

<http://dx.doi.org/10.48198/NJPAS/20.B19>

## Determination of Dependence of Attenuation on Material Thickness of Low-Density Polyethylene at Microwave Frequency

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### ABSTRACT

The attenuation of the electromagnetic wave signal due to power absorption by materials contributes to assessing the suitability of materials for use in microwave applications. One of the factors affecting power attenuation is material thickness. Therefore, this study investigates the effect of material thickness on the S-parameters and attenuation properties of low-density polyethylene (LDPE) at the X-band frequency range (8GHz-12GHz) to optimise the experimental design and reduce the cost associated with material preparation. The Waveguide measurement technique along with the finite element method (FEM) was implemented in COMSOL Multiphysics software for the study and analysis. The length of the waveguide was 200mm while the length and width of the waveguide ports were 22.28mm and 0.1143mm, respectively. The thickness of the LDPE was varied from 6mm-14mm with 2mm increment. Variation of  $S_{11}$  and  $S_{21}$  as functions of material thickness were determined and analysed.  $S_{11}$  decreased from 0.51 to 0.32 and  $S_{21}$  increased from 0.85 to 0.93 at 6mm and 14mm of the material thickness, respectively. The attenuation of the LDPE due to power loss decreased from 1.37 to 0.31 at 6mm and 14mm, respectively. It is determined from the results obtained that attenuation decreases as the thickness of the material increases, thereby reducing power loss due to absorption by the material.

**Keywords:** LDPE, S-parameters, Attenuation, Sample thickness

### Introduction

Insight into dielectric materials response to an electromagnetic field (EM, Field) at microwave frequency is vital especially for specialties such as electronics and communications, be it military, industry, or consumer applications ( Ahmad *et al.*, 2016). A dielectric material is a material capable of storage and dissipation of energy when placed in an electromagnetic field. Such materials are

employed for different applications at microwave frequency such as absorbers or printed circuit boards (PCBs). When a dielectric material is to serve as an absorber for Electromagnetic Interference Shielding (EMI Shielding), it is required to absorb almost all the incident EM waves on it (Khamis *et al.*, 2020) whereas for PCB application it is to absorb ideally zero per cent of

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the incident EM waves. In other words, for PCB application at microwave frequency, it is required that the dielectric material transmit almost all the incident EM waves upon it.

Material attenuation characteristics depend on several factors such as frequency, dielectric properties, material thickness (Yakubu *et al.*, 2014; Ahamd *et al.*, 2016) and so on. In this work, we intend to study the dependence of attenuation on material thickness of Low-Density Polyethylene (LDPE) in-silico at X-band frequency using COMSOL software. This will help us to design our experiment efficiently by reducing the cost and time consumption therein. The X-band is chosen for its importance in Military communication, satellite, radar, and weather applications. This is due to its advantage of extremely low atmospheric attenuation (Λενακάκης, 2020). The choice of LDPE was based on its excellent dielectric properties, ease of processing due to its low melting point, and mechanical flexibility that makes it suitable for use in wearable electronics.

To calculate the attenuation of a sample, the transmission and reflection coefficients or S-parameters must be obtained through either analytical, experimental, or simulation method, therefore a good grasp on how to extract these parameters for the determination of attenuation capability of microwave materials.

COMSOL software is a 3-dimensional electromagnetic wave solution environment based on the finite element method (FEM) (Zimmerman, 2006). The results acquired from COMSOL for S-parameters agree with experimental measurements and so reliable that cumbersome theoretical analysis maybe jettisons in its favour (Yakubu *et al.*, 2014; Khamis *et al.*, 2020). There are several measurement techniques available for implementation into COMSOL to calculate the S-parameters but we prefer the waveguide technique for its design simplicity and accuracy (Abbas *et al.*, 2001).

## 2.0 Theory

The finite element method (FEM) consists essentially of four (4) steps: (a) discretizing the region of solution into a finite number of elements, (b) deriving the governing equation for a given region, (c) gathering all the elements in a given region, and (d) Solving the systems of equations derived (Sadiku, 2018).

When a region of the solution is partitioned, the potential in the region is approximated as (Sadiku, 2018)

$$V(x, y) = \sum_{e=1}^N V_e(x, y) \quad (1)$$

Where N is the number of elements in the region. Thus,  $V_e$  can be further written in a polynomial approximation as

$$V_e(x, y) = a + bx + cy \quad (2)$$

Therefore, the electric field in the region is thus given as

$$E_e = -\nabla V_e = -(b\mathbf{a}_x + c\mathbf{a}_y) \quad (3)$$

When we consider a triangular element, fig. 1,  $V_e$  can be presented as

$$V_e = \sum_{i=1}^N \alpha_i(x, y) V_{ei} \quad (4)$$

Equation (4) is given as the potential at any point within the element when the potential at vertices are determined. The  $\alpha_i$  is called the element shape and is given by (Sadiku, 2018)

$$\alpha_1 = \frac{1}{2A} [(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y] \quad (5a)$$

$$\alpha_2 = \frac{1}{2A} [(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y] \quad (5b)$$

$$\alpha_3 = \frac{1}{2A} [(x_1y_2 - x_2y_1) + (y_1 - y_2)x + (x_2 - x_1)y] \quad (5c)$$

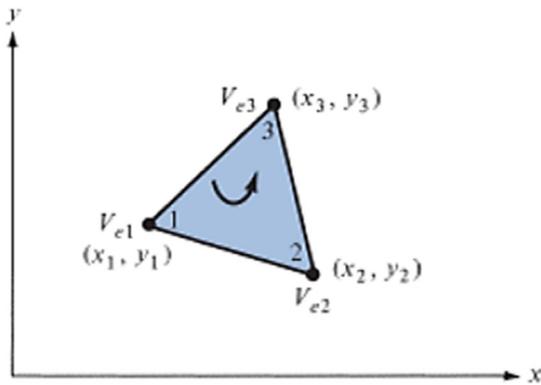
And A is the area of the elements in the region it is calculated as

$$A = \frac{1}{2}[(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)] \tag{6}$$

The energy associated with all the elements assembled in the solution region is (Sadiku, 2018)

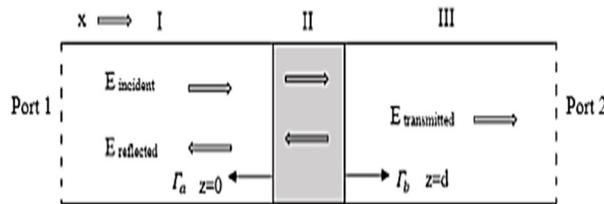
$$W = \sum_{e=1}^N W_e = \frac{1}{2} \epsilon [V]^T [C] [V] \tag{7}$$

Where  $[V]$  is the potential,  $[C]$  is the general coefficient matrix, and  $N$  is the number of the elements in the given region (Jin, 2014; Sadiku, 2018).



**Fig. 1:** Local triangular element

For the S-parameters, let's consider figure 2. Where the wave propagation in a transmission line filled with a dielectric sample is depicted. The electric field intensity in these three regions are denoted as  $E_I$ ,  $E_{II}$ , and  $E_{III}$  respectively (Soleimani *et al.*, 2012; Wang and Hashiguchi, 2019).



**Fig. 2:** Incident, Reflected, and Transmitted Electromagnetic Waves

Considering medium II, the magnitude of the S-parameters can be obtained by invoking the boundary conditions at  $z = 0$  and  $z = d$ . Thus,

$$S_{11} = \frac{\Gamma_a + \Gamma_b P_{theory}^2}{1 + \Gamma_a \Gamma_b P_{theory}^2} \tag{7}$$

$$S_{21} = \frac{1 + \Gamma_a \Gamma_b P_{theory}^2}{1 + \Gamma_a \Gamma_b P_{theory}^2} \tag{8}$$

Where

$$\Gamma_a = \frac{(Z_s - Z_i)}{(Z_s + Z_i)} = \frac{(\sqrt{\epsilon_1^*} - \sqrt{\epsilon_s^*})}{(\sqrt{\epsilon_1^*} + \sqrt{\epsilon_s^*})}$$

$$\Gamma_b = \frac{(Z_{III} - Z_s)}{(Z_{III} + Z_s)} = \frac{(\sqrt{\epsilon_s^*} - \sqrt{\epsilon_{III}^*})}{(\sqrt{\epsilon_s^*} + \sqrt{\epsilon_{III}^*})}$$

$$P_{theory} = e^{(-\gamma s d)}$$

The  $\Gamma_a$  and  $\Gamma_b$  describes the magnitude of reflection coefficients at the boundaries  $z = 0$  and  $z = d$  while  $P_{theory}$  indicates the propagation factor due to the dielectric sample at medium II. Assuming medium I and III are identical then  $\Gamma_a = -\Gamma_b$ . Therefore equations (7) and (8) can be re-written as (Baker-Jarvis *et al.*, 1990 and Soleimani *et al.*, 2012)

$$S_{11} = \frac{(1 - P_{theory}^2) \Gamma_a}{1 - P_{theory}^2 \Gamma_a^2} \tag{9}$$

$$S_{21} = \frac{(1 - P_{theory}^2) \Gamma_a^2}{1 - P_{theory}^2 \Gamma_a^2} \tag{10}$$

It is to be noted the scattering matrix is symmetrical i.e.  $S_{12} = S_{21}$ .

The attenuation is obtained from equation 11 (AF *et al.*, 2016; Yakubu *et al.*, 2015).

$$attenuation = -20 \log_{10}(S_{21}) \tag{11}$$

### 3.0 Simulation

There are five steps to be taken before any simulation session is run in the COMSOL software. First, a 3-dimensional plane is chosen and the RF module for electromagnetic waves in the frequency domain is selected. Then the geometry of the structure to be modelled is constructed which is waveguide in this case. Next appropriate physical constraints and boundary

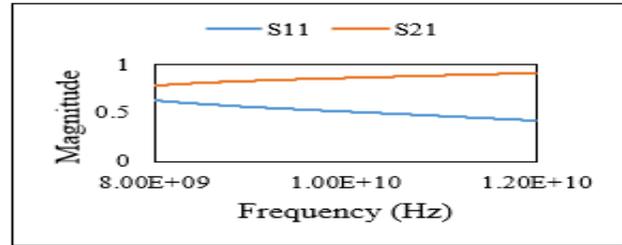
conditions are then applied to the geometry. The meshing of the structure follows while the operating frequency is assigned before the session is finally run.

The dimension of the waveguide being designed is  $0.2 \times 0.1143 \times 0.0228 \text{ m}$  while the thickness of the dielectric sample was varied from 6-14mm. The permittivity of the LDPE used was  $2.2 - j0.0004$ . This implies that the dielectric constant = 2.2 and loss factor = 0.0004.

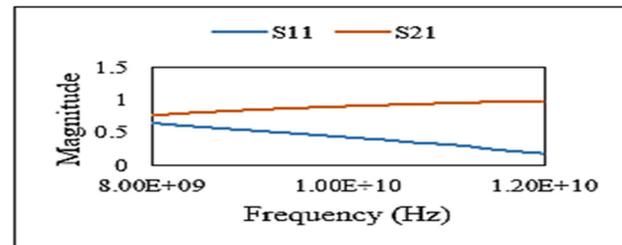
### Results and Discussion

Results of S-parameters variation due to frequency change at different thicknesses are presented in figure 3. The value for the transmission coefficient,  $S_{21}$ , is higher than the reflection coefficient,  $S_{11}$ , which is in agreement with the theory in section 2.0. Figure 3a and 3b reveal that at 6 and 8mm sample thickness, the value of  $S_{21}$  is lowest and at 8GHz and highest at 12GHz inching towards unity while the value for  $S_{11}$  is highest at 8GHz and lowest at 12GHz approaching zero. This shows that for a thin sample,  $S_{21}$  and  $S_{11}$  have direct and indirect proportionality with the frequency of operation and X-band region.

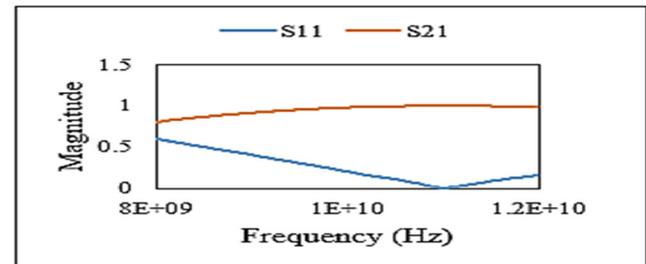
For figure 3c, 3d and 3e which corresponds with sample thicknesses of 10, 12, and 14mm, the values of  $S_{11}$  and  $S_{21}$  were the lowest and highest at 11, 9.5 and 8.5GHz respectively. This implies that for material thickness 10mm, the resonant frequency is found at 11GHz where the maximum power is transmitted through the LDPE dielectric material. The same argument goes for thickness of 12 and 14mm with their resonant frequency obtained at 9.5 and 8.5GHz respectively.



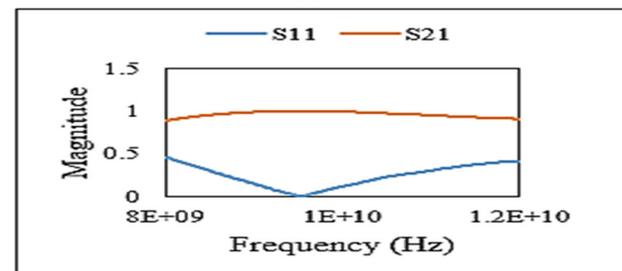
(a)



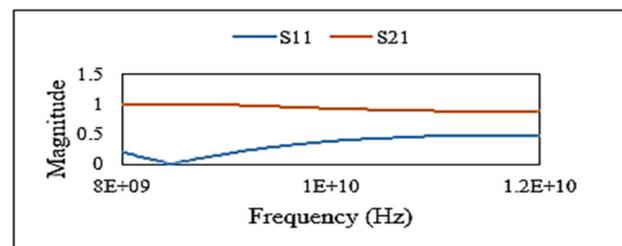
(b)



(c)



(d)

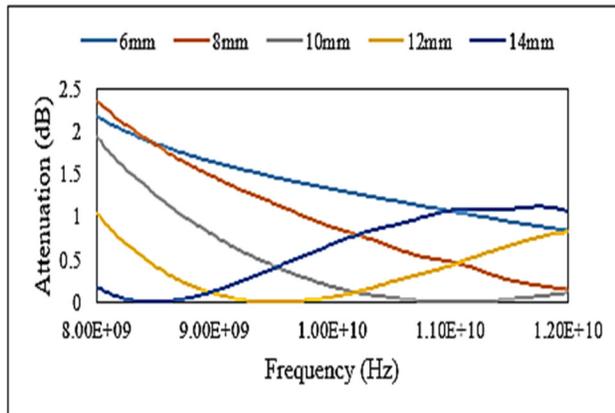


(e)

**Fig. 3:** The S-parameters for 6, 8, 10, 12, and 14mm thicknesses respectively

The attenuation of different LDPE material thickness in the x-band frequency is presented in figure 4 below. It is clearly shown in the figure that the highest values for attenuation for 6 and 8mm thicknesses were obtained at 8GHz while the lowest values of the attenuation at 12GHz even though their resonant frequencies were not found.

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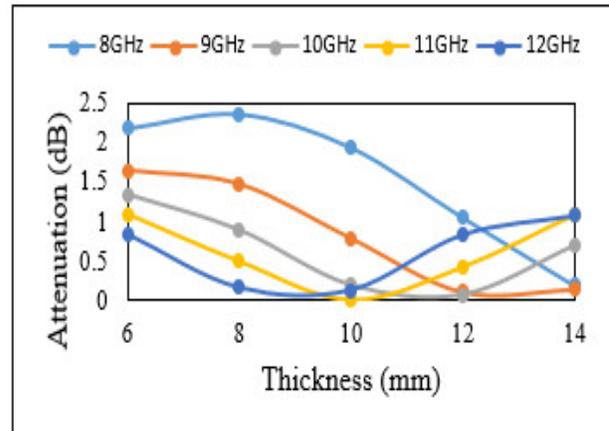
**Fig. 4:** Attenuation (dB) for different thicknesses at x-band frequency

For 10, 12, and 14mm, the attenuation levels were 2, 1, and 0.15dB at 8GHz before dropping to almost zeros at 11, 9.5 and 8.5GHz respectively. This shows that at these frequencies the power is maximally transferred and utilizing LDPE material with the respective thickness at these resonant frequencies will be suitable for PCB applications such as substrates for microstrip antennas.

**Table 1:** Mean values of S-parameter with the corresponding Attenuation at different thicknesses

Thickness (mm)	$S_{11}$	$S_{21}$	Attenuation(dB)
6	0.51485	0.854453	1.373691
8	0.42294	0.894032	0.994821
10	0.248704	0.949822	0.463755
12	0.241988	0.961006	0.350165
14	0.320908	0.933224	0.610521

Table 1 gives the mean values for S-parameters and attenuation for different thicknesses at x-band frequency which implies that mean attenuation increases with an increase in material thickness with the only exception at 14mm thickness. This is because the resonant frequency at 14mm was found at 8.5GHz slightly above 8GHz, the origin of the frequency band.



**Fig. 5:** Attenuation (dB) for different thicknesses at 8, 9, 10, 12GHz respectively

Figure 5 presents attenuation levels for different frequencies in the band for 6-14mm thickness. It is indicated that the attenuation values at 8GHz were lowest and highest at 8 and 14mm thickness respectively. This implies that maximum power is transferred at 8GHz for 14mm thickness. Similarly, for operation at 9GHz utilizing LDPE material for maximum power transfer will be recommended at 12GHz whereas for 10, 11, and 12GHz, LDPE of material thicknesses 12, 10, and 10mm are recommended respectively.

**Conclusion**

The study of attenuation properties of different LDPE thicknesses was carried out using FEM through COMSOL software version 3.5. The S-parameters were obtained for the material thickness varied from 6-14mm at x-band frequency, i.e., 8-12GHz. The mean  $S_{11}$ ,  $S_{21}$  and attenuation for different thicknesses were found to be 0.51, 0.85, and 1.37 for 6mm, 0.42, 0.89, and 0.99 for 8mm, 0.25, 0.95, and 0.46 for 10mm, 0.24, 0.94, and 0.35

for 12mm and finally 0.32, 0.93, and 0.61 for 14mm respectively. Further analysis shows that although the resonant frequencies were not found for 6 and 8mm, they have the lowest values of attenuation at 12GHz. The resonant frequencies for 10, 12, and 14mm thicknesses were found at 11, 9.5 and 10GHz respectively. The attenuation obtained for different LDPE thicknesses keeps decreasing until resonant frequency for any given thickness is found. This demonstrates the dependence of attenuation on material thickness.

### Conflict of interest

Authors declare no conflict of interest whatsoever.

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