Reflection and transmission coefficients measurements for polymer composites with a nano-pzt material using a non-resonant method

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Abstract. The recent significant growth of telecommunications systems, especially in radar applications, has created a sustained need for more smart materials for detecting and/or concealing given objects from radar systems. Key contributing factors in this respect are the reflection and transmission coefficients of such composite materials. The two main methods for calculating the reflection and transmission coefficients are non-resonant and resonant methods. In this work, non-resonant reflection/transmission methods are used to calculate the reflection and transmission coefficients of polymer composites mixed from 1-4 wt% of Nano-PZT (Lead Zirconium Titanate). The calculation of the reflection and transmission coefficients is carried out experimentally using an electromagnetic wave on a single layer made from this material. Results show that the transmission coefficient reached a maximum value at 10 GHz, while the reflection coefficient reached a maximum value at 8-9 GHz for all the distance 50-160 mm.

Keywords: Nano-PZT (Lead Zirconium Titanate), Composite Materials, Non-Resonant Method, Reflection Coefficient, Transmission Coefficient, Absorbing Coefficient.

1. Introduction

Radar-absorbing material (RAM) technologies are of significant interest to researchers in telecommunications and materials engineering, due to their effectiveness on radar performance. Radar cross-section reduction, stealth technology, electromagnetic interference (EMI) shielding, and human health protection are some example applications of RAM technologies. The radar operation exploits the growth in technologies of modern microwave devices by using higher frequencies and larger bandwidth [1]. Microwave conductivity, dipole moment in liquids, relaxation time, and effective mass in semi-conductors, are some of the parameters which can be estimated when measuring the electromagnetic properties of materials at the microwave frequency range [2].

There are two types of microwave measurement methods for electromagnetic characterisation of materials: non-resonant and resonant. The non-resonant method utilises transmission or reflection, which are open or short-line methods, respectively. Examples include free-space, waveguide, coaxial cable, and planar structures; all of which have been used successfully to measure high- and medium-loss materials in terms of permittivity and permeability. On the other hand, non-resonant methods...
require large size samples and strict sample preparation conditions. Such methods have low measurement accuracy, especially for low-loss materials. This is to be contrasted with the resonant perturbation methods, which yield a higher significant accuracy for low-loss materials [2].

The properties of the used material with non-resonant methods are derived from the impedance and velocity of the wave. The propagation of the electromagnetic wave through the samples alters the typical impedance and wave velocity. A partial reflection of the propagated wave occurs at the interface point between the two materials as a consequence of the alteration. The non-resonant method relies on the reflection and transmission effects. The evaluation of properties of the materials is carried dependent on the method applied. In the reflection method, it is calculated based on the sample reflection. Whereas, in the transmission/reflected method, it is calculated based on the reflection from the sample and transmission through the sample [1].

Polymers are used ubiquitously in a variety of industries for many reasons. In comparison with ceramic and metal materials, such reasons include ease of manufacturing, low cost, lightweight, improved chemical and electrical specifications, and ease of possessing. Many industries, especially those involved in aerospace, are favouring the use of composite materials, including more specifically polymer overlays. Previously, most polymeric overlapping materials were ceramic, fibrous, fibre-shaped or powdered. Currently, particle-filled polymers are widely used to improve the mechanical and physical properties of engineering materials used in marine, ship, vehicle and spacecraft industries [3]. For such applications, the primary materials used to manufacture the particulate composites are epoxy resins. For example, phenol-formaldehyde is reinforced with inorganic fillers such as silica, copper and alumina. Phenolic formaldehyde resin is one particular type of polymer, which consists of two main substances: formaldehyde and phenol. Phenol is a solid compound with a strong odour and penetration. It is used for the manufacture of plastic materials for everyday use and also in the clothing industry; often as a coating material. It used in the manufacture of disinfectants, lotions, ointments, topical anaesthetics. It is also used in the medical industry for the manufacture of preservative tissues, embalming and in dentistry for the production of various related chemicals [4,5]

2. Related works

Several methods have been used to measure the reflection coefficient. For example, in the work of [6], bio-composites of oil palm empty fruit bunch (OPEFB) fibres and polycaprolactones (PCL) with a thickness of 1 mm, were produced and categorised. Reflection and transmission coefficient measurements are carried out for OPEFB and PCL with different percentages of filler, using a rectangular waveguide in conjunction with a microwave vector network analyser (VNA) in the X-band frequency range [6]. In the work of [7], the epoxy resin is reinforced with five different carbon species: micro-sized granular graphite, fullerenes, carbon Nanofibers, single- and multi-walled carbon nanotubes. A waveguide method is then used to measure the reflection coefficient at X-band frequencies. In the work of [8], an absorber with a multi-layer structure was introduced using a carbon-based nanomaterial composite material. The composite material is used to reduce the reflection coefficient. A Genetic Algorithm (GA) was used for modelling and optimising the absorber. While in the work of [9], the material used is a composite material, which consists of 90% epoxy and 10% polymer. The reflection coefficient is changed due to the variation of material thickness, which is calculated using a rectangular cavity perturbation technique. In the work of [10], two materials, namely Arlon Iso 933 and Gil GML2032, are used with the transmission technique to simulate the reflection and transmission coefficients using a CST software.

In this paper, non-resonant methods, based on reflection/transmission, are used to calculate the reflection transmission coefficients of polymer composites mixed from 1 - 4 wt% of Nano-PZT (Lead zirconium titanate). The calculation of the reflection transmission coefficient is carried out experimentally using an electromagnetic wave on a single layer made from this material.
3. Theoretical analysis
This section described the manufacturing of Pzt-Nanostructure-based composites used in this study. A commercially available PZT (Lead Zirconium Titanate) particles of size 1-10 nm and purity 99.99%, are used to modify the polymer composite matrix (epoxy 80% and phenol-formaldehyde 20%) as shown in Table 1. The PZT Nanofillers were purchased from Hefei EV Nano Technology. The epoxy used is Sikadur-52 with the mixing ratio A: B = 2:1 part by weight and by volume and in the form of a transparent viscous liquid at room temperature. This is the same phenol-formaldehyde used in the manufacture of general plastic materials.

Table 1. Designation and composition of composites.

| Sample No. | Epoxy (%) | Phenol formaldehyde (%) | Wt. PZT (%) Nano |
|------------|-----------|-------------------------|------------------|
| W1         | 80        | 20                      | ---              |
| W2         | 79        | 20                      | 1                |
| W3         | 78        | 20                      | 2                |
| W4         | 77        | 20                      | 3                |
| W5         | 76        | 20                      | 4                |

3.1. Mixing process
The phenol-formaldehyde resin (20%) was mixed with the epoxy resin with the ratio of 20-80 % as a matrix, and the reinforcing material was of three types, as shown in Table 1. The PZT nanoparticles were added with several weight ratios from 1% to 4% by weight into the mixture and stirred for a period of 30 minutes for improved homogeneity [5]. A high temperature of the blend will essentially provide a good indicator for when the association process begins [4, 6]. It is essential that the mixture has a homogeneous consistency to protect the particles from precipitation. This would have an adverse effect on the heterogeneity of the mixture, which in turn would lead to agglomeration after hardening. The mixture was manufactured using the manual plucking method, i.e. by emptying the blend into the mould as shown in Figure 1. All samples were prepared at room temperature and the samples were left in the mould for a 24 hours-time period. The samples were then dried in a 65°C drying furnace for 4 hours [1,5].

Figure 1. The shape of the mould used.
3.2. Reflection coefficient of the single layer case

By using line theory and assuming a normal incident EM wave incident over a single layer of an epoxy-polyester composite material (as shown in Figure 2), the reflection coefficient (RC) is calculated, using the following equations:

\[
RC = 20 \log_{10} \left| \frac{Z_i - Z_o}{Z_i + Z_o} \right|
\]

(1)

\[
RC = \text{reflection coefficient in dB, } z_o = 377 \Omega \text{ is the free space impedance, and } z_i \text{ is the input impedance. } z_i \text{ can be calculated as follows:}
\]

\[
z_i = n_1 \frac{Z_L \cos(\beta t) + j n_1 \sin(\beta t)}{\eta_1 \cos(\beta t) + j Z_L \sin(\beta t)}
\]

(2)

\[t \text{ is the single-layer thickness, and } \beta \text{ is the propagation constant given by:}
\]

\[
\beta = 2\pi f \sqrt{\mu \varepsilon}
\]

\[
\mu = \mu_o \mu_r \quad \varepsilon = \varepsilon_o (\varepsilon' - j \varepsilon'')
\]

**Figure 2.** Single-layer scheme.

Figure 3 shows the electric circuit of a single layer. Dielectric losses and impedance matching are two factors which determine the single layer absorption capability. The dielectric losses, which in effect represent the imaginary part, is the essential function of the permittivity, while the impedance matching relies on the microwave wavelength.

**Figure 3.** Single layer equivalent electric circuit.
The imaginary part of $z_i$ is eliminated for specific values of $\beta t$. Equation (2) shows that, while for the same values of $\beta t$, the real part of $z_i$ is close to the value of $Z_0$. As a consequence of this, the reflection coefficient will effectively be infinity. $\beta t$ is dependent upon three factors: permittivity, thickness and frequency. Equation (2) provides a good explanation for this dependency and helps verify the impedance matching. The ratio of the transmitted wave amplitude (power, voltage or current) to the incident wave amplitude is defined as the transmission coefficient. This is expressed mathematically in the following equation [10, 12]:

$$\tau = \frac{2\zeta_1}{\zeta_0 + \zeta_1}$$

(3)

$\tau$ is the transmission coefficient.

The reflection and transmission coefficients are related together as follows:

$$\tau = 1 + \Gamma$$

(4)

The above clearly shows that the magnitude of the reflection coefficient is larger than one [11, 12]. Two points must be taken into account in order to obtain the optimum absorber material of the associated electromagnetic energy. Firstly, the thickness of the material which is required must be low; and secondly the ratio of permeability to the permittivity of the material needs to be high. In practice, permittivity is high at microwave frequencies [13, 14]. The resonant absorber is a common method for describing the microwave absorber, which depends on the layer of absorbing, the combination of magnetic permeability. The dielectric permittivity must be contained with the layer, whilst the surface of the absorbing layer has full impedance matching [15, 16]. The Salisbury screen and the dual magnetic absorber are the two main categories of resonant absorbers. Due to its structure, the Salisbury screen uses the simplest type of absorber, which includes a resistive sheet with 377 $\Omega$ spaced by 1/4 $\lambda$ from the conductive ground plane. However, with the dual-magnetic option, several frequencies can be absorbed. This is due to the high domination value of magnetic-dielectric loading and the thickness of the layer [13, 16]. These two methods are used to describe the reflection and absorption of materials. The essential drawbacks of the Salisbury screen, in respect of the underlying frequency, are bad elasticity, bad ecological resistance, and increased thickness.

4. Experimental set-up
A rectangular resonator $TE_{10N}$ mode for resonance frequency of 8 -10.5 GHz X-band is constructed with a brass material with cross section dimensions of $23 \times 10$ mm, width and height respectively. The far-field distance is varied: 50, 120, and 160 mm. The system is experimentally connected in a Microwave lab, which consists of a signal and power generator, power meter, horn antenna, waveguide/coaxial transition, variable attenuator, frequency meter, crystal detector and SWR meter, as shown in Figure 4.

![Figure 4. Experimental setup for RC and TC measurement.](image-url)
5. Results and discussion

For the polymer composites material fabricated with 1-4 wt.% of Nano-PZT (Lead Zirconium Titanate), the reflection coefficient is calculated using non-resonant methods (reflection or transmission methods) in an X-band of 8-10.5 GHz. The cavity is operated at TE_{10N} Mode when N is an odd number (N = 1, ..., 7). Several weights are selected for the composite material to calculate Reflection and Transmission coefficients. The absorbing coefficient can be calculated by RC and TC measurements as:

\[ Ab = 1 - \tau - \Gamma \]  

(5)

\( \Gamma \) is the reflection coefficient.
\( \tau \) is the transmission coefficient.
\( Ab \) is the absorbing coefficient.

The relationship existing between the frequency and the reflection coefficient is shown graphically in Figs. 5 to 7. These indicate that the reflection coefficient is inversely proportional to the frequency when varying the far-field distance from 50, 120, and 160 mm. The results show that the largest value of RC is obtained in the frequency range of 8.5-to-9GHz. On the other hand, when a frequency of 10 GHz is used, the recorded value for RC is lower with all different types, weight materials and the three distance values used. Figure 5 shows the maximum RC value (RC=0.9974), which has been obtained with the frequency value of 9 GHz at w0 due to the maximum reflected signal. In contrast, the equivalent minimum value (RC=0.9958) is obtained with w3 due to the minimum reflected signal.

![Figure 5. Reflection coefficient at d=50mm.](image-url)
Figure 6. Reflection coefficient at d=120mm.

Figure 7. Reflection coefficient at d=160mm.

Figures 8, 9 and 10 show the relationship existing between the transmission coefficient and the frequency band. The higher value of the transmission coefficient is obtained at 10 GHz, and the lower value is obtained with the band between 8 and 9 GHz for all varied weights. w2 and w3 materials yield the maximum value of transmission coefficient (0.1). The capability of these materials to pass the signal is clearly greater than the other ones.
Figure 8. Transmission coefficient at d=50mm.

Figure 9. Transmission coefficient at d=120mm.
For the reflection and transmission coefficient measurement results obtained, the value of the absorption coefficient was calculated using equation (5). These are shown graphically in Figs. 11, 12, and 13. These Figures show that the maximum value of the absorption coefficient is achieved at 10 GHz and recorded for w2 and w3, while the equivalent minimum value occurs between 8-9 GHz.

**Figure 10.** Transmission coefficient at d=160mm.

**Figure 11.** Absorbing coefficient at d=50mm.
6. Conclusions
A single layer was developed in this work, and it is made of polymer composites mixed from 1 - 4 wt % of Nano-PZT (Lead Zirconium Titanate) in the X-band range of frequencies. The resonant method (reflection/transmission) has been successfully used to calculate the reflection transmission coefficient. The results showed that the materials with weight w2 and w3 recorded the highest transmission coefficient at the frequency of 10 GHz for the three distances of 50, 120 and 160 mm. However, the w0 material yielded a higher reflection coefficient at a frequency between 8 to 9 GHz. Given the reflection and transmission coefficient results, the absorption coefficient recorded the highest value for the materials with weights w2 and w3.
References

[1] R. U. Nair. e. al, "Basics of Material Characterization," in EM Material Characterization Techniques for Metamaterials, SpringerBriefs in Computational Electromagnetics, 2018, pp. 3-4

[2] F. Costa, M. Borgese, M. Degiorgio and A. Monorchio, "Electromagnetic Characterisation of Materials by," Electronics, pp. 1-27, 2017.

[3] W. Thamjaree, W. Nhuapeng, A. Chaipanich and T. Tunkasiri, "Fabrication of combined 0–3 and 1–3 connectivities PZT/epoxy resin composites," Applied Physics A/ Materials Science & Processing, vol. 81, p. 1419–1422, 2005.

[4] K.-i. T. H. J. Hwang, M. Sando, M. Toriyama and K. Nihara, "Microstructure and Mechanical Properties of Lead Zirconate Titanate (PZT) Nanocomposites with Platinum Particles," Journal of the Ceramic Society of Japan, vol. 108, no. 4, pp. 339-344, 2000.

[5] D. A. van den Ende, P. de Almeida and S. van der Zwaag, "Piezoelectric and mechanical properties of novel composites of PZT and a liquid crystalline thermosetting resin," Journal Material Science / springer, vol. 42, p. 6417–6425, 2007.

[6] Hamid M. Mahan, Dawood S. Mahjoob , Khalil I. Mahmood " Mechanical Properties of Alumina Nano-Particles and Glass Fiber, Kevlar Fiber Reinforced Composites, " Journal of Engineering and Applied Sciences, vol. 13, no. 21, pp. 9096-9100, 2018.

[7] D. Micheli, C. Apollo, R. Pastore. and M. Marchetti, "X-Band microwave characterisation of carbon-based nanocomposite material, absorption capability comparison and RAS design simulation," Composites Science and Technology/ Elsevier, vol. 70, p. 400–409, 2010.

[8] D. Micheli, and et al , "Carbon-Based Nanomaterial Composites in RAM and Microwave Shielding Applications," in 9th IEEE Conference on Nanotechnology, Roma, Italy, 2011.

[9] I. H. Ali, A. M. Ahmed and H. I. Hamd, "Reflection Coefficient Measurements Experimentally and Simulation of Epoxy- Polyester in X- Band Frequencies," Journal of Advanced Research in Dynamical & Control Systems, vol. 10, no. 4- special issue, pp. 1034- 1043, 2018.

[10] I. H. Ali, "Reflection and Transmission Coefficients Simulation and comparison of two different dielectric materials in X- Band frequencies," Journal of Engineering and Applied Science / Medwell Journals, vol. 13, no. 20, pp. 8666-8669, 2018.

[11] J.-H. Oh and et al. , "Design of radar absorbing structures using glass/epoxy composite containing carbon black in X-band frequency ranges," Elsevier/locate/composites b, pp. 49-56, 2004.

[12] D. Micheli, et al, "Broadband Electromagnetic Absorbers Using Carbon Nanostructure-Based Composites," Ieee Transactions On Microwave Theory And Techniques, pp. 2633-2646, 2011.

[13] J. Chen, J. Guo and E. Pan, "Reflection and transmission of a plane wave in multi-layered nonlocal magneto-electro-elastic plates immersed in liquid," 2017

[14] Isam Salah Hameed, Hamid M. Mahan and Ahmed Salah Hameed, “Microwave Power Absorption Evaluation of River Shell Particles Reinforced Polyester Composite”, Periodica Polytechnica Electrical Engineering and Computer Science, 64(2), pp. 192–199, 2020.

[15] Halina Kaczmarek and et al., “Advances in the study of piezoelectric polymers”, 2019 Uspekhi Khimii, Russian Academy of Sciences, Turpion Ltd and IOP Publishing Ltd.

[16] Vivek T. Rathod, “A Review of Acoustic Impedance Matching Techniques for Piezoelectric Sensors and Transducers”, sensor, 20(14), July 2020.

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