 0.8), followed by a continuous increase in the rest of P/P\textsubscript{0} range. The large nanopore volume and high specific surface area of reduced cow dung was obtained to be 0.1941 cm\textsuperscript{3}g\textsuperscript{-1} and ~ 103 m\textsuperscript{2}g\textsuperscript{-1} respectively.
The recorded FTIR spectrum of PDMS and PC3 composite was shown in Figure 3. The peak observed at 2962 cm$^{-1}$ and 1259 cm$^{-1}$ corresponds to C–H stretching in CH$_3$ and CH$_3$ symmetric bending in Si–CH$_3$ respectively. The band located at 1076 cm$^{-1}$ and 1018 cm$^{-1}$ corresponds to Si–O–Si stretching, and at 798 cm$^{-1}$ corresponds to the CH$_3$ rocking in Si–CH$_3$.

In PC3 composites no shifting of these peaks (bands) were found indicating there is no primary chemical interaction in between PDMS and reduced cow dung.

Figure 4 shows the recorded relative permittivity of all the composites in the frequency range 8.2-18 GHz. The obtained real permittivity ($\varepsilon'$) and imaginary permittivity ($\varepsilon''$) value of PDMS is 2.33 and ~ 0.07 respectively. It was observed that for PC1, $\varepsilon'$ ranges from 2.5 to 2.67 across the frequency range 8.2-18 GHz and resonant peaks are observed from 15.5 GHz to 16.7 GHz. The $\varepsilon''$ values range from 0.08 to 0.15 with numerous resonant peaks throughout the frequency range indicating increased dielectric loss (Figure 4 (a)). With the increase in the
cow dung concentration, both $\varepsilon'$ and $\varepsilon''$ are enhanced and become more dependent on the frequency. For PC2, the values of $\varepsilon'$ range from 2.64 to 3.02 with several resonant peaks in the frequency range especially in Ku-band. The $\varepsilon''$ values for PC2 vary from 0.1 to 0.18 exhibiting the same trend as PC1 in terms of resonant peaks. With further increase in filler concentration, for PC3, $\varepsilon'$ continues to increase, reaching a maximum of 3.16 at 12.6 GHz. Similar trend is also observed for $\varepsilon''$ and the values vary from 0.18 to 0.24 (Figure 4 (b)). The $\varepsilon'$ value indicates the storage ability of the electric energy and $\varepsilon''$ value indicates the dissipation of electric energy through the composite material. The addition of dried cow dung as a filler, there is a heterogeneity introduced in the composite which in turn increases the interfacial polarization thus increasing the value of $\varepsilon'$ and $\varepsilon''$ with increase in addition of fillers. The observed several resonant peaks in $\varepsilon'$ and $\varepsilon''$ can be understood from the resonance-type dielectric response, and it arises due to the inertial effects which dominates charge movement. In other words, unlike Debye type behaviour or relaxation-type dielectric behaviour in PC composites resonance-type dielectric response are observed.²⁻³ It could be due to the nano pores in the reduced cow dung as PC composites are inhomogeneous medium similar to Maxwell Wagner type layer. In case of Maxwell-Wagner type microwave dielectrics (where effective permittivity plays the vital role) microwave absorption takes place due to better impedance matching.⁷⁻⁹ Thus, in PC composites impedance matching could be an important factor for microwave absorption.
Figure 4. Variation of recorded (a) real ($\varepsilon'$) and (b) imaginary ($\varepsilon''$) parts of permittivity of PC3, PC2, PC1 and PDMS in the frequency range (8.2-18 GHz).

- RL of single layer PDMS-cow dung composites

The schematic of single layer radar absorber design was shown in the Figure 5 (a). The cross-sectional surface morphology of the PC3 composite was shown in the Figure 5 (b). It indicates that the reduced cow dungs particles are embedded in PDMS. The thickness dependent simulated RL (dB) of PDMS and PDMS-cow dung composites (PC1, PC2 and PC3) were shown in Figure 6. The simulated minimum RL value of single layer PC1, PC2 and PC3 was found to be -2, -2.5 and -4 dB respectively. It was also observed that, although the variation of PC3 composite is promising, the potential minimum RL value (-10 dB, corresponds to 90 % absorption) was not achieved till the thickness was increased to 8 mm. However, a noticeable change in RL values of experimental and simulated result was observed. The comparison of experimental and simulated RL of PC3 composite (3 mm) was shown in the Figure 6(d). The power absorbed (%) by the PDMS, PC1, PC2 and PC3 composite for different thicknesses was...
investigated through standard electromagnetic (EM) simulation and respectively was shown in Figure 7 (a-d). The PC3 composite was found to have highest power absorption capability (~60%) whereas PDMS matrix can absorb ~ 10% till the thickness 4 mm.

**Figure 5.** (a) Schematic of radar absorbing composite structure, (b) cross-sectional surface morphology of PC3 composite.

The minimum RL value of single layer PC3 composites and better microwave power acceptance capability is due to the intrinsic loss of electromagnetic energy.\(^{18-20}\) It can be understood through dielectric loss tangent (DLT, mathematically \(\text{DLT} = \frac{\varepsilon''}{\varepsilon'}\)) and EM attenuation constant value.\(^{20, 21}\) The DLT of a material denotes dissipation of the electrical energy due to different physical processes such as electrical conduction, dielectric relaxation, dielectric resonance and loss from non-linear processes.\(^{22-24}\) It was observed that for PDMS composite, the DLT value ranges from 0.03 to 0.04 with peaks in the low frequency region (Figure 8 (a)). With addition of cow dung in PDMS, the DLT value increases. For PC1, DLT ranges from 0.033 to 0.051 with resonant peaks throughout the frequency range. The DLT value further increases for PC2, varying from 0.044 to 0.057. Finally, for PC3, which has the maximum filler concentration, DLT ranges from 0.063 to 0.075 and multiple peaks in the frequency range 8.2-18 GHz.
The EM attenuation constant ($\alpha$) can be expressed as,\(^{22}\)

$$\alpha = \frac{\sqrt{\mu \varepsilon}}{c} \times \left[ \left( \mu \varepsilon'' - \mu' \varepsilon' \right) + \left( \mu \varepsilon'' - \mu' \varepsilon' \right)^2 + \left( \mu' \varepsilon'' + \mu'' \varepsilon' \right)^2 \right]^{1/2}$$

(3)

Figure 8 (b) shows the variation of $\alpha$ values of PDMS, PC1, PC2 and PC3 composites. The $\alpha$ value was found to increase with frequency. Within the frequency range of 8.2-18 GHz, the $\alpha$ values of PDMS composite, PC1, PC2 and PC3 were found to be ranging from 4-13.2, 4.7-19.4, 6-22.5 and 9.34-37.9 respectively. Thus, it signifies the high EM energy loss in PC3 composite during propagation of electromagnetic wave.

Figure 6. Simulated reflection loss (RL) of (a) PC1, (b) PC2, (c) PC3. (d) Comparison of simulated and experimental RL of PC3 composite in the frequency range 8.2-18 GHz.
Conductivity ($\sigma$) of the PC composites can be calculated via the expression $\sigma = \omega (\varepsilon_0 \varepsilon_r)$, $\omega$ is the angular frequency. The calculated $\sigma$ value was shown in Figure 9. Like $\alpha$ value, the conductivity of the PC composite is positively correlated with the incident electromagnetic wave (EMW). PC3 composites possess the highest $\sigma$ value (0.19 Sm$^{-1}$). From the variation of $\alpha$ and $\sigma$ values, the electromagnetic response in PC composites can also be understood as the dielectric nature of the composite as induced by the conductivity induces
electromagnetic interaction. Furthermore, it is frequency domain as well as depends on reduced cow dung loading in the PDMS. The strong microwave absorption or RL value of PC3 composite also can be understood from electromagnetic energy conversion power due to charge transport \( P_c \) and dielectric relaxation \( P_p \). If \( \varepsilon_{c}^{''} \) is the contributor of charge transport to \( \varepsilon'' \), and \( \varepsilon_{p}^{''} \) is the contributor of relaxation to \( \varepsilon'' \), then \( P_c \) and \( P_p \) can be expressed as,\(^{25,26}\)

\[
P_c = \frac{\omega \varepsilon_{c}^{''} E_0^2}{2}
\]

\[
P_p = \frac{\omega \varepsilon_{p}^{''} E_0^2}{2}
\]

Here, \( E_0 \) is the electric field intensity amplitude of EMW. The value of \( \varepsilon_{c}^{''} \) is intrinsically depends on \( \sigma \). Since, \( \sigma \) value is predominant in PC3 composite, and contribution of \( \varepsilon_{p}^{''} \) is minor, therefore, expected \( P_c \) is higher than the \( P_p \). In other words, PC3 composite has high electromagnetic power conversion density due to the charge transport, and it is resulting better RL value.

![Figure 9](image_url)

**Figure 9.** Variation of Conductivity (\( \sigma \), Sm\(^{-1} \)) of PC composites.
The bulk material microwave absorption properties can be tuned through macroscopic pattern design. The classical pyramidal structure of dielectric material is well known for microwave absorption due to intrinsic power flow properties from top to bottom. Herein, the classical pyramidal structure was designed in mm (height 8 mm) for PC3 composite as shown in the Figure 10(a-b). The width of the bottom of the unit cell set as a variable parameter “a” and the height of the pyramid was fixed (8 mm). The electromagnetic parameters of PC3 composite were employed in order to carry out the standard electrodynamic simulation in CST-microwave studio. The value of “a” was varied from 13 to 25 and the resulted RL was shown in the Figure 10 (c-d). It was observed that the RL value of PC3 is very promising for all the designs, and minimum RL value was reached - 43 dB for a = 23. From Figure 10 (c-d), the optimized “a” value can be taken as 13, 20, 23. Figure 11 shows the power accepted by the designed structure (Figure 11 (a)) of PC3 (Figure 11 (b)) and PDMS (Figure 11 (c)). From Figure 11 (b-c), it can be understood that power accepted by the PC3 meta structure is predominant for all “a” values. The power loss distribution takes plays predominantly through the edges of the designed structure and due to that noticeable enhancement in RL was observed. The further modifications in structural design can be carried out based on that, viz., if the more edges as well as multiple scattering sites is introduced expected power loss distribution will be more and more effective RL can be expected.
Figure 10. (a-b) Schematic of the designed pyramidal structure, (c-d) simulated RL of the PC3 composites in the frequency range 8.2-18 GHz.

Figure 11. (a) Schematic, (b) simulated power absorbed (%) by PC3 composite and (c) PDMS.
- **Tuning of RL of PC3 composite through multi-layered meta-structure**

In order to tune the minimum RL value and absorption bandwidth, another multi-layer meta-structure design of the PC3 composite was also carried out. As shown in Figure 12(a-b), the thickness (8 mm) was divided into multilayer (8 layers) having thicknesses of 1 mm each. The magnified parameter “m” was assigned to tuning the unit cell size in the artificial array. The RL value of PC3 composite was shown in the Figure 12(c-d) respectively for different “m” values. Clearly, two distinct and very promising RL value peak was observed for all “m” value (1.4, 1.6, 1.8, 2, 2.2, 2.4, 2.6 and 2.8) in both X-band and Ku-band. The minimum RL value -37 dB and -30 dB was achieved for X-band and Ku-band respectively for m = 2 mm, indicating more than 99.99% absorption. The simulated power accepted by the PC3 composite for different “m” value is shown in the Figure 13(a-b). The power acceptance capability of designed multi-layered meta-structure of PC3 composite is intrinsically dominant in both the X-band and Ku-band respectively and also indicates the validation of the obtained RL trend.

![Figure 12. (a-b) Schematic, (c-d) simulated RL of the designed artificial multi-layered PC3 composite array in the frequency range 8.2-18 GHz.](image)
Mechanism

In the three types of the designed PC3 composites viz., the traditional uniform single bulk layer, pyramid unit cell array, and multi-layer pyramid unit cell array, each pattern was observed to possess specific radar absorption performances. This is because each pattern has a unique absorption mechanism. The schematic of absorption mechanism was shown in Figure 14 (a). The single layer bulk PC3 composite could generate quarter wavelength resonance depending on absorber thickness, and due to that for smaller thicknesses effective absorption takes place in high frequency region.\(^1\)\(^,\)\(^17\) In case of pyramidal meta structure, the millimetre range pyramid interfaces played the key role, and the impedance matching at the top was maximized and gradually decreased and maximum power loss is at the edges.\(^17\) The power loss distribution of multi-layered pyramidal PC3 composite was shown in Figure 14(b). As shown in the Figure 14(a), in the case of multilayer pyramidal structure, the synergistic effect of thicknesses, internal multiple reflections, corner scattering and different mode of resonances favoured the effective absorption of PC3 composite at X-band and Ku-band.

Figure 13 (a) Schematic, (b) simulated power absorbed (%) by PC3 composite for various “m” values.
Figure 14. (a-b) Schematic of radar absorption mechanism of bulk single layer and multi-layered artificial pattern, (c) Power loss distribution of multi-layered PC3 composite (at 12 GHz).

In order to validate the simulated results, we have fabricated the optimized multi-layered pyramidal meta structure of PC3 composite through solution processing. Figure 15 shows the comparison of experimental RL and simulated RL results (optimized multi layered pyramidal meta structure, $m = 23$). The trend of both experimental and simulated RL matches well, indicating that multi-layered pyramidal structural design of PC3 is effective to enhance RL ($\leq -10$ dB) bandwidth. The experimental RL shows two distinguish bandwidth (RL$\leq -10$ dB) viz. 10-13 GHz (minimum RL - 42 dB) and 14-16 GHz whereas single layer PC3 composite has minimum RL -6 dB. The observed deviation of RL peaks in simulated and experimentally recorded curves of optimized PC3 composite is believed to be due to many factors, viz., (a) raw data fitting error, (ii) structural error and (iii) random power absorption density. In electrodynamic simulation (CST-microwave studio), the input electromagnetic parameters, by default it takes linearly. However, we have seen the noticeable variation of ($\varepsilon'$) and imaginary ($\varepsilon''$) in Figure 4. Therefore, a significant difference in RL values of simulated and experimental data can be expected. The error due to structural fabrication is also considered here as it was fabricated using facile molded solution casting.
very high microwave power absorption density can be expected in multi layered PC3 pyramidal structure. This is because $Q$ (Wm$^{-3}$) depends on phase constant ($\beta$), and it can be expressed as,$^{27}$

$$Q_{av} = \frac{1}{2d \omega \varepsilon_0} |E_0|^2 |T|^2 \frac{|R|^2 e^{-2\alpha d} - |R|^2 e^{-2\alpha d} \sin(\delta) - |R|^2 e^{-2\alpha d} \sin(2\beta d - \delta) - \frac{|R|^2 e^{-4\alpha d}}{1 - 2|R|^2 e^{-2\alpha d} \cos(2\beta d - 2\delta) + |R|^4 e^{-4\alpha d}}} \left(\frac{1}{2\alpha} e^{-2\alpha d} - \frac{1}{2\alpha} e^{-4\alpha d} \cos(2\beta d - 2\delta) + \frac{1}{4\alpha} e^{-4\alpha d}\right) \right)$$

(6)

Here, $\omega$ is the angular frequency, $E_0$ is the amplitude of the electric field strength, $T$ and $R$ are the transmission and reflection coefficients, respectively. In the case of multi layered PC3 pyramidal structure, due to many corner scatterings random power absorption density is prominent, especially at the edges, resulting in better microwave absorption characteristics. Thus, because of these factors a noticeable difference in simulated and experimental RL results are found. The above discussion also indicates that the variation of simulated and experimental RL is obvious in composite based multi layered pyramidal macroscopic design, however, experimental RL values are towards more promising.

![Figure 15. The comparison of RL of simulated and experimental PC3 composite (multi layered pyramidal pattern, m = 23).](image-url)
CONCLUSION

PDMS-cow dung (PC) composite as a superior radar absorber was investigated for X-band and Ku-band. Leveraging the macroscopic pattern comprising of a pyramidal meta-structure design on the PC3 composite, dual band absorption performance was observed in case of multi layered pyramidal structure. The tunability of absorption of PC3 composite up to 99.99 % can be achieved with multi layered pyramidal meta-structure. The obtained RL of different designs of PC composites were guided with mechanism and explanations. Simulated result was compared with the experimental result, indicating suitability for real time applications.

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- Conflict of interest: None