Measurement of the Dielectric Constant and Loss Tangent of Polyester / Walnut Shells by the Cavity Perturbation Method at the Microwave X-band Frequencies

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Abstract

In this paper, the cavity perturbation method was used to measure the dielectric properties of materials that are important for understanding the response to microwave waves, in terms of the ability of these materials to store energy and dissipate it as heat, respectively. Compounds (polyester / walnut shells) were prepared, and for different weight concentrations of walnut shells (WS) additive, the proportions ranged between (0% - 25%). The used cavity is rectangular in shape with a theoretically resonance frequency of around (9.9978 GHz) and exiting the dominant mode (TE_{101}). The study shows the highest values of each dielectric constant with a weight concentration (25%) of the walnut shells, and the loss tangent without any material change to the sample. These compounds have been found to be useful in applications of electromagnetic materials such as microwave engineering and protection from biological influences when exposed to the field of microwaves, which is why it is very important to test their dielectric properties.

Key Words: Cavity Perturbation, Walnut Shells, Dielectric Properties.

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Introduction

With the widespread use of microwaves, the technology of materials absorbing microwave waves has become the subject of much research due to the increase in electromagnetic pollution due to the rapid development of telecommunications and electronic systems and their use of high frequencies, in addition to new standards and rules regarding compatibility and electromagnetic interference resulting from this type of equipment (Khadoor, 2019). The measurement procedure is also carried out using the cavity perturbation method to calculate the dielectric properties of materials at microwave frequencies, because of its high precision and the probability of easily finding data where an electromagnetic signal is sent to a cylindrical cavity and the resonance frequency is determined from the parameters within the cavity **(Ahmed, 2013).**

Cavity perturbation calculations can be extremely precise and are basically helpful in assessing the relative permittivity of dielectrics with a slight loss tangent where this method differs from the others because of its high sense of permittivity sensitivity. Cavity measurements, as understood here, are measurement techniques, which are based on exact solutions of the electromagnetic problem (Sarita et al., 2013).

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The measurement procedure demands that changes in quality factor (Q), resonant frequency or cavity length should be measured Cavity method involves many different techniques according to the range spectra of frequency. In microwave experiments the cavity perturbation technique is one of the most widely used, because of its relative simplicity and accuracy. In this technique one measures the adiabatic change of the characteristics of a resonator upon the penetration of a foreign body (the sample under test). Cavity perturbation is a common technique used to measure the complex permittivity at microwave frequencies. In this technique a small sample is inserted into a resonant cavity of quality factor (Q) (Sarita et al., 2013; Marvin-Ray, 2017). The inserted sample must be small compared to the special variation of the field and its disturbing influence must not be strong enough to force a jump from the unperturbed cavity. The change in the cavity characteristics (i.e. the resonant frequency, f_o, and the width of resonance band, Δf) due to the penetration of the sample under test are measured and a direct evaluation complex dielectric constant $(\varepsilon = \varepsilon' - j\varepsilon'')$ is possible provided by coming derivation. This technique includes some basic conditions for the results to be more accurate, which is the sample size must be small compared to the size of the used cavity, the cavity used must be the same with the presence of the sample and the a bsence of the sample (Manisha et al., 2018; Chul-Ki and Seong-Ook, 2018). The main objective of this study is to find the dielectric constant and the loss tangent of (polyester / walnut shells) compositions and weight ratios 0% to 25% of the walnut shells additive using the cavity perturbation method.

Theory of Cavity Perturbation

There is a relationship between angular frequency and quality factor and this relationship is important to obtain the required parameters in finding the dielectric constant and tangent loss, where The complex angular frequency ω associated with a dissipative system can be written as (Qusai, 2005; William, 2016; Mohamed et al., 2014).

$$\omega = \omega_r + j\omega_i \quad (1)$$

The real part, ω_r, is of course related to real frequency f_r, by

$$\omega_r = 2\pi f_r \quad (2)$$

When the time variation is taken as $e^{j\omega t}$.

Since $e^{j\omega t}$ associated with field quantities, and energy involves the square of field quantities, $e^{j\omega t}$ will be associated with energy. One sees then that energy decreases as $e^{-2\omega_i t}$.

Energy loss per unit energy, i.e., the difference between energies at times 0 and t is $(1 - e^{-2\omega_i t})$. Over any short interval of time t, assuming energy is constantly being replenished, the energy loss per unit energy can be written as:

$$\text{Energy loss per unit energy} = 1 - (1 - 2\omega_i t) = 2\omega_i t \quad (3)$$

by expanding the exponential.

Power loss per unit energy then is $2\omega_i$ so that the total average power loss in the system is $2\omega_i U$. With references to definition of quality factor, where U is the energy stored in the cavity

$$Q = \frac{\omega(\text{energy stored in the cavity at resonance})}{(\text{average power loss})} \quad (4)$$

Which can be written as

$$Q = \frac{2\pi f U}{2\omega_i U} = \frac{\omega_r}{2\omega_i} \quad (5)$$

The particular Q factor involved depends on which energy losses are considered. The only loss included in this study is due to dielectric loss only.

Consider the expression

$$\frac{\delta\omega}{\omega} = \frac{\omega_2 - \omega_1}{\omega_2} \quad (6)$$

Where both ω_2 and ω_r are complex in the sense of Equation (1), $\omega_{r2} \approx \omega_{r1}$ and $\omega_i << \omega_r$

$$\frac{\delta\omega}{\omega} = \frac{(\omega_{r2} - \omega_{r1}) + j(\omega_{i2} - \omega_{i1})}{\omega_{r2}\left(1 + j\frac{\omega_{i2}}{\omega_{r2}}\right)} \quad (7)$$

On expanding $\delta\omega/\omega$, and taking advantage of the indicated approximation, one has obtain

$$\frac{\delta\omega}{\omega} \approx \left[\left[\frac{f_{r2} - f_{r1}}{f_{r2}}\right] + j\left[\frac{1}{2Q_2} - \frac{1}{2Q_1}\right]\right]\left[1 - j\frac{1}{2Q_2}\right] \quad (8)$$

Where f_{r1} and f_{r2} are employed to designate resonant frequencies. Where they represent the resonance frequencies with the presence and absence of the sample in the rectangular cavity. Since $1/(2Q_2)$ can be neglected compared with unity, then

$$\frac{\delta\omega}{\omega} = \frac{f_{r2} - f_{r1}}{f_{r2}} + \frac{j}{2}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) \quad (9)$$

The above equation provides the link between the two quantities (f_r and Q). And to find the final relationships for perturbation of the cavity, consider two cavities, which are completely alike and let them be distinguished by subscriptions 1 and 2, the numbers 1 and 2 symbol for the cavity without the sample and the presence of the sample. For the present purpose the essential difference between the two cavities is the cavity assigned to 2, differs slightly due to the dielectric constant and magnetic permeability of the small sample materials. Maxwell's equations for these cavities are:

$$\nabla X E_i = -j\omega_i \mu_i \overline{H}_i \quad (10a)$$

$$\nabla X\overline{H}_i = j\omega_i\varepsilon_i\overline{E}_i \quad (10b)$$

Where i=1 or 2

Where the angular frequencies w; are complex and reflect all losses, so that losses through the coupling mechanism are included.

For the Equation (10), one can write:

$$\int_{V_c}\{[\overline{E}_2\cdot(\nabla X\overline{H}_1)-\overline{E}_1\cdot(\nabla X\overline{H}_2)]+[\overline{H}_2\cdot(\nabla X\overline{E}_1)-\overline{H}_1\cdot(\nabla X\overline{E}_2)]\}dV$$
$$= j\int_{V_c}[(\omega_1\varepsilon_1-\omega_2\varepsilon_2)\overline{E}_1\cdot\overline{E}_2-(\omega_1\mu_1-\omega_2\mu_2)\overline{H}_1\cdot\overline{H}_2]\,dV \quad (11)$$

The left hand side of Equation (11) is zero.

Then;

$$\omega_1\int_{V_c}(\varepsilon_1\overline{E}_1\cdot\overline{E}_2-\mu_1\overline{H}_1\cdot\overline{H}_2)dV = \omega_2\int_{V_c}(\varepsilon_2\overline{E}_1\cdot\overline{E}_2-\mu_2\overline{H}_1\cdot\overline{H}_2)dV \quad (12)$$

When each side of the Equation (12) is subtracted from the integral:
$\omega_2\int_{V_c}(\varepsilon_1\overline{E}_1\cdot\overline{E}_2-\mu_1\overline{H}_1\cdot\overline{H}_2)dV$, one can obtain:

$$(\omega_2-\omega_1)\int_{V_c}(\varepsilon_1\overline{F}_1\overline{E}_2-\mu_1\overline{H}_1\overline{H}_2)dV = \omega_2\int_{V_c}[(\varepsilon_1-\varepsilon_2)\overline{E}_1\overline{E}_2-(\mu_1-\mu_2)\overline{H}_1\overline{H}_2]dV \quad (13)$$

Re-arranging the terms of this equation yields (BALMUS et al., 2006):

$$\frac{\omega_2-\omega_1}{\omega_2} = \frac{\int_{V_c}[(\mu_2-\mu_1)\overline{H}_1\cdot\overline{H}_2-(\varepsilon_2-\varepsilon_1)\overline{E}_1\cdot\overline{E}_2]dV}{\int_{V_c}(\varepsilon_1\overline{E}_1\cdot\overline{E}_2-\mu_1\overline{H}_1\cdot\overline{H}_2)dV} \quad (14)$$

This equation is the basic cavity perturbation formula from which subsidiary results are derived.

We emphasis here when the cavity is empty, then $\varepsilon_1=\varepsilon_0$ and $\mu_1=\mu_0$, and if the sample is homogeneous (ε_2 and μ_2 are constants) and the volume of the sample V_s, is very small compared with the volume of cavity V_c. Under these conditions, Equation (14) can be written as follows:

$$\frac{\omega_2-\omega_1}{\omega_2} = \frac{(\mu_2-\mu_0)\int_{V_s}[\overline{H}_1\cdot\overline{H}_2]dV-(\varepsilon_2-\varepsilon_0)\int_{V_s}\overline{E}_1\cdot\overline{E}_2dV}{\int_{V_c}(\varepsilon_0\overline{E}_1\cdot\overline{E}_2-\mu_0\overline{H}_1\cdot\overline{H}_2)dV} \quad (15)$$

The integrations in the numerator of Equation (15) are over V_s, since $\varepsilon_1=\varepsilon_0$, and $\mu_1=\mu_0$, in cavity 1, except in the small volume V_s itself, so that ($\varepsilon_1-\varepsilon_2=0$) and ($\mu_1-\mu_2=0$) everywhere except in V_s.

Since the sample is very small and consequently be assumed to change the field in the cavity as a whole only slightly, then

$\overline{E}_2=\overline{E}_1$ and $\overline{H}_2=-\overline{H}_1$, in the integrals in the denominator of equation (15) and from principal equability of electric and magnetic energies in a losses cavity ($\overline{H}_1\cdot\overline{H}_2=-|H|^2$).

So, Equation (15) becomes:

$$\frac{\omega_2-\omega_1}{\omega_2} = \frac{(\mu_2-\mu_0)\int_{V_s}\overline{H}_1\cdot\overline{H}_2dV-(\varepsilon_2-\varepsilon_0)\int_{V_s}\overline{E}_1\cdot\overline{E}_2dV}{\int_{V_c}\varepsilon_0|\overline{E}_1|^2+\mu_0|\overline{H}_1|^2)dV} \quad (16)$$

$$\frac{\omega_2-\omega_1}{\omega_2} = \frac{(\mu_2-\mu_0)\int_{V_s}[\overline{H}_1\cdot\overline{H}_2]dV-(\varepsilon_2-\varepsilon_0)\int_{V_s}\overline{E}_1\cdot\overline{E}_2dV}{2\varepsilon_0\int_{V_c}|\overline{E}_1|^2dV} \quad (17)$$

This is obtained by using the assumption of perfect lossless

cavities, i.e., $\int_{V_c}\varepsilon_o\left|\overline{E_1}\right|^2dV = \int_{V_c}\mu_o\left|\overline{H_1}\right|^2dV$

If the sample assumed in Equation (17) is non magnetic ($\mu_2=\mu_0$), the first term drops out, and one has:

$$\frac{\omega_2-\omega_1}{\omega_2} = \frac{(1-\varepsilon_r)}{2}\frac{\int_{V_s}\overline{E}_1\cdot\overline{E}_2dV}{\int_{V_c}|\overline{E}_1|^2dV} \quad (18)$$

Where ε_r is the relative complex dielectric constant of the sample in cavity 2.

The complex angular frequenciesw$_1$, and w$_2$ in Equation 2-21 are related to the measurable quantities via Equation (9), so that the relative dielectric constant must, eventually, be obtained by the use of:

$$2\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)-j\left(\frac{1}{Q_2}-\frac{1}{Q_1}\right) = (\varepsilon_r-1)\frac{\int_{V_s}\overline{E}_1\cdot\overline{E}_2dV}{\int_{V_c}[\overline{E}_1|^2dV} \quad (19)$$

Here the field $\overline{E}_1$, in the empty cavity is presumed to be known and only the perturbed field $\overline{E}_2$, in the sample volume V_s, remains unknown. As will be explained, $\overline{E}_2$, is found only in context with a knowledge of sample geometry and $\overline{E}_1$. Using Equations (19) for dielectric slab of length L, width W and thickness h lies on geometric center of the bottom wall of a rectilinear cavity, one gets (Mohamed et al., 2014);

$$2\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)-j\left(\frac{1}{Q_2}-\frac{1}{Q_1}\right) = (\varepsilon_r-1)\frac{\frac{1}{\varepsilon_r}\int_{V_s}|\overline{E}_1|^2dV}{\int_{V_c}|\overline{E}_1|^2dV} \quad (20)$$

The sample is located in an essentially uniform field E_1, which is in fact the maximum field in the cavity. The integral over V_s therefore is given by:

or

$$\varepsilon_r = \frac{\left[1-\frac{V_c}{2V_s}\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)\right]-j\left[\frac{V_c}{4V_s}\left(\frac{1}{Q_2}-\frac{1}{Q_1}\right)\right]}{\left[1-\frac{V_c}{2V_s}\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right)\right]^2+\left[\frac{V_c}{4V_s}\left(\frac{1}{Q_2}-\frac{1}{Q_1}\right)\right]^2} \quad (21)$$

We know that (Ravika et al., 2015):

$$\varepsilon_r = \varepsilon'-j\varepsilon'' \quad (22)$$

Where ε' represents the real part of dielectric constant (perceptivity) and ε'' represents the loss coefficient of energy inside the material.

Comparing the last two equations:

$$\varepsilon' = \frac{F}{F^2+Q^2} \quad (23a)$$

$$\varepsilon'' = \frac{Q}{F^2+Q^2} \quad (23b)$$

where

$$F = 1 - \frac{V_c}{2V_s}\left(\frac{f_{r1}-f_{r2}}{f_{r2}}\right) \qquad (24a)$$

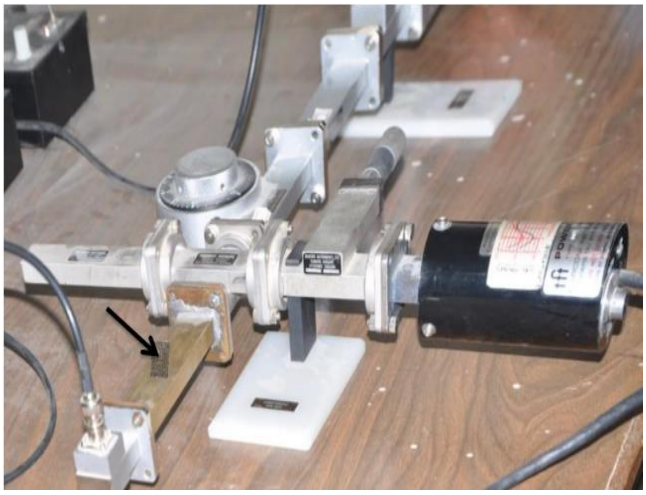
And

$$Q = \frac{V_c}{4V_s}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) \qquad (24b)$$

Equation (23) makes the evaluation of ε' and ε'' very easy to be calculated as will be shown in the next chapter.

One can define a parameter for detecting the loss in material as tangent loss, which represents the ratio of imaginary to real part of dielectric constant, i.e. (Nima et al., 2016).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (25)$$



Picture 1. Showing the System Used for Measurement

Experimental Measurements

In this research, unsaturated polyester resin was used, which is of the commercial type supplied by the Saudi Company for Industrial Resins (Jeddah), and the use of a solid methyl ethyl ketone peroxide at a rate of 2% and an accelerated cobalt actuate 0.5%.

Walnut shells have also been used as additives, which fall within the category of natural organic fillers, the shells were grinding by an electric machine to obtain a powder after that, a sieve was used to obtain minute sizes less than 450 μm. Where the manual method was used by using the casting mold to prepare the plates from the overlays and the required percentages dimensions (130mm x 130mm x 3mm) and leave a period of time to dry, then cut the overlays into dimensions (the length L_s=1.02 cm, w_s=0.52 cm in width, and h_s=0.3cm in thickness (height).

The measurement of the dielectric properties is carried out using a cavity perturbation method by introducing a small sample of the compounds into the cavity. The cavity consists of a rectangular copper waveguide of dimensions (L_c=13.5 cm, w_c=2.28 cm, h_c=1.02 cm). The wider upper side of the guide has a hole for dimensions (5.3mm x 3.2mm) As in the picture (1).

This method has been tested on known materials such as Teflon, by setting the microwave frequency of the empty cavity at 9.9978 GHz. The output power level is detected and the resonant frequency is determined, then the higher and lower resonant frequency frequencies are measured at the half-power, and if the sample is inserted into the cavity, these steps are repeated.

Results and Discussion

The results revealed that, as is obvious in table (1), the data obtained in this analysis were very similar to the theoretical resonance frequency in the rectangular cavity. The cavity quality factor is determined from the figure(1), which represents a plot of the transmitter power with the frequency and the resonance frequency is transferred after inserting the sample to be examined into the hole on the upper surface of the cavity. For each sample and according to the ratios, the measured values from the equations are used to find both the dielectric constant and the loss tangent, as shown in the table, depending on the graph of the transmitter power as a function of the frequency, since there are eight different experiments in the drawing. Where it was found that, with an increase in the concentration of the walnut shells, the dielectric constant and loss factor values increased, reaching their values (6.0914, 0.0975) respectively for the composite containing the walnut shells additive with 25%. The increase in the polarization between (PS) and (WS) when concentrating (25%) the walnut shells as a result of holding (WS) together, as the results showed by increasing the concentration of (WS), there was an increase in both the dielectric constant and the loss tangent. In the case (isolators / conductors), most of the time a model used Maxwell-wagner-sillar to describe the electrical insulation properties. This model confirms that the values of (dielectric constant and loss tangent) increase with the increase in the concentration of the walnut shells, taking into consideration the interpolarization (Doaa and Rahim, 2017; Hamon, 1953).

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Table 1. Showing the values of the dielectric constant and the loss tangent of (polyester / walnut shells) composite

Composition	Fs(GHz)	ε′	tan δ
Empty	9.8938	1	0
Teflon	9.7698	2.2522	0.0041
100% PS + 0% WS	9.6812	3.1666	0.0042
95% PS + 5% WS	9.5951	4.0714	0.0048
90% PS + 10% WS	9.5168	4.9085	0.0057
85% PS + 15% WS	9.4947	5.1472	0.0631
80% PS + 20% WS	9.4596	5.5287	0.0841
75% PS + 25%WS	9.4083	6.0914	0.0975

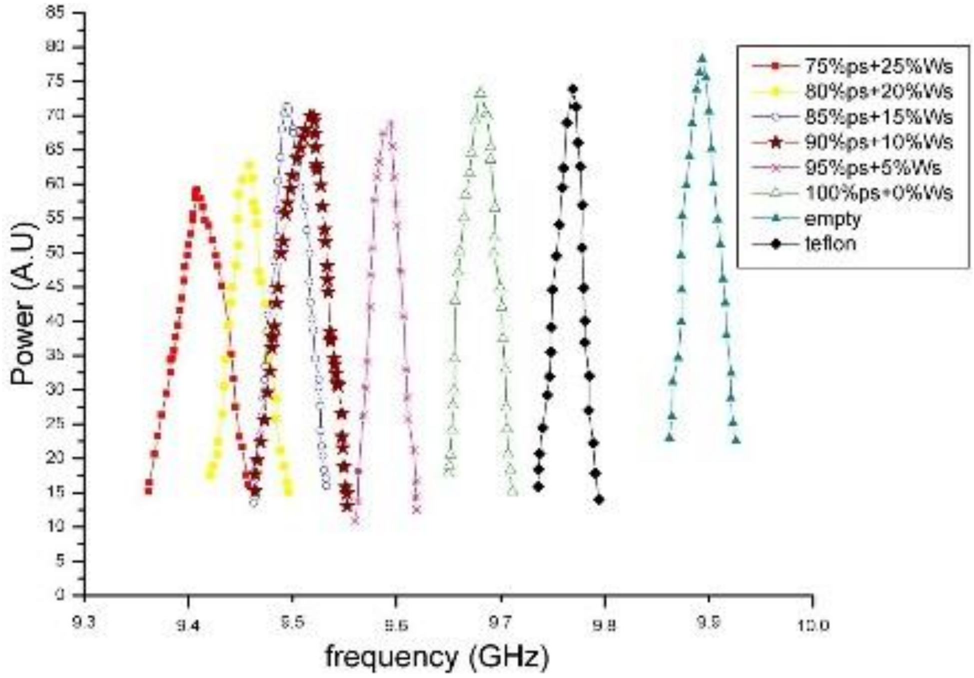

Figure 1. Showed the relationship between power and different frequencies

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Conclusion

The cavity perturbation method is an excellent method for calculating the permittivity for the composite (polyester / walnut shells). The concentration of (WS) increases, the dielectric constant and loss tangent of the composite also increase. This composite is very useful for radar absorbing materials (RAM) and shielding electromagnetic (SE).

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