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The cavity perturbation method for the measurement of the dielectric properties of (polystyrene/carbon black) composite

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Abstract:

The cavity perturbation method has been used to measure the dielectric constant and loss factor of (polystyrene/carbon black) composites of different concentrations of carbon black fillers (5 wt% - 20 wt%) . The used cavity is rectangular in shape that exited the dominant mode (TE_{101}) with a theoretical resonance frequency of about (9.7757 GHz). The composite having (20 wt%) carbon black fillers shows higher values of the dielectric constant ($\varepsilon' = 8.96$) and loss tangent ($\tan\delta = 0.089$). Finally composites are very useful for electromagnetic shielding (SE) and radar absorbing materials (RAM).In general ,in case of the heterogeneous mixture, the behavior of the dielectric constant and loss tangent is found to increase with the increase of carbon black(CB) fillers.

Keywords: - cavity perturbation, polymer composites, complex permittivity

Introduction:

The measurement of complex dielectric properties of materials at microwave frequencies has gained increasing importance especially in many fields, such as material science, microwave circuit design, absorber development, biological research, etc. Many techniques have been developed to measure these complex permittivities such as techniques in time domain or frequency domain with one port or two ports, etc.

The permittivity cannot be measured directly, but it is usually calculated via other measurable parameters such as propagation constant , transmission/reflection coefficients, resonance frequency ,etc. [1,2].

The cavity perturbation technique has been used widely for measuring dielectric properties and the impedance of thin films of homogeneous materials because of its simplicity , easy data reduction , accuracy and high temperature capability [3-6].

Cavity perturbation measurements can be highly accurate and are practically advantageous in the determination of relative permittivity of dielectrics with a small loss tangent where this technique differs from the others due to its high sensitivity. It involves an approximation in its formulation which leads to acceptable results only under very restricted conditions : (i) the sample must be very small compared with the cavity itself so that a frequency shift which is small compared with the resonant frequency shift of the empty cavity is produced by the insertion of the sample. (ii) the cavity without and with the sample must be very much alike. The most convenient shapes of samples are (sphere , rods , and slabs). The permittivity of dielectric films or foils or composites or conductive polymers has been of interest due to their application in microwave electronic circuits and devises [7] , radar absorbing materials and shielding effectiveness[9-13].

The aim of this work is to introduce a cavity perturbation method in which a cavity has been designed with a very small hole at the center of the broader side of the waveguide to insert a sample material. The rectangular cavity is designed to measure the dielectric parameter of Teflon(tested) at the dominant mode (TE_{101}) , after that this cavity is used to measure both the dielectric constant and loss tangent of the (polystyrene/carbon black) composite.

Theory of cavity perturbation:

When a material is introduced into a resonant cavity, the cavity field distribution and resonant frequency change depending on its shape, electromagnetic properties and position in the field of the cavity. When a sample of complex permittivity $\varepsilon_r = \varepsilon' - j\varepsilon''$ is introduced, it must be kept at the maximum electric field location of the cavity. According to the theory of cavity perturbation and after the introduction of the sample, let f_o and Q_o be the resonance frequency and quality factor of the cavity without sample, and f_s , Q_s all corresponding resonance frequency and quality factor with the sample. The complex frequency shift due to lossy sample in the cavity is given by [3]

$$\frac{-df^*}{f^*} = \frac{(\varepsilon_r - 1)\varepsilon_0 \int_{vs} E.E_0^* dv + (\mu_r - 1)\mu_0 \int_{vs} H.H_0^* dv}{\int_{vc} \left(D_0.E_0^* + B_o H_o^*\right) dv} \quad \ldots\ldots\ 1$$

Where df^* is the complex frequency shift, because the permittivity of practical materials is a complex quantity, so the resonance frequency is also complex. B_0 , H_0 , D_0 and E_0 are the fields in the unperturbed cavity and E and H are the fields in the interior of the sample. From equation (1) we see the numerator represent the energy stored in the sample and the denominator represent the total energy stored in the cavity with the aforementioned assumptions applied on equation(1), it leads to [3,10]

$$\frac{-df^*}{f^*} = \frac{(\varepsilon_r - 1)\varepsilon_0 \int_{vs} E . \overset{*}{E}_{\max\ 0}\, dv}{2\int_{vc} |E|^2 dv} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 2$$

The complex resonant frequency shift is related to measurable quantities by equation [3, 10]

$$\frac{df^*}{f^*} = \frac{f_s^2 - f_0^2}{f_s^2} + \frac{j}{2}\left(\frac{1}{Q_s} - \frac{1}{Q_0}\right) \quad \ldots\ldots\ldots\ldots\ldots\ 3$$

Equating real and imaginary parts of eq. (2) and eq. (3) and after integrating and rearranging we get:-

For the real part

$$\varepsilon' - 1 = \left(\frac{V_c}{V_s}\right)\left(\frac{f_o - f_s}{2 f_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 4$$

And For imaginary part

$$\varepsilon'' = \frac{V_c}{4V_s}\left(\frac{Q_0 - Q_s}{Q_s Q_0}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 5$$

V_c and V_s are corresponding volumes of the cavity and the sample respectively.

Equation (4) , (5) are the standard forms of the expression for the dielectric constant (ε') and loss factor (ε'') of the materials using the perturbation technique.

Experimental measurements:

The samples of (polystyrene/carbon black) composites are prepared by their mixing together. First the matrix polymer (Polystyrene) of a density (1.13 gm/cm^3) and molecular-weight (48000) is dissolved in the toluene solvent while carbon black is dispersed separately in toluene by a high-energy sonication using an Ultrasonic wand dismembrator. Thirty minutes later, both dissolved carbon black and PS are mixed together in a 10 ml size a glass cylinder. This cylinder is then set in the Ultrasonic wand dismembrator for thirty minutes. The mixture is then cast drop into a rectangular die with dimensions (2cm×1cm×1cm), and the toluene is allowed to evaporate completely in a period of (24) hours, to produce uniform films that are (0.6 mm) thick.

The measurements of complex permittivity are carried out by using the cavity perturbation method. The cavity is made up of a standard (x-band) brass wave guide of the length (d=2.07cm). The cross section dimensions are (a=2.286 cm) in width and (b=1.02 cm) in height. The upper broad wall of the guide has a hole (2mm) diameter. Conducting plates with a small aperture opening (4.6mm) on the other side of the guide provides the inductive coupling to the cavity. Figure (1) schematically shows the sample inside the rectangular cavity resonator.

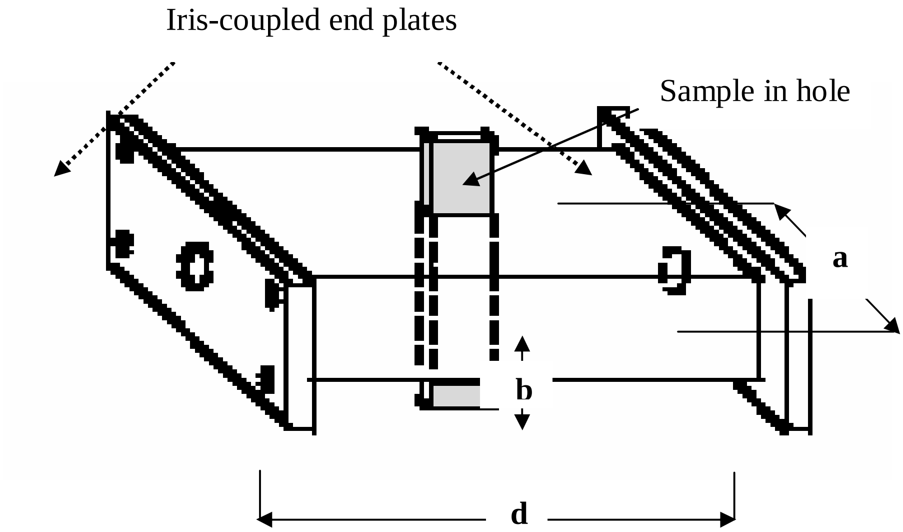


Figure (1)Sketch of the Rectangular Cavity with Sample Position

Figure (2) shows the schematic diagram of typical equipments required. First we test this technique on known materials like (Teflon), where the microwave frequency is adjusted to cavity resonance , as indicated by the maximum power output with respect to frequency variation. The indication of the output power level is noted ,and the resonant frequency (f_o) is measured. Then frequencies upper and lower than the resonance frequency are examined to record the amount of power. A plot of power versus frequency is sketched in order to find the quality factor(Q_o).

The above steps are repeated with the Teflon sample, which is inserted inside the cavity in the same way the resonance frequency (f_s) and quality factor(Q_s) are found.

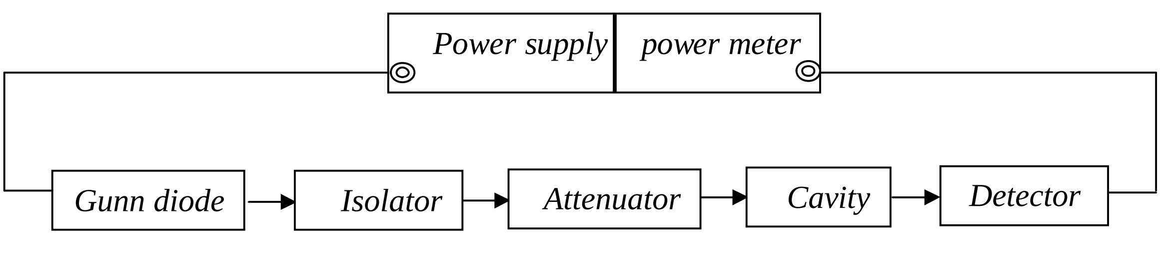


Figure (2) Block Diagram of the Experimental Setup.

Results and Discussion :

The obtained results show that the experimental data of the resonant frequency is very close to the theoretical resonant frequency in the rectangular cavity for the dominant mode TE_{101} as shown in figure(3) which represents a plot of the transmission power measured versus the frequency. The quality factor of the empty cavity is calculated from figure(3) . The insertion of a small sheet of Teflon in a cavity causes a shift in the resonant frequency. The quality factor of cavity filled up with Teflon sheet is found. These computed values in equations (4 , 5) are used to evaluate both the dielectric constant and loss factor of Teflon as shown in table (1) where the obtained results are in good agreement with the dielectric constant value as measured and reported by researchers [6].

A plot of transmission power as a function of frequency is shown in figure (4) , where six different experiments are included : empty cavity, cavity with samples (PS + 0% CB), (PS + 5% CB) , (PS + 10% CB) , (PS +15% CB) and (PS +20% CB). The behavior of the dielectric constant and loss factor is calculated from the analysis of these results by using equations (4) and (5) , and the results are listed in table (2). The values of the dielectric constant and loss tangent increase with the increase of the carbon black concentration which as high as (8.96 , 0.089) respectively, for the composite with 20 wt% carbon black fillers. In this concentration, the (CB) particles must touch one another directly forming conductive chains, therefore the interfacial polarization between (PS) and (CB) fillers increases. It is obvious that these composites show an increasing of both the dielectric constant and loss tangent with increasing the carbon black concentration.

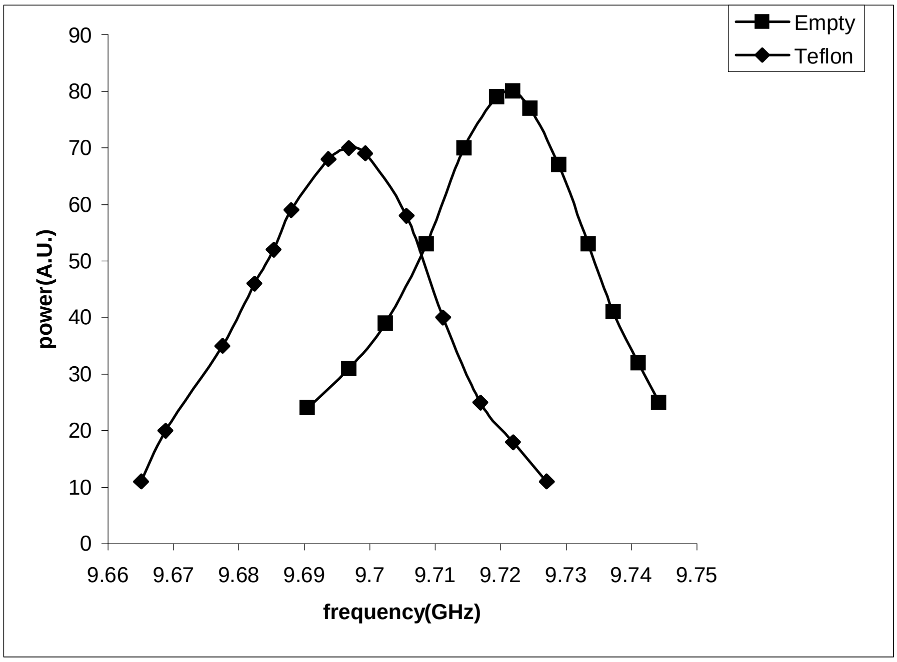
Generally for the case of the heterogeneous mixture (isolators/conductors), the behavior of dielectric properties is governed by the Maxwell-wagner-sillar model. This model predicts that the values of the dielectric constant and loss tangent are increasing with the increase of the concentration as well as the conductivity of the fillers. This model takes into consideration the interfacial polarization between the fillers and the host matrix [7,11,14].

Table (1) dielectric constant and loss tangent of Teflon in TE_{101} mode.

Volume sample(cm^3)	F_o(GHz)	F_s(GHz)	ε'	$\tan\delta$
0.006	9.7219	9.6968	2.04	0.0040

Table (2) dielectric constant and loss tangent of (Polystyrene/Carbon Black) composite in TE_{101} mode.

Composition	Volume sample (cm^3)	F_s(GHz)	ε'	$\tan\delta$
100% PS + 0% CB	0.005	9.6937	2.40	0.0030
95% PS + 5% CB	0.011	9.62480	3.21	0.0031
90% PS + 10% CB	0.010	9.6176	3.61	0.0336
85% PS + 15% CB	0.0049	9.5948	4.40	0.050
80% PS + 20% CB	0.005	9.5641	8.96	0.089



Figure(3) Transmission power (A.U.) versus frequency

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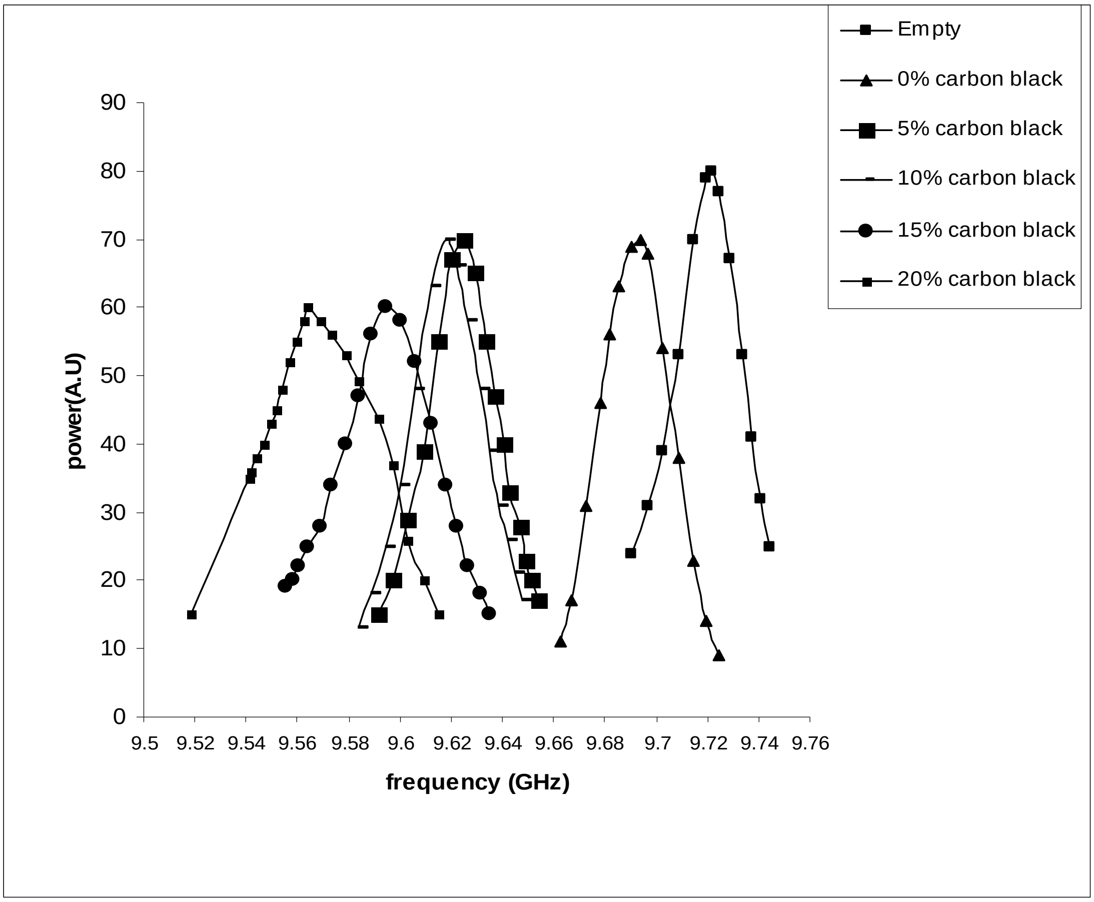

Figure(4) Transmission power (A.U.) versus frequency

Conclusions:

This work confirms that the cavity perturbation technique is a very accurate method to measure the complex permittivity of the (polystyrene/carbon black) composite. The dielectric constant and loss factor of the composite increase with the increase of carbon black fillers.

This composite is very useful for the electromagnetic shielding (SE) and radar absorbing materials (RAM).

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طريقة اضطراب التجويف لقياس خواص العزل لمتراكبات (بولي ستايرين/ اسود الكاربون)

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المستخلص:

تم في هذا البحث استعمال طريقة اضطراب التجويف لقياس خصائص العزل الكهربائي (ثابت العزل وعامل الفقد) لمتراكبات (بولي ستايرين/اسود الكاربون)، ولتراكيز وزنية مختلفة من مضاف اسود الكاربون تتـــراوح نـــسبها بـــين (20% - 5%) ، إن التجويف المستعمل في هذا البحث ذو شكل متوازي مستطيلات ويثار بنمط أساسي (TE_{101}) وبتردد رنيني (نظري) مقارب إلـــى (9.7757 GHZ) ، وبينت النتائج المستحصلة إن المركب الذي يمتلك تركيزا وزنيا (20%) من مضاف اسود الكاربون اظهـــر أعلى قيم لثابت العزل ($\varepsilon' = 8.96$) وظل الفقد ($\tan\delta = 0.089$). أخـــيرا فان هـــذه المتراكبـــات مفيـــدة جـــدا لأغراض صناعة الدروع الكهرومغناطيسية (SE) والمواد الماصة للرادار (RAM) ،بصورة عامة في حالة المتراكبات المتجانسة ، وجد إن سلوك ثابت العزل وظل الفقد يزداد بزيادة حشوات اسود الكاربون (CB).

الكلمات الدليلة : اضطراب التجويف ، المركبات البوليمرية ، السماحية المعقدة