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Measurement of Electromagnetic Properties of Polymer Material for Rocket Propulsion Applications at Microwave Frequencies

Sarita Sharma
Assistant Professor, Chandigarh College of Engineering and Technology. Chandigarh. INDIA.
saritasharma@ccet.ac.in

ABSTRACT

Rapidly growing hybrid rocket propulsion systems has put forth the demand for new thermoplastic materials for fuel. Polymer materials due to their novel mechanical, and chemical properties along with their unique electromagnetic field response, find suitable applications in other domains such as, for the construction of high-frequency circuits, antenna substrate, filters, and in sensor based smart clothing. Electromagnetic field response of Polymer materials at gigahertz (GHz) frequency range is crucial for various research problems and also in the development of electronic products at these frequencies. Polymers with good electromagnetic shielding properties are being developed and explored for use in the GHz frequency range. There is an absolute need for better understanding of interaction of these materials with electromagnetic field at these frequencies.

This article describes the applicability of Cavity perturbation technique to measure the electromagnetic properties of Polymer materials such as Nylon 6 (Semi crystalline Polyamide) over 8 to 12 GHz frequency range. This techniques proved to be extra advantageous due to its sensitivity, simplicity and ease of sample fabrication.

Key words: Cavity perturbation, Cavity resonator, Dielectric Constant and Dielectric Loss

1. Introduction

Modern day advances in rocket propulsion systems and high-frequency electronics technology is making abundant use of polymers due to its flexibility, durability and specific dielectric properties. Recently explored hybrid polymer fuel using Nylon 6 has shown promising combustion efficiency. Widespread use of polymer materials in microwave and telecommunication systems has made it crucial to develop a deeper understanding of variation of their dielectric properties and applicable measurement techniques.

Polymers are generally considered insulators or dielectrics, meaning they resist the flow of electric current at lower frequencies which however show increase in transmission of some electrical energy at higher frequencies [1-2]. Dielectric constant (□□) and Loss factor (tan∂) is measure of response of a material to application of electromagnetic field. It is desired that a material hold the stored charge for longer time and Loss factor (tan∂) is a measure of this ability. High (tan∂) represents the inefficiency of dielectric materials. It is the ratio of the dielectric loss (□″) in a dielectric to the dielectric constant (□□□ of that material.

A detail discussion on the technique for measurement of dielectric properties of material at X band of frequencies has been given in the literature [1-11]. To build upon existing knowledge of these techniques; a new cavity perturbation technique has been used as developed in our previous work. [6], [12]. In this method, a resonant cavity is loaded with the dielectric sample that produces a perturbation of the field distribution inside the cavity resonator. By measuring the shift in resonant frequency (f_0) and quality factor (Q), the complex permittivity of the sample can be calculated. This technique is based on the theory of perturbation and a very small sample which is

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just enough to bring only a slight change in the field distribution inside the empty cavity is used. Compared to other methods, the cavity perturbation method is highly sensitive and provides accurate measurements.

The accuracy of some dielectric measurement techniques is limited by certain assumptions made during their development. These approximations can lead to reliable results only under specific conditions, including the requirements that the sample being measured is much smaller than the cavity size so that the total shift in the resonant frequency due to presence of sample in the cavity is comparatively less than the resonant frequency of the empty cavity. Additionally, the cavity with and without the sample must be very similar. However, despite these limitations, the cavity perturbation method is known to be a highly precise and reliable method for determining the loss factor of materials with very low losses.

Nylon 6 polymer find wide applications in the production of textile-based transmission lines and electrospun nylon-6 nanofibers. Various Composites of these materials are being explored for different application areas, like aircraft, space vehicles, and for high frequency telecommunication technology. [13][14] Measurement of dielectric properties of this polymer at X band range can provide better insight to tailor the requisite usage.

2. Measurement Technique

Proposed cavity resonator is fabricated from brass waveguide. Decision on the length of cavity is made upon the consideration of modes to be propagated. The dominant mode is TE_{10n}, as n correspond to half wavelength number in the direction of propagation. The cavity is excited by the mean of inductive coupling with two holes of 4 mm diameter in two end sheets of the cavity. The designed cavity resonator with dimensions of 23 x 10 x 140 mm^3 can support five modes (TE_{105}, TE_{106}, TE_{107}, TE_{108}, TE_{109}).

Cylindrical samples of Nylon 6, are used to perturb the cavity. Perturbation is done at the position of maximum electric field. The sample under test has been inserted in cavity upon through the sample hole. Insertion of the sample causes a change in the total capacitance and conductance of the cavity which in turn changes the empty resonant frequency and the *Q*-factor.

The complex resonant frequency shift can be expressed as [2-3]

$$\frac{df^*}{f} = \frac{f_s^2 - f_0^2}{f_s^2} + \frac{j}{2}\left(\frac{1}{Q_s} - \frac{1}{Q0}\right) \qquad (4)$$

Where f_0 and Q_0 denotes resonance frequency and quality factor of cavity in unloaded condition. Corresponding shifted in both the parameter upon loading of the cavity loaded with the sample is denoted by f_s and Q_s.

Further considering real and imaginary parts of equation (3) and (4) we have

For real part:

$$\frac{-(f_s - f_0)}{f_s} = \frac{(\varepsilon_r^{/} - 1)\int_{V_s} E.E_{0\max}^{*}\, dv}{2\int_{V_c} |E_0|^2\, dv} \qquad (5)$$

Here it is assumed that $E = E_0$ and at resonant mode TE_{10n} , $E_0 = E_{0max} \sin(p\pi z/l) \sin(p\pi z/l)$.

For the given cavity '*a*' depict the broader dimension and '*l*' represents the length of the cavity in direction of propagation. Equation (5) on Integrating and rearranging the equation, results in following

$$\frac{f_0^2 - f_s^2}{f_s^2} = \frac{4V_s\varepsilon^{/}}{V_c}$$

$$\varepsilon' = \frac{V_c(f_0^2 - f_s^2)}{4V_s f_s^2} \qquad (6)$$

The volume of the cavity $V_c = a \times b \times l$ and $V_s = \pi r^2 h$ (volume of the sample).

For the Imaginary part:

$$1/2\left(\frac{1}{Q_s} - \frac{1}{Q_0}\right) = \frac{\varepsilon_r'' \int_{v_s} E.E_{0\max}^* dv}{2\int_{v_s} |E|^2 dv} \qquad (7)$$

Solving and rearranging the equation (7), we obtain

$$\left(\frac{1}{Q_s} - \frac{1}{Q_0}\right)\frac{V_c f_0^2}{4V_s f_s^2} = \varepsilon'' \qquad (8)$$

3. EXPERIMENTAL SET UP

The measurements set up includes the rectangular waveguide cavity resonator with a sample hole in the center of broader wall of cavity and connected to the two ports of the Vector Network Analyzer S-parameter test set. S-parameter (transmission co-efficient) measurement using experimental set up is shown in Fig. 1

TE_{10n} modes of the cavity at which measurements are made are 8.46 GHz, 9.15 GHz, and 9.96 GHz and11.64 GHz frequencies of the X band.

Fig 1 shows the amplitude shift in Transmission coefficients of the Cavity after insertion of sample towards the left side, hence showing a decrease in resonant frequency and quality factor. The central frequency and 3 dB down points on the resonance curves correspond to the resonant modes are marked to measure the values of (f_s) and (Q_s). Using the measured values of f_0, f_s, Q_0 & Q_s in equation (6) and (8) the dielectric constant and dielectric loss of Nylon sample has been calculated respectively.

4. RESULTS AND DISCUSSION

The measured dielectric parameters and computed values of Loss factor of Nylon 6 are tabulated in table 1 at various resonant modes.

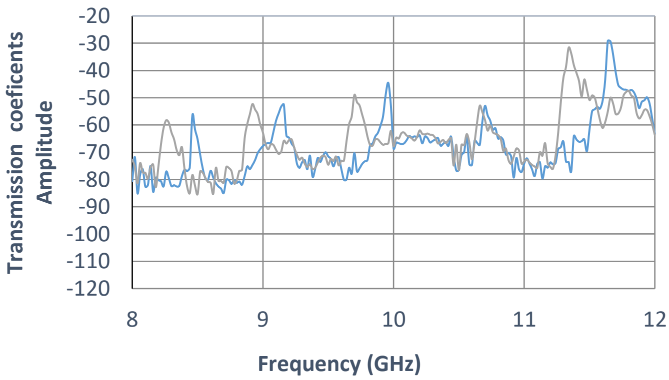

Figure 1 Amplitude shift in Transmission coefficients of the Cavity after insertion of test sample.

Table 1 Dielectric Constant, Dielectric Loss and Loss Tangent of Nylon-6

MODE	f_0 GHz)	Nylon 6			
		f_S (GHz)	□□	□″	tan∂
TE_{105}	8.46	8.28	2.96	0.0021	0.0021
TE_{106}	9.15	8.95	3.01	0.0013	0.0024
TE_{107}	9.96	9.63	3.02	0.0012	0.0029
TE_{108}	10.7	-	-	-	-
TE_{109}	11.64	11.26	3.04	0.0002	0.0034

The variation of dielectric constant and loss factor of Nylon 6 over the frequency range of 8-

12 GHz are clearly depicted as shown in fig 2 and fig 3.

Earlier measurement data available in the literature on dielectric properties of Nylon and its composites has been measured in low frequency range (MHz). [15-18] Relatively little data is measured for the dielectric behavior of Nylon at frequencies above 1 GHz.

The measured dielectric properties of Nylon 6 at 8-12 GHz are compared with data available in the literature through the use of other method.

Table 2 shows a comparison of dielectric constant of Nylon6 obtained with the proposed method and other method in literature (Juan Munoz et al, 1998). Fairly good agreement has been observed between measured values and literature values.

Table 2 Comparison of measured Dielectric Constant of Nylon 6 sample with other methods

f_0 (GHz)	Measured	Literature Free space method (Juan Munoz et al, 1998)		Literature (wave Guide method) (Juan Munoz et al, 1998)
	ε′	Frequency(GHz)	ε′	ε′
8.46	2.96	-	-	-
9.15	3.01	9.5	3.07	2.91
9.96	3.02	10	3.09	2.93
10.7	-	10.5	3.06	2.94
11.64	3.04	-	-	-

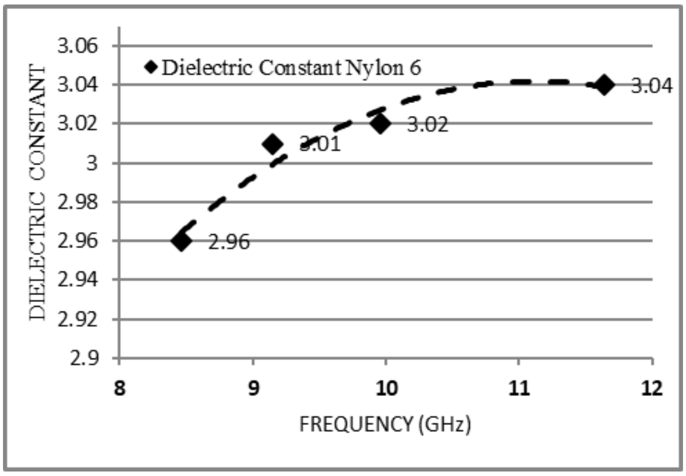

Fig 2- Frequency dependence of Dielectric constant of Nylon-6

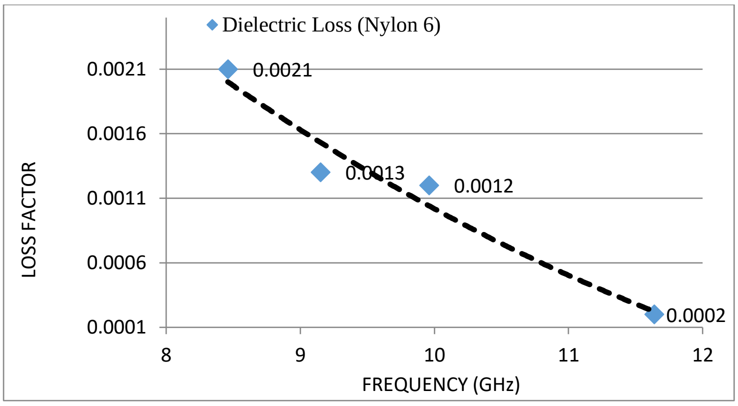

Fig 3- Frequency dependence of Dielectric Loss of Nylon-6

5. Conclusion

The developed technique has shown good accuracy in measuring the complex permittivity of plastic dielectric materials at microwave frequencies. The measurements of Nylon 6, shown the dielectric constants increase with the increase of frequency. The loss tangent or dissipation factor, which is a measure of degree of loss the dielectric material is, has also been measured. The results obtained are in good agreement with the existing literature.The measured values will help to provide better insight while using these materials at high frequency applications ,hybrid rocket fuel and for preparing composite materials. From the obtained results, it can be concluded that the dielectric properties of microwave plastic material can be accurately measured using the cavity perturbation technique.

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