The Effect of Reinforcement of Alumina Matrix Composites by ZrB_2 and FeSiAl Inclusions on the Dielectric Property at Microwave Frequencies

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In this paper, two composites ZrB_2/Al_2O_3 and $FeSiAl/Al_2O_3$ were characterized using the Transmission/Reflection characterization technique. The volume contents of ZrB_2 and FeSiAl inclusions in these composites vary between 0 and 15%. The results obtained indicate that the percentage of the inclusions in the composites effectively improves the dielectric property. The comparison of the effect of ZrB_2 and FeSiAl inclusions on the dielectric properties of these composites confirms that reinforcing these composites with FeSiAl particles results in better dielectric properties. Furthermore, these results indicate that the dielectric property of the two composites studied decreases progressively with increasing frequency in the X band. This frequency dependence of the dielectric property of the composites studied is very important and shows that the composites studied are good candidates for microwave absorption applications in the X-band and for antenna design. Additionally, a comparison between the numerical results obtained in this work and the experimental results published in the literature reveals a close agreement, validating the reliability of the study's findings.

Keywords: *Composite materials, alumina matrix composites, complex permittivity, rectangular waveguide, transmission/reflection (T/R), finite element method, ZrB_2, FeSiAl, X-band.*

1. INTRODUCTION

Composite materials are among the most widely used materials in many practical applications, and their use is increasing in many industrial sectors, especially in the electronics industry [1]. These materials have better electromagnetic properties than their individual primary components, allowing them to perform many technical functions. These materials are used in the field of aviation and space because of their lightness [2]. In addition, its robustness makes it a first-choice material for sports and leisure applications [3]. These applications also extend to the maritime industry, due to the corrosion resistance that this material possesses [4].

Recently, great importance has been given to the study of ceramic composite materials [2]. Alumina-matrix ceramic composites are used in a wide variety of fields, including commercial, civil, and military applications [5]. They are also selected for engineering applications [6]. Moreover, the design and manufacture of microwave-absorbing materials rely on this type of materials, due to their high microwave absorption properties [7,8]. They have become one of the most important structural materials [9] due to the excellent properties they possess, including high wear resistance [10] and high corrosion resistance.

In recent years, the reinforcement of alumina matrix composites by semiconductor and ceramic particles, notably Titanium Carbide (TiC) [11], Silicon Carbide (SiC) [12], Zirconium diboride (ZrB_2) [7,8], NiCrAlY [13], Chromium (Cr) [14] and FeSiAl particles [15], has made it possible to obtain composites that absorb microwaves [16] and improve the dielectric property of composite materials. These properties are important in several fields, notably in telecommunications [17], and in the design of microwave circuits and radar-absorbing materials (RAM) [18,19].

At present, these composites have attracted the attention of researchers [11,13,14,20], due to their high conductivity [21], very high dielectric properties, and excellent microwave absorption properties [22,23]. This type of composite has become one of the new class of high-quality microwave absorption materials [7,8] and they are increasingly used in potential applications such as microwave absorbers to absorb and dissipate electromagnetic waves and in the design of antennas and waveguides operating in the microwave range.

With the increasing use of these materials, there is a growing industrial demand to characterize them in order to predict their dielectric properties before production [24], this is because adapting the dielectric properties of engineered materials is necessary in many applications [25]. Consequently, the characterization of these materials has become essential for understanding their electrical and electromagnetic properties, which is crucial in many fields such as electronics, telecommunications, and energy [26].

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In the literature, there are many methods for charac–terizing a dielectric material at microwave frequencies. Each characterization method has its advantages and disadvantages. The choice of method depends on the objectives of the study, the specific properties to be characterized, and the experimental constraints. Among these methods, we can cite the free space method [27], the Transmission/Reflection technique [28], and the resonant method [29,30].

Several researchers have adopted the transmission/ reflection characterization method to measure the die–lectric constant of materials [31-34], due to its simp–licity and ability to characterize materials over a wide frequency range [35,36]. This method is based on the rectangular waveguide technique which has been widely used as a simple means to determine the complex per–mittivity of dielectric materials in the microwave fre–quency domain.

This research aims to study the dielectric properties of two alumina matrix ceramic composites at high fre–quency. In these composites, the FeSiAl and ZrB_2 inc–lusions are dispersed in the alumina matrix Al_2O_3 with volume concentrations varying from 0% to 15%. The goal is to determine the complex permittivity of the FeSiAl/Al_2O_3 and ZrB_2/Al_2O_3 composites in part real and part imaginary when the frequency varies from 8 GHz to 12.4 GHz. Furthermore, the comparison of the effect of reinforcement of these composites by FeSiAl and ZrB_2 particles on the dielectric property. We used the trans–mission/reflection (T/R) characterization method to extract the S_{11} transmission and S_{21} reflection coeffici–ents, then we calculated the real and imaginary parts of the complex permittivity using a program in MATLAB.

2. THEORY AND METHOD

In this study, we adopted the transmission/reflection (T/R) characterization method. This technique makes it possible to study the dielectric properties of composite materials in the microwave frequency range [28]. Due to its ability to characterize materials over a wide range of frequencies, this method has been adopted by several researchers [32, 37, 38].

The principle for calculating the dielectric property of a composite sample using this method is to use a rectangular waveguide WR_{90} shown in Fig. 1. A die–lectric sample to be characterized is placed precisely inside this waveguide.

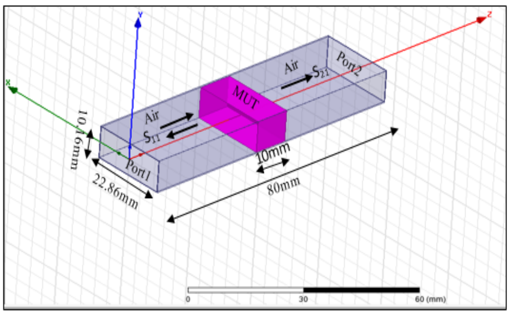

Figure 1. Transmission/reflection measurement cell used to extract the S_{11} and S_{21} parameters.

The configuration illustrated in Figure 1 is used to characterize a composite material in the X-band. This material has a thickness of d=10 mm. It is well placed in a port of the rectangular waveguide. The reflection parameters and the transmission parameters are extracted by simulation software (Fgure 2).

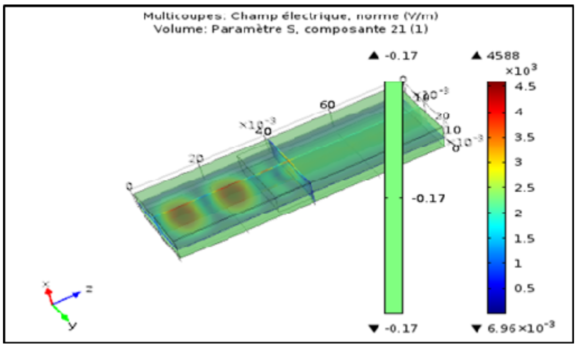

Figure 2. Representation of the spatial distribution of the electric field modulus for the extraction of parameters S_{11} and S_{21}

The procedure we used to study the dielectric property in the X-band frequency range is the Nic–holson-Ross-Weir technique (NRW) [39, 40], this technique allows us to study dielectric materials in a broad frequency range [31]. It is fast, direct, and non-iterative. The dielectric property has been determined from the reflection and transmission parameters S_{11} and S_{21}. These parameters are given as a function of the coefficients Γ and T by the following relations [41, 42]:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2} \tag{1}$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2} \tag{2}$$

The reflection coefficient is defined by the following relationship [43]:

$$\Gamma = \frac{\eta-\eta_0}{\eta+\eta_0} = X \pm \sqrt{X^2-1} \tag{3}$$

with $|\Gamma| \langle 1$ and X is given from the parameters S_{ij} by the relation :

$$X = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}} \tag{4}$$

where η and η_0 are the impedances for the sample and free space, respectively.

The transmission coefficient T is given by the following relationship:

$$T = \frac{S_{11}+S_{21}-\Gamma}{1-(S_{11}+S_{21})\Gamma} \tag{5}$$

The relative permeability of a material is calculated by the formula below (6):

$$\mu_r = \frac{\lambda_{0g}(1+\Gamma)}{\Lambda(1-\Lambda)} \tag{6}$$

with λ_{0g} is the guided wavelength in the cell without sample, it is given by the relation below:

$$\lambda_{0g} = \frac{1}{\sqrt{\left(\frac{1}{\lambda_0}\right)^2 - \left(\frac{1}{\lambda_c}\right)^2}} \qquad (7)$$

where λ_0 represent the wavelength in free space and λ_c the cutoff wavelength.

Λ is the normalized wavelength expressed by the relationship below with d being the length of the sample.

$$\frac{1}{\Lambda^2} = \left[\frac{j}{2\pi d}\ln(T)\right]^2 \qquad (8)$$

The relative permittivity is calculated from the following relationship:

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\Lambda^2} + \frac{1}{\lambda_c^2}\right) \qquad (9)$$

The Nicholson-Ross-Weir algorithm [39, 44] can be summarized in Figure 3 below.

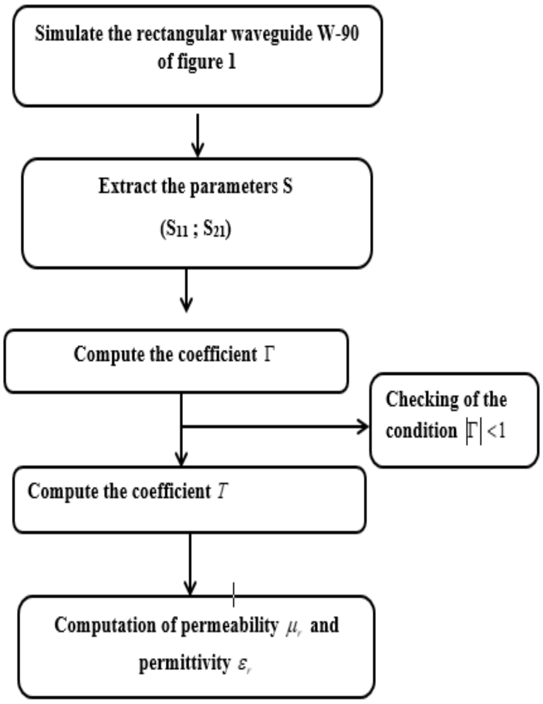

Figure 2. Simplified Schematic of the Nicholson-Ross-Weir algorithm.

3. RESULTS AND DISCUSSION

First, we study the dielectric property for six samples of the alumina matrix composites reinforced by FeSiAl and ZrB_2 particles in the X-band. The volume concen–trations of inclusions in the composites vary from 0% to 15%.

To characterize these samples in the X-band, we adopt the transmission/reflection (T/R) method detailed in the theory and method section. The material to be characterized is of a size (22.86mm*10.16mm*10mm) and well-fitted in a rectangular waveguide for measu–ring the S_{11} reflection and S_{21} transmission parameters. Using three-dimensional electromagnetic simulation software, we performed simulations for the extraction of these parameters (Figure 2). Then, the complex permi–ttivity has been calculated from the reflection coeffi–cients S_{11} and transmission S_{21} using a program on MATLAB.

Figures (3.a) and (3.b) illustrate the variation of the real part ε' and imaginary part ε'' of the complex relative permittivity, respectively, as a function of frequency, for the six samples of the FeSiAl/Al_2O_3 and ZrB_2/Al_2O_3 composites in the X band. The volume content of FeSiAl and ZrB_2 inclusions in the composites ranges from 0% to 15%.

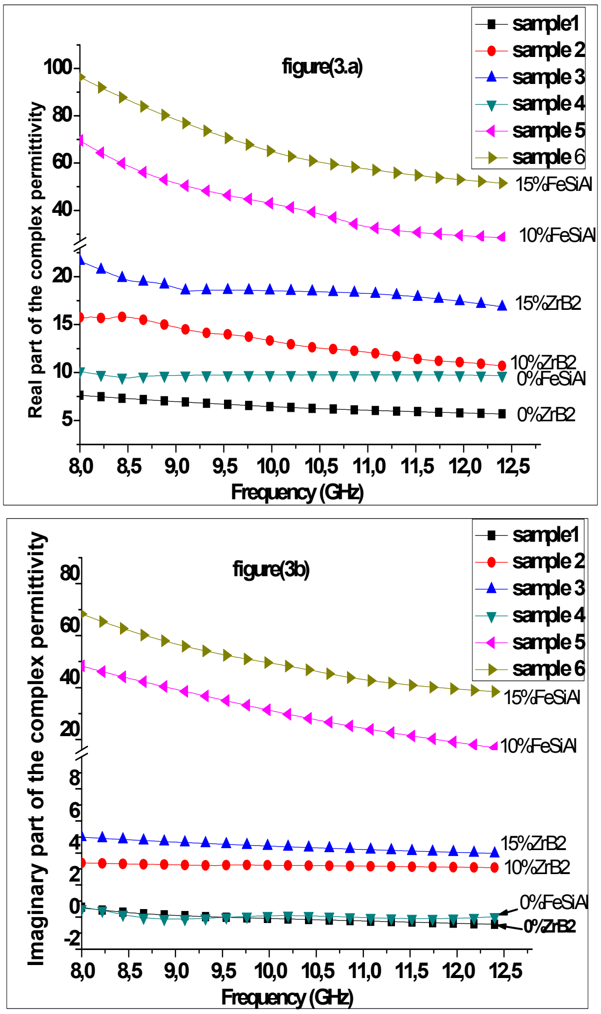

Figure 3. The variation as a function of frequency of the complex relative dielectric permittivity of FeSiAl/Al_2O_3 and ZrB_2/Al_2O_3 composites for different concentrations of inclusions in the X band.

Figure (3.a) real part and figure (3.b) imaginary part.

From Figure 3, we observe that the complex permittivity of the ZrB_2/Al_2O_3 and FeSiAl/Al_2O_3 cera–mic composites is closely correlated with the volume fraction of the ZrB_2 and FeSiAl inclusions in the com–posites. Both the real part (ε') and the imaginary part (ε'') of the complex permittivity increase over the entire X-band frequency range with increasing inclusion content. When the volume fraction of inclusions inc–reases from 0% to 15%, the values of the real part of the complex permittivity ε' increase from 7.4 to 20.9 for the ZrB_2/Al_2O_3 composite at frequency 8.2GHz, while these values increase in the same frequency point for the FeSiAl/Al_2O_3 composite from 9.67 to 86.58. Similarly the values of the imaginary part of the complex permittivity ε" for the ZrB_2/Al_2O_3 composite increase from 0.46 to 4.9 and these values for the $FeSiAl/Al_2O_3$ composite increase from 0.42 to 65.40. This indicates that increasing the ZrB_2 and FeSiAl content improves both the real and imaginary parts of the complex per–mittivity of ZrB_2/Al_2O_3 and $FeSiAl/Al_2O_3$ ceramic composites. We find that the effect of FeSiAl inclusions on the dielectric property is significant compared with the effect of ZrB_2 inclusions on the same property. In effect, the values of the complex permittivity of the $FeSiAl/Al_2O_3$ composite increase more than the values of the complex permittivity of the ZrB_2/Al_2O_3 compo–site. This is due to the improvement in the conductivity of mobile electrons in the absorber, which was affected by defects such as bonds and gaps, particularly those caused by the interface between the phases of the inc–lusion and the Al_2O_3 matrix . In addition, these results show that complex permittivity values are greater for the composites charged by the particles in comparison with those not charged. Composites loaded with more inclusions have higher values of dielectric permittivity. This indicates that the percentage of inclusions in the composite effectively improves the dielectric property of alumina matrix composites and that the homogeneous dispersion of ZrB_2 and FeSiAl inclusions in the alumina matrix enhances the complex permittivity of this type of composite.

Table 1 shows the values of the real and imaginary parts of the complex permittivity of the ZrB_2/Al_2O_3 and $FeSiAl/Al_2O_3$ ceramics studied at 8.2 GHz. These valu-es were obtained by simulation for different ZrB_2 and FeSiAl contents in the ZrB_2/Al_2O_3 and $FeSiAl/Al_2O_3$ composites. The table includes the simulation results in our work and the experimental results in the work of Zhou, L et al [45] and Liu, Y et al [46].

Table 1. Values of the real and imaginary parts of the complex permittivity of ZrB_2/Al_2O_3 and $FeSiAl/Al_2O_3$ ceramics for different ZrB_2 and FeSiAl concentrations at 8.2 GHz.

	Simulated value of ε' in this work	Approximate value of ε' in the literature [45] and [46]	Simulated value of ε" in this work	Approximate value of ε" in the literature [45] and [46]
Al_2O_3- 0% FeSiAl	9.67	9.5	0,42	0.50
Al_2O_3- 10% FeSiAl	68.48	70	44.53	44
Al_2O_3- 15% FeSiAl	86.58	85	65.40	65
Al_2O_3- 0%ZrB_2	7,40	7.20	0,46	0.50
Al_2O_3- 10%ZrB_2	15,65	16.50	3,32	3.30
Al_2O_3- 15%ZrB_2	20,90	21.00	4,90	4.85

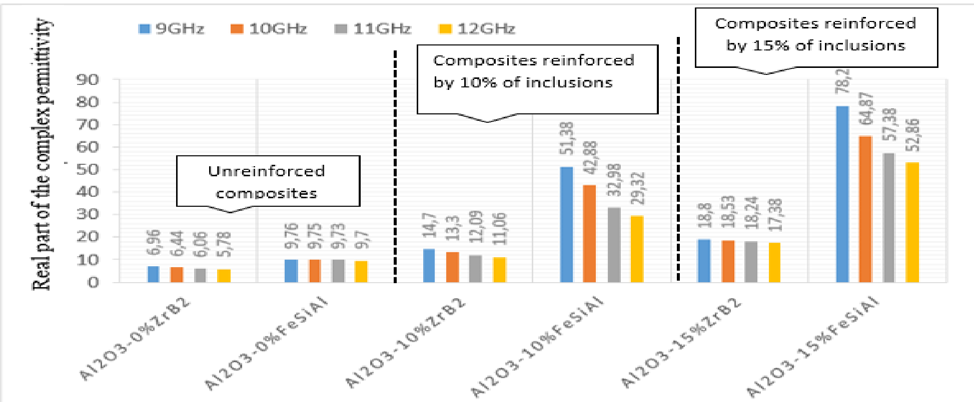

Figure (4.a)

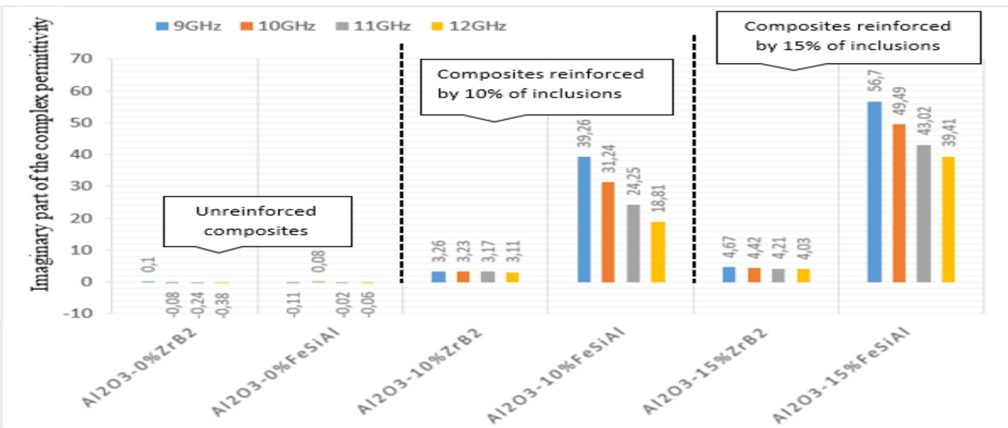

Figure (4.b)

Figure 4. the comparison between the dielectric properties of $FeSiAl/Al_2O_3$ and ZrB_2/Al_2O_3 composites for different concentrations of inclusions in the composite.

Figure (4.a) real part of complex permittivity, and figure (4.b) imaginary part of this property.

The comparison between simulation values and published values in Table 1 shows that the values of the real and imaginary parts of the permittivity obtained in this work are very close to the experimental values published in the literature [45, 46]. This means that there is a good agreement between the numerical simulation results and the experimentally measured values, confirming that the method used in this work can be adopted to study the dielectric behavior of composite materials of the same family as the materials we have studied.

To compare the effect of reinforcing the composites with ZrB_2 and FeSiAl inclusions on the dielectric pro–perty. The histograms in Figures (4.a) and (4.b) show the values of the real and imaginary parts of the com–plex permittivity of the composites studied for the three inclusion contents.

The comparison between the effects of the inclu–sions on the dielectric property in figures (4.a), (4.b), affirms that the composites reinforced with FeSiAl particles have higher dielectric property values than those reinforced with ZrB_2 particles. We remark that the values of the dielectric property for the FeSiAl /Al_2O_3 composite are a little higher than those of the ZrB_2/Al_2O_3 composite, due to the enhancement of the electrical conductivity, as well as the appearance of the electronic and atomic polarization in the composite material. The FeSiAl/Al_2O_3 composite reinforced with 15% by volume of FeSiAl has higher dielectric proper–ties values than the others. This indicates that the na–ture of the inclusions has an effect on the dielectric properties of these ceramic composites. Because of this very high dielectric permittivity, ceramics are widely used in the manufacture of capacitors for various electronic components and microwave devices. Furt–hermore, due to their low price, ceramic-based compo–sites have been developed to combine several pro–perties: low density, low dielectric losses, and high dielectric permittivity. These materials are used, for example, in printed circuit board structures and in other areas of electronics [47].

We also observe that the values of the dielectric property decrease progressively as the frequency increases in the X-band. These results demonstrate that the dielectric property depends on the frequency, this behavior can be explained by Debye's theory [48].

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2} \tag{10}$$

where:
ε_s is the static permittivity.
ε_∞ is the relative permittivity at the high-frequency limit.
$\omega = \pi f$ is the angular frequency.
τ is the temperature-dependent polarization relaxation time.

According to equation (10), we note that the values of the real part of the complex permittivity decrease with the increase of the frequency, as indicated in figure (3a).

Figure (3b) shows the dielectric behavior of the imaginary part of the complex permittivity, which can be interpreted by the equation:

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon_0} + \varepsilon''_{relax} = \frac{\sigma}{2\pi f \varepsilon_0} + \varepsilon''_{relax} \tag{11}$$

where:
ε''_{relax} is the loss caused by polarization relaxation.
σ is the electrical conductivity.
ω is the angular frequency .
ε_0 is the permittivity of free space.

From equation (11), we can see that the values of the imaginary part decrease with increasing frequency.

When the frequency varies from 9GHz to 12GHz, the real part of the complex permittivity of the alumina matrix composite varies from 78.2 to 52.86 when this composite is charged with 15% by volume of FeSiAl inclusion and from 18.8 to 17.38 when this composite is charged with 15% by volume of ZrB_2 inclusion. Si–milarly, the imaginary part of this property varies in this frequency range from 56.7 to 39.41 if this com–posite is charged with 15% by volume of FeSiAl inc–lusion and from 4.67 to 4.03 when charged with 15% by volume of ZrB_2 inclusion.

As the concentration of ZrB_2 and FeSiAl inclusions increases, conductive metal clusters are generated, increasing the conductive paths and therefore the loss of conductance. Furthermore, ZrB_2 and FeSiAl rein–forcements possess high electrical conductivity, and the conductance loss of these composite materials would be even higher with increasing ZrB_2 and FeSiAl con–tent. We also observed that the values of the imaginary part of the complex permittivity ε" for the FeSiAl/ Al_2O_3 composite loaded with 15% of FeSiAl show a clear decrease with increasing frequency, demons–trating the frequency dispersion characteristic over the entire frequency range. Similar phenomena have also been reported by other researchers [49].

Alumina matrix composites reinforced with ZrB_2 and FeSiAl inclusions can have significant effects on dielectric properties, particularly at microwave frequencies. The behavior of these compounds in the X-band demonstrates that alumina matrix composites have the ability to absorb microwaves, these dielectric properties are important for materials used in micro–wave applications, as they influence the electro–magnetic response, transmission, and reflection of microwave signals. This improvement in composite performance is mainly due to dielectric relaxation, polarization relaxation, and electric dipole polarization in composites. Dielectric properties are important for materials used in microwave applications, as they influence the electromagnetic response, transmission, and reflection of microwave signals.

The previous results indicate that alumina matrix composites reinforced by FeSiAl inclusions improve the dielectric property more than composites reinforced by ZrB_2 particles. To compare the improvement perfor–mance of the investigated composites, tables 2 and 3 show the percentages of real part enhancement of FeSiAl/Al_2O_3 composite compared to that of ZrB_2/ Al_2O_3 composite and the percentages of imaginary part enhancement of FeSiAl/Al_2O_3 composite compared to that of ZrB_2/Al_2O_3 composite, respectively. These per-centages are calculated at selected frequency points in the X-band.

Table 2. The percentage improvement of the real part of the complex permittivity of the composite $FeSiAl/Al_2O_3$ compared to that of the composite ZrB_2/Al_2O_3 at selected frequency points in the X-band.

frequency (GHz)	composites reinforced by 10% inclusions			composites reinforced by 15% inclusions		
	ε'_1	ε'_2	$\frac{\Delta\varepsilon''}{\varepsilon''_1}$	ε'_1	ε'_2	$\frac{\Delta\varepsilon'}{\varepsilon'_1}$
9	51.38	14.70	71.38%	78.2	18.8	75.96%
10	42,88	13,30	68.98%	64,87	18,53	71.44%
11	32.98	12.09	63.34%	57.38	18.24	68.21%
12	29.32	11.06	62.28%	52.86	17.38	67.12%

with:

ε'_1: Real part of complex permittivity for the composite $FeSiAl/Al_2O_3$

ε'_2: Real part of complex permittivity for the composite ZrB_2/Al_2O_3

$\frac{\Delta\varepsilon'}{\varepsilon'_1}$: The percentage improvement of the real part of the complex permittivity

Table 3. The percentage improvement of the imaginary part of the complex permittivity of the composite $FeSiAl/Al_2O_3$ compared to that of the composite ZrB_2/Al_2O_3 at selected frequency points in the X-band.

frequency (GHz)	composites reinforced by10% inclusions			composites reinforced by 15% inclusions		
	ε''_1	ε''_2	$\frac{\Delta\varepsilon''}{\varepsilon''_1}$	ε''_1	ε''_2	$\frac{\Delta\varepsilon''}{\varepsilon''_1}$
9	39.26	3,26	91.70%	56.7	4,67	91.76%
10	31,24	3,23	89.66%	49,49	4,42	91.07%
11	24.25	3.17	86.93%	43.02	4.2	90.24%
12	18,81	3,11	83.47%	39,41	4,03	89.77%

with:

ε''_1: Imaginary part of complex permittivity for the composite $FeSiAl/Al_2O_3$

ε''_2: Imaginary part of complex permittivity for the composite ZrB_2/Al_2O_3

$\frac{\Delta\varepsilon''}{\varepsilon''_1}$: The percentage improvement of the imaginary part of the complex permittivity

The results presented in Tables 2 and 3 show that the values of the real and imaginary parts of the complex per–mittivity of the $FeSiAl/Al_2O_3$ composite are generally higher than the values of this dielectric property for the ZrB_2/Al_2O_3 composite. In addition, the percentage improvement of the real and imaginary parts of the alumina matrix composite reinforced by FeSiAl are higher than these values for the alumina matrix composite reinforced by ZrB_2.

To facilitate the comparison of the enhancement effect of alumina-based compounds by FeSiAl and ZrB_2 particles, the histograms in Figures 5 and 6 show the enhancement percentages at these frequency points.

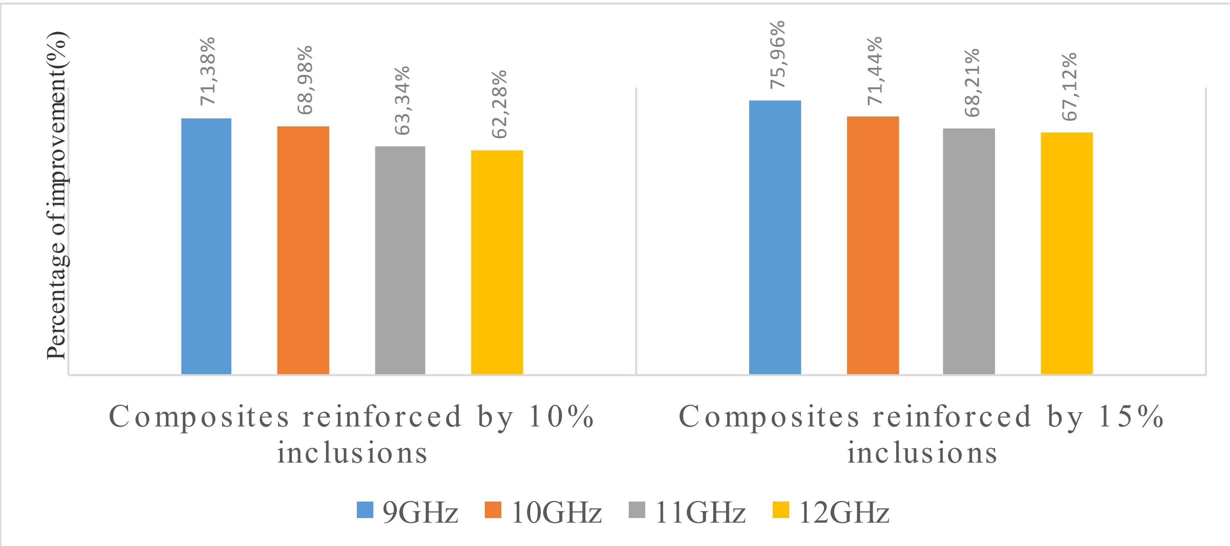

Figure 5. Percentage improvement of the real part of $FeSiAl/Al_2O_3$ composite compared to that of ZrB_2/Al_2O_3 composite.

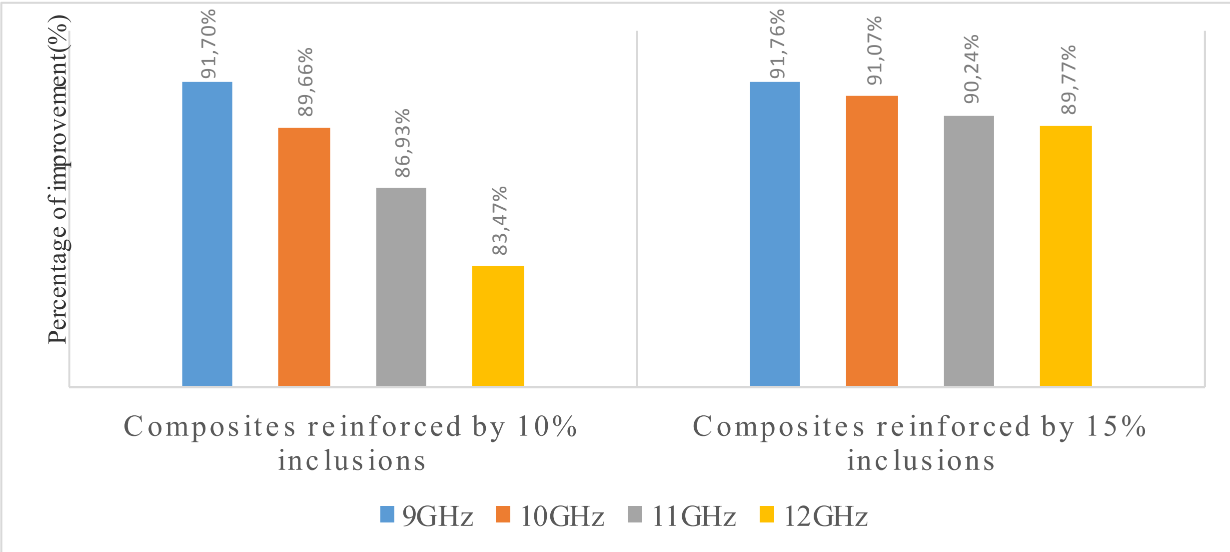

Figure 6. Percentage improvement of the imaginary part of FeSiAl/Al_2O_3 composite compared to that of ZrB_2/Al_2O_3 composite.

The results illustrated in the histograms of Figures 5 and 6 indicate that both the real and imaginary part values of the complex permittivity of the FeSiAl /Al_2O_3 composites are generally improved compared to those of the ZrB_2/Al_2O_3 composites. The percentage of imp–rovement can reach more than 91% for the imaginary part and more than 75.5% for the real part. This means that the reinforcement of the composites by the FeSiAl inclusions improves the dielectric property more than the reinforcement of the composites by the ZrB_2 particles. The FeSiAl /Al_2O_3 composite reinforced by 15% volume of FeSiAl has a significant ability to improve the complex permittivity in the X-band and can be used in electronic devices for microwave absorption.

4. CONCLUSION

In this research, we employed the method of characterization in transmission/reflection by rectan–gular waveguides to characterize alumina matrix com–posites. First, the goal of this technique is to determine the dielectric properties of two composites FeSiAl/ Al_2O_3 and ZrB_2/Al_2O_3 in the X band. Secondly, we compared the effect of FeSiAl and ZrB_2 inclusions on the dielectric properties of alumina matrix composites. We studied six samples of ceramic composites with inclusion concentrations varying from 0% to 15%. This study shows that the complex permittivity of composites depends on the type of particles that constitute the rein–forcement. Composites reinforced by FeSiAl particles have improved dielectric properties than composites reinforced by ZrB_2 particles. In addition, the filling rate of the inclusions has an impact on the dielectric property. This property is more significant for compo–sites with a high concentration of inclusions. We also remarked that the dielectric property of the composites depends on the frequency in the X band. The dielectric behavior of the composites studied confirms that they can be used in applications to absorb electromagnetic waves and for antenna design. The comparison between the simulation results in this work and the experimental results published in the literature shows good agree–ment, making it possible to use the method adopted in this work to characterize other composite materials.

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NOMENCLATURE

ZrB_2	Zirconium diboride
FeSiAl	Iron Silicon Aluminum
Al_2O_3	Alumina
S_{11}	Reflection parameter
S_{ij}	Scattering parameters
S_{21}	Transmission parameter
Γ	Reflection coefficient
T	Transmission coefficient
T/R	Transmission/Reflection Method
ε_r	The relative permittivity of material
μ_r	Relative permeability of material
λ_{0g}	The guided wavelength in the cell without the sample
λ_0	The wavelength in free space
Λ_c	The cutoff wavelength
Λ	The normalized wavelength
η	Impedance for the sample
η_0	Impedance for the free space
NRW	Nicholson-Ross-Weir

ЕФЕКАТ ОЈАЧАЊА КОМПОЗИТА ГЛИНИЦЕ МАТРИКСОМ ИНКЛУЗИЈАМА ZrB_2 И FeSiAl НА ДИЕЛЕКТРИЧНА СВОЈСТВА НА МИКРОТАЛАСНИМ ФРЕКВЕНЦИЈАМА

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У овом раду су два композита ZrB_2/Al_2O_3 и $FeSiAl/Al_2O_3$ окарактерисана техником карактериза–ције Пренос/Рефлексија. Запремински садржај инк–лузија ZrB_2 и FeSiAl у овим композитима варира између 0 и 15%. Добијени резултати показују да проценат инклузија у композитима ефективно по–бољшава диелектрична својства. Поређење утицаја инклузија ZrB_2 и FeSiAl на диелектричне особине ових композита потврђује да ојачавање ових ком–позита честицама FeSiAl доводи до бољих диелек–тричних својстава. Штавише, ови резултати показују да се диелектрична својства два проучавана ком–

позита прогресивно смањују са повећањем фрек–венције у X опсегу. Ова фреквентна зависност дие–лектричне особине испитиваних композита је веома важна и показује да су проучавани композити добри кандидати за примене микроталасне апсорпције у X-опсегу и за дизајн антене. Поред тога, поређење између нумеричких резултата добијених у овом раду и експерименталних резултата објављених у литератури открива блиску сагласност, потврђујући поузданост налаза студије