FEMC Performance of Pyramidal Microwave Absorber using Sugarcane Baggasse and Rubber Tire Dust at 1 GHz to 18 GHz Frequencies

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Abstract ─ The solid, geometrically tapered microwave absorbers are preferred due to their better performance. The goal of this study is to design absorbers that can reduce the electromagnetic reflections to less than −10 dB. Two waste materials of sugarcane bagasse and rubber tire dust in the powder form were used to fabricate independent samples in the pyramidal form. This paper presents the complex permittivity measurements of sugarcane bagasse and rubber tire dust materials. These two materials are found to be potential absorbing materials in microwave frequency to allow absorption of microwave EMI energy. The materials were combined and fabricated in the composite structure. A measurement system using open- ended coaxial probe method was used for characterizing the dielectric properties of the materials in the range of 1 to 18 GHz microwave frequencies. The dielectric property was used to compare the propagation constants of the material. Comparison of the results proved that these two materials have industrial potential to be fabricated as solid absorbers.

Index Terms ─ Microwave absorber, open-ended coaxial probe, permittivity.

I. INTRODUCTION

In line with the rapid growth of microwave device fabrication technology, communication systems can now operate at higher and broader frequencies. The requirement of the electromagnetic compatibility (EMC) applications such as microwave absorbing material within the microwave signal's frequency range of kilohertz (kHz) to gigahertz (GHz) have incredibly extended the applications in GHz range for mobile phones and local area network and radar systems, among others [1], [2]. Electromagnetic interference is the degradation which occurs in the performance of a device, equipment, or a system caused by an electromagnetic disturbance. Electromagnetic disturbance can be caused by an electromagnetic noise, or an unwanted signal, or a change in the propagation medium itself [3]. The effects of EMI include malfunction, or even the permanent damage to the electronic devices which may lead to permanent failure [4]–[11]. Therefore, absorbers are used in a wide range of applications to eliminate stray or unwanted radiation that could interfere with a system's operation. Previous research showcased several materials

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which exhibited the potential applications in the design and development of the microwave absorber. Carbon loaded plaster, carbon black, iron powder, aluminum flakes and copper are some of such materials [12]. However, the principle element in the dielectric absorber is the carbon itself. The carbon is used as the dielectric loss adder in lossless polymer matrix materials. This process is also known as carbon consumption and it is used in the microwave industry, especially in the production of foam based absorbers. In humid surroundings, the carbon is chosen due to its resistance to corrosion [13]. Besides, carbon has less density as compared metal; hence, it is preferred in the fabrication of the absorbers [14]–[16].This project is focused on microwave absorber using sugarcane bagasse and rubber tire dust (SCBRTD) as the main composite materials to design and develop the absorber. The adding of filler, namely the rubber tire dust increases the performance of the microwave absorber. These absorbers were designed based on wave attenuation and depth of penetration data. Additionally, their EMC performance was evaluated in terms of bi-static reflectivity performance. The different concentrations of the fillers were measured, and the reflectivity was found to be better than -20 dB when the amount of rubber tire dust was increased.

II. MICROWAVE ABSORBER PROPERTIES

In this work, sugarcane (*Saccarhum officinarum*) bagasse was used as the main material to design the microwave absorber. Sugarcane bagasse is a residue produced in large quantities by sugar industries. In general, 1 ton of sugarcane generates 280 kg of bagasse, the remaining fibrous by-product of sugarcane after sugar extraction [17]. Sugarcane bagasse is also a potential material for the pyramidal microwave absorbers used in anechoic chamber to eliminate signal reflections [18]. The large percentage of carbon that is produced naturally in sugarcane bagasse can provide good reflectivity performance [19]. The first stage of this study involved the preparation of samples for the dielectric measurement.

In this work, the fillers are the agricultural waste which is sugarcane bagasse (SCB) and rubber tire dust (RTD) from tire wear whereas the polymer matrix is unsaturated Polyester Resin RP9509 (UPR) which is a rigid, flexible and electromagnetically transparent polymer. UPR is one type of the thermosetting polymers and it is needed to be added with a binder to start the cross linking process. Methyl ethyl ketone peroxide (MEKPO) which is in liquid state was being used as the binder with UPR. In the composites with more filler, the composites seem to be more compact and have less air space.

Dielectric properties of the materials in a broad frequency range of 1.0 GHz to 18 GHz were investigated. The samples were fabricated in composite form. There are two methods of measuring the dielectric properties: the coaxial probe technique and transmission line method. Figure 1 shows the fabricated pyramidal absorbers using mold.

(a) (b)

Fig. 1. Fabricated pyramidal parts of the absorbers: (a) Sugarcane Bagasse pyramidal Microwave Absorber without the square base part with height of 13 cm, and (b) Rubber Tire Dust pyramidal Microwave Absorber without a square base part with height of 13 cm.

A. Frequency spectrum, dielectric properties and wave propagation properties of the material

In this work, the results of dielectric characterization, along with the wave propagation characteristics of the composite samples composed of lossy sugarcane bagasse and lossy rubber tire dust are presented. Sugarcane bagasse and rubber tire dust are dielectric materials with μ_r = 1+0j; therefore, only relative complex permittivity was measured, and the results are presented in this section. In dielectric materials, the dielectric constant and the dissipation factor of energy are the main properties that enable them to be applicable for microwave absorbers. In designing the absorber materials, equation (1) can be used to determine their absorption capability, which relies on the conductivity, dielectric loss, or magnetic loss of the absorber materials [20]. The dielectric properties are essential to determine the materials' performance in the context of microwave absorption. Permittivity is a function of frequency that could vary significantly over a small range [21]:

$$A = \frac{1}{2}\,\sigma E^2 + \frac{1}{2}\omega\varepsilon_0\varepsilon_R\,E^2 + \frac{1}{2}\omega\mu_0\mu_R H^2, \qquad (1)$$

where A (W/m3) is the electromagnetic energy absorbed per unit volume, E (V/m) is the electric field strength of the electromagnetic signal, H (A/m) is the magnetic field strength of the electromagnetic signal, σ (S/m) is the conductivity of the material, ω (sec-1) is the angular speed of the electromagnetic wave, ε_0 is the dielectric permittivity of vacuum, ε_R is the complex permittivity of the material, μ_0 is magnetic permeability of the vacuum and μ_R is the complex permeability of the material.

Open-ended coaxial probe has been used for measurements on a number of agricultural products such as rice husk and grain [22],[23]. Calibration is required before the measurements are carried out by connecting the coaxial probe with open and broadband load as referred in Fig. 4 [24], [25]. This method consists of a network analyzer and a coaxial probe. It includes a mechanical load for short circuit calibration, air for open calibration and water (at room temperature) as a broadband load. Instead of using water as a broadband load, any solid dielectric material with known dielectric properties can also be used as the broadband load. However, the dielectric properties of the known materials in broad frequency ranges are unavailable. Many researchers have used this calibration technique due to the unavoidable air gap at the probe-sample interface to determine the dielectric properties of the solid samples [26]–[28].

At first, the samples were fabricated in three categories, namely, pure sugarcane bagasse, pure rubber tire dust and composite of lossy filler of sugarcane bagasse and rubber tire dust. The permittivity and permeability of the samples were determined by using the transmission line rectangular waveguide technique. Full 2-port calibration or transmission-reflection-load (TRL) calibration is essential for accurate phase measurements [29]. It is imperative that a sample fit inside the coax or waveguide since a poorly fit sample will not yield good results. As frequencies extend into millimeter waves, calibration and sample fit become even more critical due to the short wavelength. Magnetic constant and magnetic loss factor of the sugarcane bagasse (SCB), rubber tire dust (RTD) and sugarcane bagasse rubber tire dust (SCBRTD) composite samples were measured by using this technique. The results showed that relative magnetic properties of the tested materials were nearly equal to free space, $\mu_r = 1 - j0$. Therefore, these materials are non-magnetic materials. Figures 2 and 3 show the magnetic constant and magnetic loss factor of the material.

Since the materials used in this work are dielectric materials, the loss mechanism is purely dielectric. The loss can arise from a variety of sources within the dielectric. The commercial dielectric absorbers are usually made with low cost foam but can also be used with elastomers. Absorbers are characterized by their electric permittivity and magnetic permeability. Permittivity is a measure of the material's effect on the electric field in the electromagnetic wave. It arises from the dielectric polarization of the material.

The quantity $\varepsilon^{'}$ is sometimes called the dielectric constant, which is something of a misnomer when applied to absorbers as $\varepsilon^{'}$ can vary significantly with frequency. The quantity $\varepsilon^{"}$ is a measure of the attenuation of the electric field caused by the material. So, the dielectric constant of SCB, RTD and composite samples composed of SCB and lossy RTD need to be defined first to identify the material performance. Figure 4. shows the schematics of the experimental setup, indicating the field infringement at the open end of the probe due to the abrupt change in impedance.

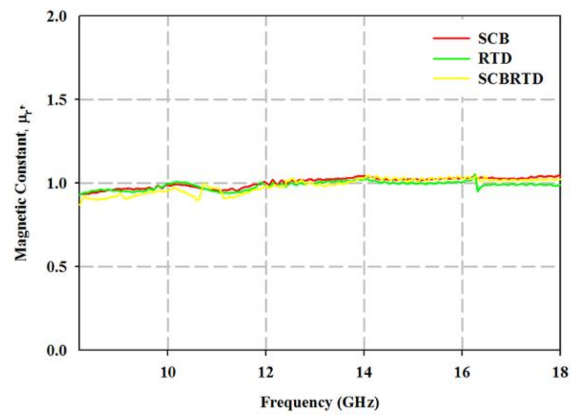

Fig. 2. Magnetic constant of the material.

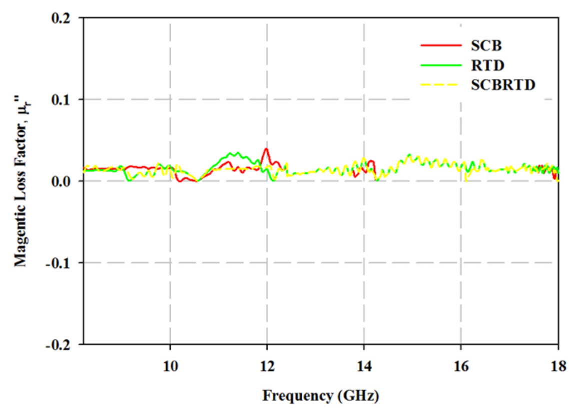

Fig. 3. Magnetic loss factor of the material.

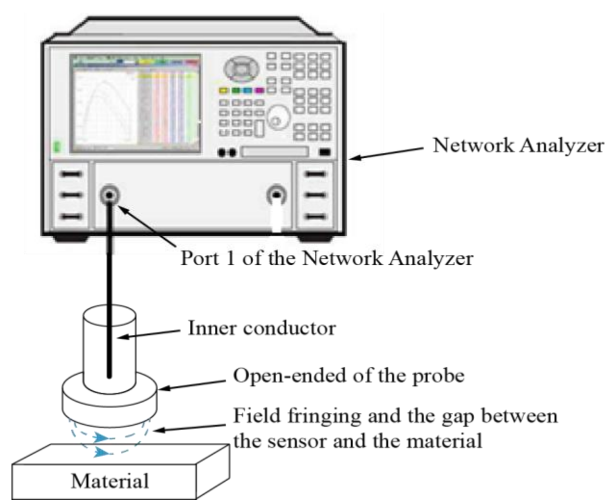

Fig. 4. Diagram of the experimental setup, showing field infringement at the open end of the probe due to abrupt change in impedance.

The complex dielectric properties of a medium can impact the propagation parameters of an electromagnetic

(EM) plane wave in defining the wave behavior in that medium. Absorbers are usually composed of materials that are affected by dissipation of loss. Hence, they attenuate the propagating wave inside the material. The impedance of electromagnetic wave propagating in free space is:

$$\eta_o = \sqrt{\frac{\mu_o}{\varepsilon_o}}, \quad (2)$$

where

μo =4π×10-7 Henry/m,
ε0 =8.854 ×10-12 Farad/m.

III. GEOMETRIC TAPERING OF LOSSY MATERIAL

A. Solid pyramidal microwave absorber

Impedance at each interface can be found by using the propagation constant and the characteristic impedance of each layer, according to the following transmission line theory:

$$Z_i = \eta_i \frac{\eta_{i+1}+\eta_i tanh(\gamma_i d_i)}{\eta_i+\eta_{i+1} tanh(\gamma_i d_i)}. \quad (3)$$

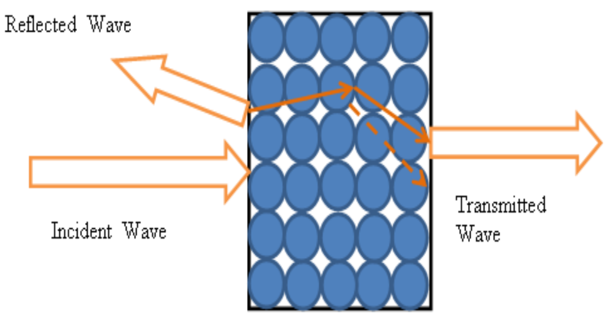

Fig. 5. Wave transmission into the absorber material.

Figure 5 shows the wave transmission into the absorber material. If the same wave interacts with a lossy dielectric medium such as SCB and RTD, the characteristic impedance of the medium can be expressed as:

$$\eta_m = \frac{\eta_o}{\sqrt{\varepsilon'_r - j\varepsilon''_r}}. \quad (4)$$

The impedance lies in the discontinuity at the interface of the air-dielectric (η0 ≠ ηm); so, the wave energy is reflected on the source medium. The remaining propagated energy within the lossy material can be expressed with a complex wave propagation constant, as follows:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\sqrt{\varepsilon'_r - j\varepsilon''_r}. \quad (5)$$

α is the real and β is the imaginary part of the propagation constant, which resembles the phase shift per unit length in the medium and the speed at which the signal was propagated. Hence, α and β express the dielectric properties of the material, as follows:

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'_r}{2}(\sqrt{1+tan^2\delta}-1}, \quad (6)$$

$$\beta = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'_r}{2}(\sqrt{1+tan^2\delta}+1}. \quad (7)$$

The function of an absorbing material is to attenuate the EM electromagnetic wave and prevent the EM wave from being reflected or transmitted pass through the material. The characteristic impedance is important in determining the performance of the absorbing material. Reflection can happen at the air-absorber interface due to the impedance mismatch between free space and characteristic impedance of the material. The reduction of the reflected wave from the front layer or surface can occur when the impedance of the material matches the impedance of free space (377Ω). The impedance of a material is given by the following relation:

$$Z = 120\pi\sqrt{\mu_r/\varepsilon_r}. \quad (8)$$

From this equation, it can be clearly inferred that the basic parameters for the absorption characteristics depend on permittivity and permeability of material. At microwave frequencies, when a dielectric material is exposed to a time varying electromagnetic field, the electric field component of the wave polarizes the molecules [30].

B. Wave propagation properties and dielectric properties of SCBRTD

The characteristic impedance, depth of penetration and phase constant of the materials are calculated to determine the wave propagation properties of the materials. The fraction of the incident wave energy (R) reflected off the interface of the dielectric material depends upon the characteristic impedance of the material. It should be noted that greater values of α are desired for absorbers, but these values are important only for the attenuation of the wave fraction that enters the material. Therefore, the characteristic impedance of the target medium is a very important parameter in the selection of the appropriate filler loading.

Five composite samples were fabricated in different compositions of SCB and RTD. Figure 6 below shows the dielectric constant of five samples with different percentages of fillers (sugarcane bagasse and rubber tire dust (SCBRTD)).

The complex permittivity increased when there is an increment in percentage of fillers in the composite samples. The addition of sugarcane bagasse and rubber tire dust increased the number of dipoles as they are lossy dielectric fillers. The electrostatic dipole energy and capacitance of the medium is increased when the energy from the incident wave is stored in these dipoles. Therefore, the dielectric constant increased with the increasing filler loading. From this result, the attenuation constant can be determined to examine the wave propagation into the material. Figure 7 shows the attenuation constant of the material for different filler loadings.

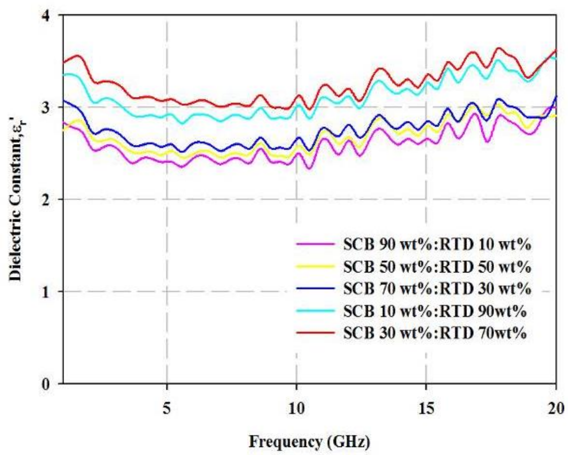

Fig. 6. Dielectric constant of different percentage of fillers (sugarcane bagasse mixed with rubber tire dust).

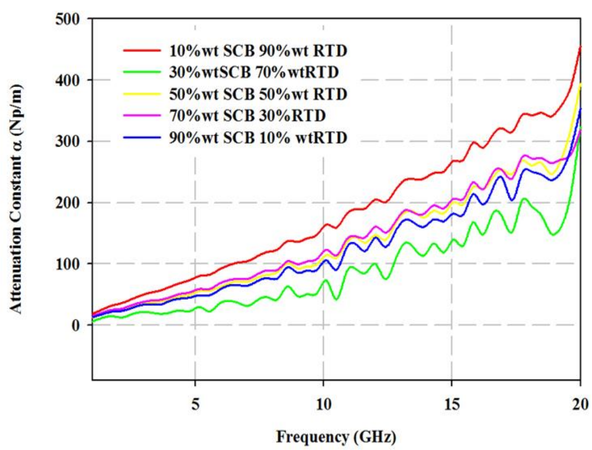

Fig. 7. Attenuation constant of the material for different filler loading.

Attenuation constant is inversely proportional to the frequency. The penetration depths were lower at high frequencies and become higher at lower frequencies. At high frequencies, the wavelength was shorter; so, the wave cannot penetrate deep into the medium due to the large attenuation offered by the medium as the reason. Figure 8 shows the penetration depth of the material. The values are calculated using the following formula:

$$D_p = \frac{1}{2\alpha}. \tag{9}$$

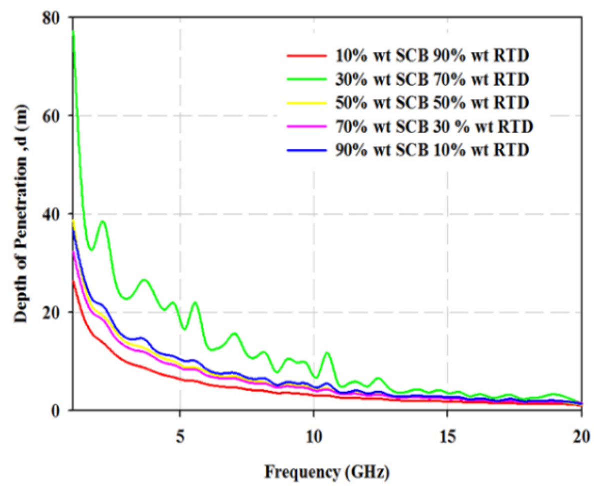

Fig. 8. Depth of material penetration.

Table 1 shows the measured relative values of the complex permittivity and magnitude of normalized characteristic impedance |Za| for different SCB and RTD filler compositions.

Table 1: Values of complex permittivity and magnitude of normalized impedance of the composite of sugarcane bagasse and rubber tire dust

Samples		Properties	Average
SCB (wt %)	RTD (wt %)		
10	90	εr’	3.12
		εr”	0.24
		tan δ	0.005
		| Z |	207 Ω
30	70	εr’	3.25
		εr”	0.12
		tan δ	0.003
		| Z |	250 Ω
50	50	εr’	2.69
		εr”	0.22
		tan δ	0.007
		| Z |	230 Ω
70	30	εr’	2.76
		εr”	0.18
		tan δ	0.005
		| Z |	227 Ω
90	10	εr’	2.60
		εr”	0.15
		tan δ	0.004
		| Z |	234 Ω

Impedance discontinuity (ΔZ = 377 − Za) is the least for 30 wt% of SCB loading; however, in this case, the value of the tangent loss is also minimum. This shows the maximum transmission of the signal with less attenuation and it is not preferred in the case of absorbers. An absorber must have a lossy medium with minimum impedance discontinuities at the interfaces. The best value of tangent loss is (0.007) when 50 wt% of SCB and RTD filler are used at the impedance of 230.

IV. MEASUREMENT OF ANECHOIC PROPERTIES OF PYRAMIDAL MICROWAVE ABSORBER

A. Method for reflectivity measurement

Commercially, the geometrically tapered (GT) absorbers can be found in a wedge or pyramidal shapes in truncated or non-truncated geometries with different heights. They are designed to transform the high impedance (377 Ω) of the incident wave to a very low impedance of the metal. The pyramidal absorbers have the most preferred shape for the anechoic chambers due to their enhanced ability to transform the impedance in wide bands of frequencies smoothly. This pyramidal shape was developed so that there is a gradual transition in impedance from air to the tip of the absorber and to the base of the pyramidal. In this work, the samples were fabricated in pyramidal microwave absorber (PMA) shape using the lossy filler of RTD and the SCBRTD PMA. In the case of the pyramidal absorbers, the broadband performance was achieved by the wave trapping. In other words, there are multiple reflections of the high frequency waves in-between the adjacent pyramids and the wave attenuation (or absorption) of the low and high frequency waves within the pyramidal lossy material [31]. The energy of the wave is lost in both the processes and a very weak signal is returned to the incident medium. Figure 9 shows the schematics setup for the measurement of reflectivity of the absorber using the S_{21} parameter.

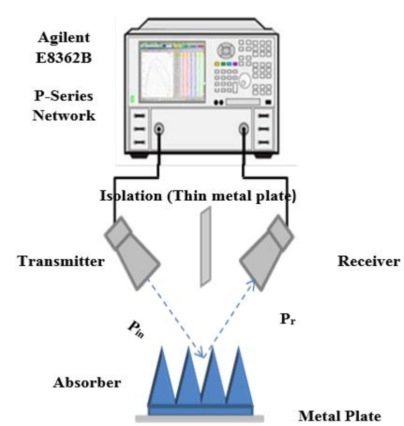

Fig. 9. Diagram of test setup for the reflectivity measurement of the absorber by using the S21 parameter.

B. Rubber Tire Dust (RTD) Pyramidal Microwave Absorber

The addition of RTD filler in SCB composite can increase the dielectric constant of the composite because of its high dielectric value. Based on the numerical study in X band and Ku Band frequency, the addition of rubber tire dust increased the reflectivity performance of the absorber to less than -10 dB (90% of absorption). Therefore, in this section, the frequency spectrum of the free-space, bi-static, reflectivity measurements for the pure rubber tire dust in an array of 4×4 pyramids are presented to investigate the performance of rubber tire dust in solid pyramidal form. Figure 10 shows the bi-static, normal reflectivity performance of a RTD PMA with reference to a metal plate in frequency range of 1 GHz to 18 GHz. The investigation was performed with the presence and absence of the base part.

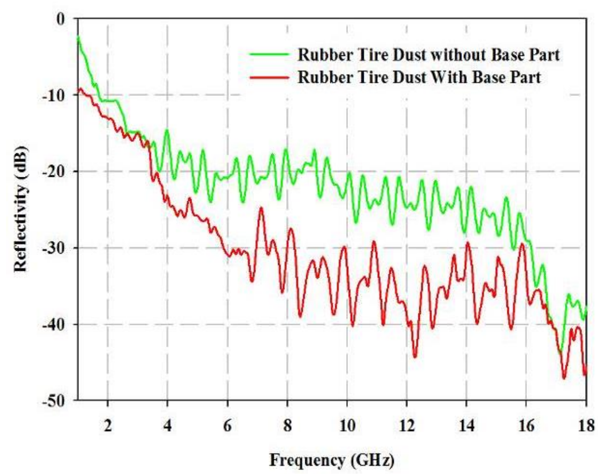

Fig. 10. Bi-static, normal reflectivity performance of a RTD PMA with reference to a metal plate in a frequency range of 1 to 18 GHz.

All the reflectivity measurements were done with reference to a metal plate that was used as a perfect reflector. It is observed that the values of the reflectivity was not below - 10 dB in the frequency range of 1 GHz to 2 GHz; however, in higher frequency (2 GHz to 18 GHz), the reflectivity can be achieved up to -45 dB (99.999% of absorption). The pyramidal part plays its role along with the base part and the reflectivity values were found to be lower than -20 dB from 4 GHz to 18 GHz. The best reflectivity performance of -30 dB to -45 dB is observed in the frequency range of 8 GHz-18 GHz of the X-band and Ku-Band. From the result, it is obvious that when the pyramidal part is placed along with the base part, there is improvement in the performance of the reflectivity of PMA. All the values of reflectivity were better than -10 dB for 1 GHz to 18 GHz frequency range.

In order to identify the use of those composite materials in microwave applications, their electromagnetic properties need to be defined first. In dielectric absorbers, there is no magnetic loss component involved. Therefore, the absorption of the dielectric absorber depends on dielectric properties of the absorber. The characteristic impedance (η_m) of a dielectric material will match with the free space impedance (η_0) only when $\mu_r = 1 + jo$, $\varepsilon'_r = 1$ and $\varepsilon''_r = 0$. Under these conditions, no partial reflection of the wave exists at the air-dielectric interface and the entire wave will be transmitted in the dielectric medium. As the SCB and RTD-based absorbers are composed of non-magnetic lossy materials with $\varepsilon'_r > 1$ and $\varepsilon''_r > 0$, their characteristic impedances will never match the free space impedance. However, the input impedance, Z_{in} that will be experienced by the incoming wave at the interface can be matched to the free space wave impedance.

Input impedance is a function of absorber's geometry, dielectric properties as well as the frequency of the incident wave. Therefore, the impedance will be matched only at certain frequencies and the resonance behavior will be observed at those (resonant) frequencies.

The different fillers' loadings can affect the performance of a microwave absorber. In Section 3.2, the dielectric properties and the wave propagation of the different weight percentage of sugarcane bagasse and rubber tire dust are discussed. There are five different weight percentages for each filler (SCB and RTD). Figure 11 shows the bi-static, normal reflectivity performance of a different filler loading of RTD and SCB PMA with reference to a metal plate in the frequency range of 1 GHz to 18 GHz. The large attenuation value occurred when 30 wt% SCB and 70 wt% RTD were used. The reflectivity of less than -25 dB to -40 dB (99.99% of absorption) was achieved for the frequency range of 1 GHz to 12 GHz. At 18 GHz, the reflectivity was approximately -42 dB.

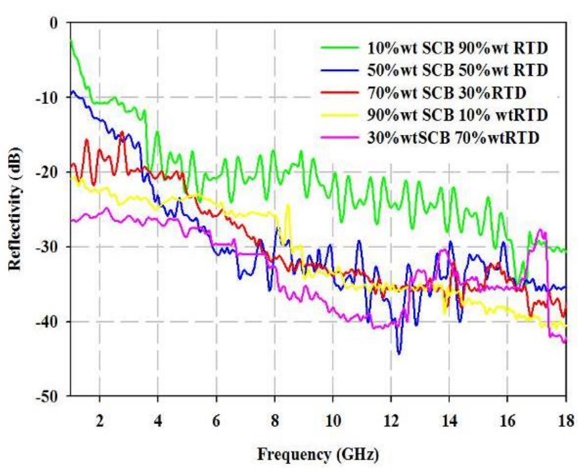

Fig. 11. Bi-static, normal reflectivity performance of a different filler loading of RTD and SCB PMA with reference to a metal plate in frequency range of 1 GHz to 18 GHz.

When 50 wt% for SCB and RTD was being used respectively, the result indicated better reflectivity of -10 dB for the range of 2 GHz to 4 GHz frequencies. However, at X band and Ku Band frequencies (8.2 GHz to 18 GHz), the reflectivity was much better, from - 30 dB to -40 dB. Poor performance was exhibited at the frequency range of 1 GHz to 2 GHz when 10 wt% SCB and 90 wt% RTD were measured. However, the rest of the frequency showed good reflectivity, with better than -10 dB and from the frequency range of 4 GHz to 18 GHz, the reflectivity was better than -20 dB to -30 dB. The composition of 90 wt% SCB and 10 wt% of RTD showed a better reflectivity of -20dB at low frequency. In the frequency range of 8.0 GHz to 18 GHz, the reflectivity was in the range between -30 to -40 dB. Different concentrations of filler loadings affected the performance of the microwave absorber. In this case, 30:70 SCBRTD demonstrated better reflectivity at 1 GHz to 12 GHz frequency range.

V. CONCLUSION

In this paper, we have described the experimental investigation to fabricate a microwave absorber for future EMC solutions. In addition, we have included the experimental measurement of dielectric properties and the performance of the proposed materials to be used as absorber. The experimental results show that these materials can be used to fabricate the microwave absorber to provide an anechoic surrounding (non-reflective) isolated from the waves entering from the surroundings and is able to absorb completely the reflections of electromagnetic waves. The design that has been investigated in this work was pyramidal solid shape and the results show that their performance was better than -10 dB, which indicates almost 90% of the incident microwave energy absorption. Based on the permittivity result, SCB and RTD materials can be considered as dielectric and lossy materials. The real part of permittivity has been found to be strongly dependent on frequencies. When the frequencies are increased, the permittivity values decrease. The imaginary part of the permittivity also showed variation with frequency, although not parallel to the real permittivity. From the permittivity, the propagation constant including attenuation constant and the depth of penetration were investigated. From the calculated wave impedance of the material result, the composition of 50 wt% of SCB and 50 wt% of RTD revealed to have the highest lost tangent and less impedance discontinuities, indicating its potential to be a good absorbent material. The reflectivity of the materials was analyzed for varying thickness values of the samples. When the RTD filler was added to the SCB composite, the reflectivity of the absorber achieved was better than -10 dB. The usage of agricultural waste materials such as SCB could be a potential solution in developing a microwave absorber that helps to reduce agricultural wastes that are usually burned off, which in turn leads to the emission of CO2 gas in the atmosphere and causes harm to the ecology. The cost of the pyramidal microwave absorber can be reduced by using SCB as the main material. An effort was made to adopt simple and low cost methods for the fabrication and evaluation that can easily be repeated and arranged on laboratory scale. This alternate use of sugarcane waste, or bagasse, reduce the amount of agricultural waste that contaminating the environment, so here in Perlis, Malaysia the sugarcane bagasse is available for free. The methods that were used in this study, to fabricate and measure the dielectric properties and performance of the pyramidal impedance graded absorber shape (15 cm height) samples were fabricated manually by using the open-mold. This SCB-based material is an eco-friendly raw material in the microwave absorber fabrication industry. The pyramidal microwave absorber made with waste materials (SCB and RTD) achieves 20dB of reflectivity which corresponds to the absorption of ~99.99 % of the waves.

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