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Variations in the absorption of x-band electromagnetic waves on the thickness of Polypyrrole Polymer shell

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ABSTRACT

In the current study, the influence of polypropylene polymer shell on the absorption properties of the electromagnetic waves of the sample containing hard and soft magnetic particles was examined. The hard core of strontium hexaferrite magnetic material doped with aluminum metal cation was synthesized by sol-gel method and applied by reduction method to the surface of particles of Fe-Co soft magnetic alloy. Finally, a layer of polypyrrole was placed on the surface of the magnetic particles between the magnetic particles and the polymer with different weight ratios (1:1, 1:2 and 1:3). Fuzzy, microstructural, magnetic and electromagnetic tests were performed by XRD, SEM, VSM and VNA, respectively. The results of X-ray diffraction patterns revealed the formation of a single-phase compound of strontium hexaferrite after contamination and the presence of peaks related to the alloy of Fe-Co and pyrrole indicated the formation of these two phases. The results of the Vibrating-sample magnetometer indicate the occurrence of the phenomenon of exchange coupling between hard and soft magnetic particles and on the other hand, the decrease of saturation magnetism and the increase of the coercive force was witnessed after the application of non-magnetic polypropylene shell. Also, microstructural studies and elemental analysis suggested proper particle dispersion and formation of uniform polymer shell on the particle surface. Conversely, the results of electromagnetic testing on the prepared samples indicate an increase in the absorption bandwidth after the application of the polymer shell, which in the best case, i.e. when a weight ratio of 1:2 between magnetic particles and the polymer shell is employed, at a thickness of 2 mm, the maximum reflectance loss was achieved at -22 dB and the bandwidth at about 2.7 GHz. Decreasing the thickness and increasing the absorption bandwidth at the optimal amount of polymer shell resulted an increase in the values of dissipation parameters. The optimal ratio for application of polypyrrole polymer shell on the particle surface was determined 1:2.
Keywords: Polypyrrole, Strontium hexaferrite, Fe-Co alloy, Core-shell, Microwave absorption.

Introduction

Recent breakthroughs in the field of wireless electronics such as televisions, radio systems, cell phones, radar devices, and local area networks among others have led to a plethora of complications in the functioning of MHz to GHz frequency range, including electromagnetic interferences. Thus, protection against electromagnetic waves is of paramount importance not only owing to the interference with waves and disrupting the performance of electronic and telecommunication systems, but also due to the harmful nature of these waves to human health.

Electromagnetic wave absorbers are necessary to reduce radiation pollution resulting from the increased number of devices and sources of electromagnetic waves. thus far, a broad range of electromagnetic wave absorbers have been identified that are capable of absorbing waves at both high and low frequencies. In practical applications such as reflectivity reduction of metal structures, these surfaces are coated with radar absorbing material.

Various magnetic and dielectric materials have been extensively studied to be employed as Radar Absorbing Material (RAM). RAMs are used to coat the interior and exterior surfaces of aircraft, ships and military vehicles, to reduce radar cross-section and, as a result, to increase their level of stealth from radar detection. RAMs should be selected based on mechanical strength, weight, thickness, price, availability and material usage.

Magnetic materials including iron carbonyls and ferrites (such as magnetite, hematite, spinel ferrites, and hexaferrites among others), dielectric materials such as Barium titanate, carbon-based materials (like carbon fiber, carbon black, graphite, graphene, single-walled and multi-walled carbon nanotubes and mesoporous carbons) and conductive polymers (such as polyaniline, polypyrrole, polyethylene, polyacetylene) are among the materials used in adsorbent coatings.

Among the aforementioned materials, ferrites exhibit the interesting characteristics of absorbing energy from electromagnetic waves and providing the most optimal trade-off between the performance of the absorber and its final thickness. Through their unique magnetization, hexagonal-type ferrites absorb microwave energy through magnetic field interactions. Hexagonal ferrites are considered suitable RAMs due to permeability greater than 1, high magnetization and two-dimensional anisotropic behavior at microwave frequencies,

Compared to metals, ferrites have many important characteristics such as low dielectric constant, high resonant frequency, high strength and good chemical stability, which are important factors in microwave absorbing materials.

Technologically, among various types of hexaferrites, the M-type strontium hexaferrite ($SrFe_{12}O_{19}$) has garnered the most interest. High magnetic permeability (necessarily more than 1), high magnetism and proper dielectric properties of this ferrite as well as its cost-effectivity have made it a unique candidate for being used as a RAM at microwave frequencies [2, 1].

Hexaferrites with magnetoplumbite structure, including barium and strontium hexaferrites, were first discovered by Brown and Smith in the 1950s and 1960s [3]. These materials were widely used in the manufacture of permanent magnets owing to their high magnetocrystalline anisotropy, magnetic permeability, saturation magnetism and high coercivity, and excellent chemical stability. These materials were also used in the construction of electromagnetic wave absorbers [4-7].

In a previous study [8], barium hexaferrite, as the hard core, and magnetite (Fe_3O_4), as the soft magnetic shell, were used to construct an absorber through the magnetic exchange property, exhibiting a reflective dissipation of -33.6 dB at a thickness of 2.5 mm at a frequency of 11.6 GHz. When the hard-magnetic phase of barium hexaferrite is sufficiently exchange-coupled with the soft magnetic phase material in the shell core structure, its magnetic properties increase. This increase causes its magnetic permeability to be closer to its electrical conductivity, thus leading to well-adapted impedance, thereby increasing the absorption performance in the process. In this study, the structure of $BaFe_{12}O_{19}$@Fe_3O_4 was combined with paraffin with a 1:1.5 ratio. By combining the two aforementioned magnetic materials, the amount of saturation magnetization increased, which is one of the major characteristics of exchange coupling interaction.

On the other hand, multi-walled carbon nanotubes (MWCNTs) have been extensively used as building blocks in various fields of science and technology owing to their striking properties such as high specific surface area, distinct one-dimensional tube structure, high absorbing capacity and proper stability. Nanocomposites based on multi-walled carbon nanotubes have been the subject of extensive research.

Magnetic adsorbents have both electrical and magnetic losses, but dielectric adsorbents only have electrical losses. Although magnetic adsorbents are usually heavy, they compensate by being able to absorb at low frequencies up to 100 MHz in a small thickness, while in dielectric adsorbents, the lower the frequency, the higher the required thickness. Since the magnetic permeability is higher at low frequencies and decreases as the frequency increases, absorption at high frequencies is often performed by dielectric properties. [11-9].

Nonetheless, the use of such materials alone for coating has led to a plethora of complications. For instance, metal-based protective materials (including metal foil, metal foams, and metal laminates) are mechanically hard, heavy, and susceptible to corrosion and chemical oxidation. Nano-scale carbon materials are widely used as fillers in conductive composites owing to their high mechanical strength as well as their excellent electrical conductivity. Still, the use of these carbon fillers in polymer matrices entails complex processes for manufacturing them, leading to their increased production costs.

One of the rather more effective methods to alleviate such inherent shortcomings is to combine two or more substances with different properties. A two- or three-component adsorbent composite can have better adsorption properties than each of them separately, which is perhaps because of improvement of magnetic and electrical losses along with the complementary effects between wave absorption and wave reflection.

Polymer-based composites containing conductive fillers are also extensively employed in the manufacture of dielectric absorbers. The fillers used in these adsorbents include graphite, carbon black, metals, metal oxides, semiconductors and conductive polymers. By altering the amount of the composite components, values for dielectric constant and loss can be optimized. The density of these adsorbents is less than that of magnetic ones [12].

Recently, a lot of efforts have been put on designing and preparing composite particles, including shell-coated cores with various chemical compositions. The interest garnered in these materials is owing to the fact that the properties (mechanical, optical, electrical, magnetic and catalytic) of the core or shell can be adjusted through their size, morphology, components and structure. Conductive polymers are highly significant materials in the field of radar absorption. Among conductive polymers, polypropylene (PPy) has been greatly sought-after owing to its simple synthesis, sufficient environmental stability and high electrical conductivity.

Conductive polymers such as polypyrrole (PPy) exhibit proper microwave absorption as their dielectric loss is controllable. Also, the simple preparation of polypyrrole and its suitable environmental stability are among other advantages of this material.

In addition, the structure of the adsorbent composite also has a notable effect on its absorption properties. This feature can involve layered or monolayer structures. Layered structures are created using step-by-step coating of layers. Monolayer structures are simply synthesized by spreading the filler in the conductive or non-conductive polymer matrix field. Matching the magnetic and dielectric losses simultaneously is of great importance in optimizing the amount of reflection loss in the whole desired range. Therefore, employing a large share of feasible mechanisms is the key to achieve high absorption properties as well as high bandwidth.

Methods and Materials

This research was performed the purpose of synthesizing adsorbents using doped strontium hexaferrite magnetic powders and FeCo non-oxidized magnetic powder once with polypyrrole powder and then by applying this polymer as a shell on the surface of particles using different weight ratios.

First, strontium hexaferrite magnetic powder was synthesized by sol-gel auto-combustion method, after which FeCo non-oxidized powder was reduced on the particle surface. Finally, polypyrrole powder was first synthesized using in situ polymerization and the resulting powder was compared with composite magnetic powders and their adsorption behavior was examined. At the second attempt, polypropylene polymer shell was applied on the surface of particles and the absorption behavior of electromagnetic waves was again examined with the purpose of studying the effect of core-shell structure. FeCo non-oxide powder was synthesized through reduction method.

Materials used

The raw materials used in this research are presented in Table 1. Most of the required precursors were Merck products with a purity of over 99.5% and no any initial purification.

Table 1: Raw materials used for synthesizing powders

Material	Chemical formula	Manufacturer
Ferric nitrate	Fe(NO3)3.9H2O	Merck
Strontium nitrate	Sr(NO3)2	Merck
Aluminium nitrate	$Al(NO_3)_3.9\ H_2O$	Merck
Cobalt nitrate	Co(NO3)2.6H2O	Merck
Ethylene glycol	EG	Merck
Citric acid	Citric acid	Merck
Chloric acid	HCl	Merck
Pyrol monomer	Pyrrole	Merck
Ammonium peroxodisulfate	Ammonium peroxodisulfate	Merck
Hydrazine hydrate	Hydrazine hydrate	Merck
Sodium hydroxide	Sodium hydroxide	Merck

Synthesis of aluminum-doped strontium hexaferrite powder

In order to synthesize the magnetic powder, strontium hexaferrite doped with aluminum cation (SrFe10Al2O19) was completely dissolved in distilled water according to the stoichiometric ratio of ferric nitrate with 9 molars of H_2O. Strontium nitrate was then dissolved in distilled water and added dropwise to the solution containing ferric nitrate and was then stirred for 30 minutes. Aluminum nitrate was then dissolved in water and then added to the aforementioned solution through drops.

Consequently, citric acid was added to the above solution in a ratio of 1: 1 of the total moles of added cations, and after stirring for 1 hour, it was added to the liquid ethylene glycol solution with 1:1 ratio. The pH of the solution was then raised to 7 using the caustic soda solution.

After adjusting the pH, the solution was heated in such a way that for every 30 minutes of stirring the temperature increased by 50°C. After achieving a temperature of 300°C, the water was completely evaporated and after the combustion reaction, the resulting powder was washed several times using distilled water and ethanol and then calcined for 9 minutes at 950°C.

Synthesis of Fe-Co non-oxide powder using the reduction method

The molar ratio of ferric nitrate and cobalt nitrate according to stoichiometric conditions in the chemical formula was adjusted 1:1. At first, the synthesized strontium hexaferrite particles were placed in a double-distilled water under the condition that the ratio of strontium hexaferrite in Fe-Co alloy would be 1: 1. Ferric nitrate and cobalt nitrate were added to the above solution, achieving the state of complete homogeneity and uniformness after 30 minutes of stirring. The soda solution was then added dropwise to the above-mentioned suspension. After adding hydrazine hydrate to the prepared solution, it was placed in an ultrasonic cleaner at 65°C. The color of the suspension gradually turned black, after which the reduction process was completed and lastly the final product was washed several times with distilled water and ethanol and dried in a vacuum oven.

Synthesis of polypyrrole powder

First, 5 ml of pyrrole monomer was dispersed in 0.5 M of hydrochloric acid solution. After preparing the ice water cleaner and bringing the solution temperature to the range of 0-5 ° C, solution no. 2 (including

17 g of ammonium proxy disulfate in 15 ml of 0.5 M hydrochloric acid solution) was added dropwise to solution no. 1, after which the solution was stirred for 2 hours and then the sediments were collected and washed.

Applying pyrrole coating on magnetic particles

Following the preparation of the magnetic powder, first 5 g of the prepared powder is dispersed in a solution of 0.5 M hydrochloric acid. Then, according to the ratio considered (ratios of 1: 1, 1: 2 and 1: 3 for magnetic powder to pyrrole) 5 ml of pyrrole monomer is added to the above suspension. After preparing the ice water cleaner and dropping the solution temperature down to the range of 0-5 ° C, solution no. 2 (including 17 g of ammonium proxy disulfate in 15 ml of 0.5 M hydrochloric acid solution) was added dropwise to solution no. 1, after which the solution was stirred for 2 hours and then the sediments were collected and washed.

Synthesizing the absorbent sample

In order to synthesize the absorbent sample, powders were dispersed in polyester resin for 5 minutes using a 300-watts ultrasonic probe. the samples were synthesized in different thicknesses with a filler weight percentage of 30% in X-band dimensions.

Absorbent samples include the following, respectively:

1. 30% weight percent of strontium hexaferrite dispersed in polyester resin
2. 30% weight percent of SrFe10Al2O19@FeCo in polyester resin
3. A composite containing SrFe10Al2O19@FeCo and polypyrrole powder were mixed with 90% and 10% weight percent, respectively, and dispersed in the polyester field with 30% weight percent.
4. SrFe10Al2O19 @ FeCo @ PPy was dispersed in polyester resin with 30% weight percent for the case where the ratio of pyrrole to magnetic powder was considered 1:1.
5. SrFe10Al2O19 @ FeCo @ PPy was dispersed in polyester resin with 30% weight percent for the case where the ratio of pyrrole to magnetic powder was considered 1:2.
6. SrFe10Al2O19 @ FeCo @ PPy was dispersed in polyester resin with 30% weight percent for the case where the ratio of pyrrole to magnetic powder was considered 1:3.

Problem formulation

The decrease in the actual and imaginary values of electrical conductivity with increased frequency is perhaps owing to the level of electrical conductivity. The contribution of conductivity to electrical permittivity is expressed by the Maxwell equation as follows:

$$\boldsymbol{\varepsilon}''(\boldsymbol{\omega}) = \boldsymbol{\varepsilon_P}''(\boldsymbol{\omega}) + \frac{\boldsymbol{\sigma_{dc}}}{\boldsymbol{\varepsilon_0\omega}} \tag{1}$$

In which, $\boldsymbol{\varepsilon_P}''(\boldsymbol{\omega})$ is the imaginary part of the electrical permittivity depending on the frequency of polarization, $\boldsymbol{\sigma_{dc}}$ is the conductivity of the composite dc, while $\boldsymbol{\varepsilon_0}$ and $\boldsymbol{\omega}$ are respectively the electrical conductivity in vacuum and the angular frequency.

Also, by dividing the imaginary part by the real one for both dielectric permeability parameters ($\boldsymbol{\varepsilon''/\varepsilon'}$) and magnetic permeability ($\boldsymbol{\mu''/\mu'}$), the dielectric and magnetic losses tangents are obtained.

The reflective loss of an electromagnetic wave absorber under vertical impact, in a single layer based on the amount of its input impedance according to the theory of transmission lines is calculated using the following formula:

$$R(\mathrm{dB}) = 20\log\left|\frac{Z_{\mathrm{in}}-1}{Z_{\mathrm{in}}+1}\right| \tag{2}$$

In which, Z_{in} is related to the magnetic parameters of the adsorbent by the following equation:

$$Z_{\text{in}} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left[j\left(\frac{2\pi}{c}\sqrt{\mu_r \varepsilon_r}\right)\text{f.d}\right] \tag{3}$$

Where μ_r and ε_r are respectively the magnetic permeability and electrical conductivity of the adsorbent environment, C is the speed of light in the open air, f is the frequency and d is the thickness of the absorber layer. For an ideal absorber, the condition should be such that the input impedance is 1.

If the thickness of the absorber layer is an odd coefficient of a quarter of the wavelength (i.e. the matching thickness) of the microwave waves, then the back-propagation wave from the metal layer nullifies the wave striking the absorber surface.

$$\boldsymbol{d} = \frac{\boldsymbol{nc}}{\boldsymbol{4f}\sqrt{|\boldsymbol{\varepsilon}||\boldsymbol{\mu}|}}\,(\boldsymbol{n} = \mathbf{1}, \mathbf{3}, \mathbf{5}, \dots) \tag{4}$$

where c is the speed of light, f is the frequency, while ε and μ are electrical conductivity and magnetic permeability, respectively.

Results

Fuzzy examination of samples with XRD

Figure 1 show the results of X-ray diffraction analysis of aluminum-doped strontium hexaferrite (SrFe10Al2O19), core-shell sample containing hard and soft phase of strontium alloy and Fe-Co alloy (SrFe10Al2O19@FeCo) and a sample consisting of a polypropylene polymer coating placed on the polypropylene coating particles with a weight ratio of 1: 1.

As it is known, the characteristic peaks of strontium hexaferrite with the reference code 1207-024 are observed in the angles of 30.37, 32.30, 34.19, 37.13, 40.39, 40.52, 55.18, 56.82 and 63.25 and indicates the single-phase composition of strontium hexaferrite after contamination without the presence of hematite impurity phase. Following the substitution of aluminum ions in the structure of strontium hexaferrite, according to the results, the intensity of the peaks is relatively reduced while their width is increased, which is owing to the smaller size of particles. On the other hand, the displacement of the peaks towards larger angles is also evident in the X-ray diffraction pattern, which is possibly due to the reduction of the parameters of the strontium hexaferrite matrix after being doped with aluminum cation, because the atomic radius of the aluminum ion is about 0.535 angstroms, in contrast to the atomic radius of iron ions is 0.645 angstroms.

Hence, Given the small atomic radius of the substituted ions in the structure, the peaks should be shifted to higher angles. The mean particle size of the crystallite was determined by calculating full width at half maximum (FWHM) of the peaks (107) and (114) using the Scherer equation ($\boldsymbol{D = 0.9\lambda/\beta \cos\theta}$), in which λ is the wavelength of the X-ray, β is FWHM of the peak, and θ is the diffraction angle.

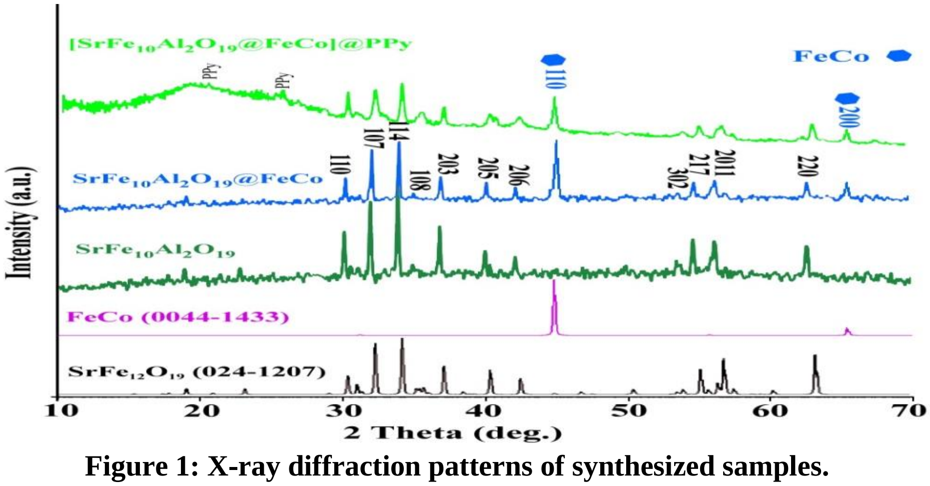


Figure 1: X-ray diffraction patterns of synthesized samples.

The X-ray diffraction pattern of the sample consisting of strontium hexaferrite doped with aluminum cation as the core and the magnetic Fe-Co alloy as the shell also confirms the formation of the Fe-Co cubic single phase and the presence of peaks of this phase at angles of 44.82 and 65.26 belong to the planes (110) and (200), respectively. It is evident that following the application of the magnetic shell on the hard core of the magnet, the intensity of the core peaks is reduced, indicating the alignment of particles of Fe-Co alloy particles on the hard-magnetic particles of strontium hexaferrite.

Changes in electromagnetic parameters with frequency

Figure 2 illustrates the changes in complex electrical conductivity ($\boldsymbol{\varepsilon = \varepsilon' - i\varepsilon''}$) and complex magnetic permeability ($\boldsymbol{\mu = \mu' - i\mu''}$) as electromagnetic characteristics with a frequency in range of 8-12 GHz for samples prepared in the polyester field.

Excessively high conductivity in the 1:3 ratio sample led to a decrease in the electrical conductivity at frequencies in the range of 10.5 GHz to 12 GHz, which is possibly because of the excessive amount of polypyrrole as a conductive polymer on the particle surface.

As can be seen from the results of the complex electrical conductivity, by adding Fe-Co alloy to the hard magnetic structure of strontium hexaferrite, or even in the composite and core-shell state, the application of polypyrrole polymer shell on the particles, by increasing the level of interface in each phase and entry of the dielectric component into the system, the amount of electrical conductivity parameters is increased. This is possibly due to the increase of the interface between the components and consequently the improved interfacial polarizations.

It is evident that both electrical conductivity parameters have increased by applying the polypropylene polymer shell to the particle surface. As can be seen in the 1:3 and 1:2 ratio samples, there is not much change in the values of electrical conductivity, as even at some frequencies, these values were reduced in the 1:3 ratio state compared to the 1:2 ratio one, indicating that even with the application of more polymer coating, no significant change occurs in the amount of permeability.

The high conductivity of the adsorbent leads to increased electrical conductivity of the sample. If polypropylene is used as a shell on magnetic particles, a conductive network is generated between the magnetic particles because of the presence of polypyrrole, which leads to a notable increase in electrical conductivity. On the other hand, the electrical conductivity is inversely proportional to the angular frequency ($\mu \frac{1}{\omega}$). Increased electrical conductivity and mechanisms for polarization loss lead to an increase in electrical conductivity parameters following the application of polypropylene shell.

It is apparent from the results that, in the presence of purely doped strontium hexaferrite in the field in the whole frequency range, the values of $\boldsymbol{\varepsilon'}$ and $\boldsymbol{\varepsilon''}$ have been subject to changes in the range of 3.5 and 1, respectively. In the sample including hard and soft phases, the changes of these two variables are respectively in the range of 4.5 and 1.2. In the sample where only polypyrrole powder was composited with magnetic powders and dispersed, the changes of these two variables are respectively in the range of 4.5 and 2.1. However, if the pyrrole shell is applied to the surface of the particles, the behavior becomes completely wavy and the changes shift towards the range of 7 to 9.5 for $\boldsymbol{\varepsilon'}$ and 3 to 4.3 for $\boldsymbol{\varepsilon''}$, respectively. These changes and the waviness of electrical conductivity across the frequency range can be due to multiple relaxation processes including electrical dipole and interfacial polarization, i.e. the transfer of charges occurs along the polypyrrole chains and on the interface between the polypyrrole and the magnetic particles. Basically, different dielectric constants in the interface of two different environments will lead to the generation of interfacial polarization. Moreover, due to the presence of polypyrrole, the conductor network can function as polar centers and thus be involved in absorbing electromagnetic waves.

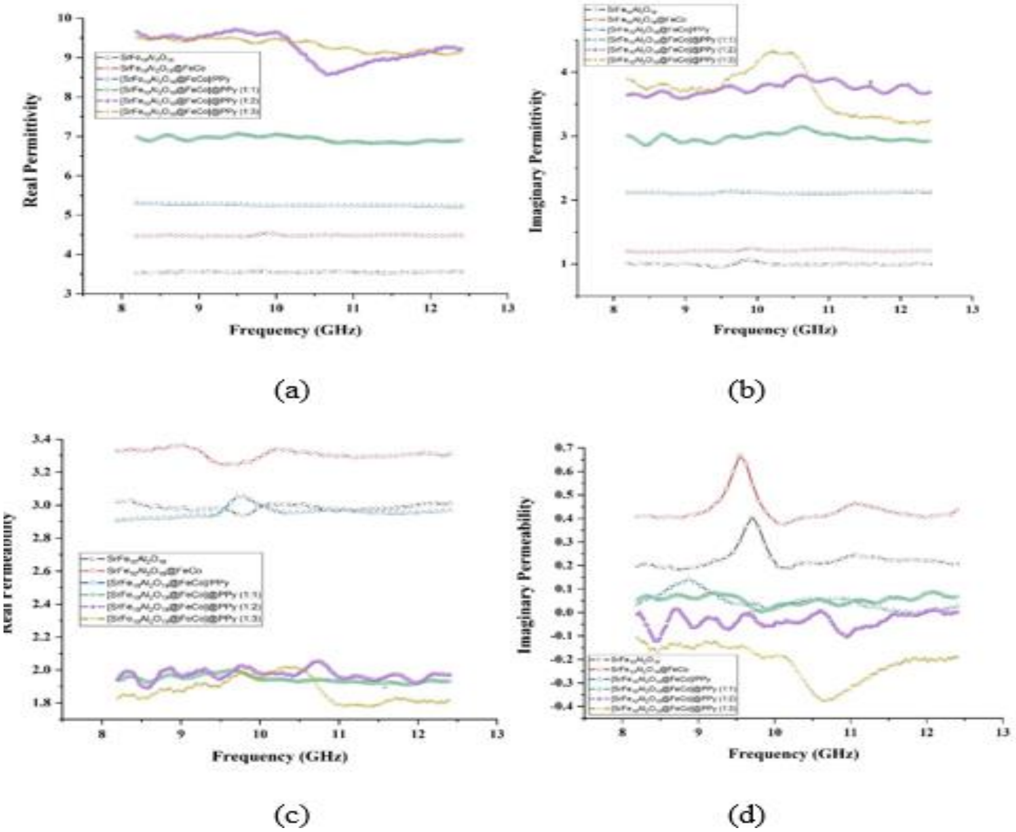
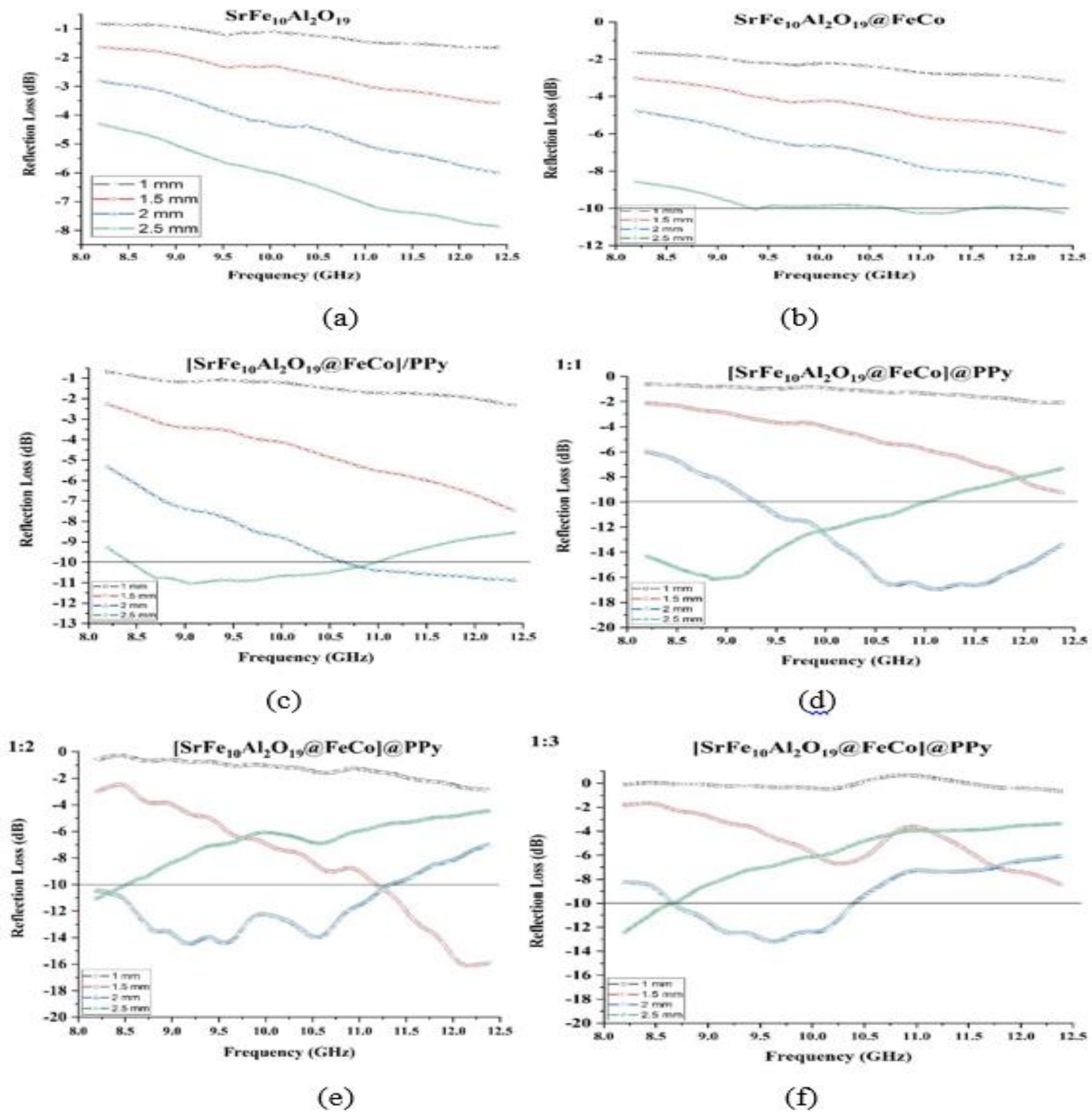


Figure 2: Electromagnetic parameters of samples prepared in X band, (a) ε′, (b) ε′′, (c) μ′, (d) μ′′

Simulation of microwave absorption behavior in X band

Strontium hexaferrite and its substituted composites have received extensive attention as microwave absorbers in the GHz range due to their high magnetic permeability coefficient, high magnetic resonance frequency and magnetism, as well as good dielectric properties. To reduce the reflectance of the absorbers, the intrinsic impedance of the absorber must be equal to the impedance of the wave in the open space, as a result of which an intensification state emerges and the maximum amount of absorption in the material is yielded. In this case, the energy of the electromagnetic wave absorbed by the material is converted to heat as a result of magnetic and dielectric losses. The ferromagnetic resonance frequency of M-type strontium hexaferrite is in the range of 50-60 GHz due to high magnetocrystalline anisotropy. Although the magnetic properties of the strontium hexaferrite sample indicate the hardness of the synthesized sample, its absorption properties alone cannot be judged, particularly since each of the electromagnetic wave absorber in a given range exhibit good absorption properties. Therefore, the absorption of electromagnetic waves at different frequencies by each of the studied composites should be measured.

Figure 3 depicts the extent of microwave wave loss in the frequency range of the simulated X band (8.4-12 GHz) of the prepared samples. It is apparent from the figures the occurrence of low absorption when employing doped strontium hexaferrite, indicating the inability of this material to absorb electromagnetic waves even at a thickness of 2.5 mm. After using the soft magnetic composition of Fe-Co alloy in the structure, as can be seen, at a thickness of 2.5 mm, the sample has a reflection loss of about 10.2 dB and an absorption bandwidth of 0.5 GHz. This shows the positive effect of the exchange coupling phenomenon and the consequent improvement of the absorption behavior. Also, the absence of the dielectric component in the samples has led to a low reflective loss along with low bandwidth, which indicates that the resonant frequency of these composites is at frequencies above the measured range. After the introduction of polypyrrole powder in the matrix, as can be seen, the absorption behavior of electromagnetic waves improved. At a thickness of 2.5 mm, the reflective loss was about 11.2 dB and the bandwidth about 2 GHz, which suggests improvement compared to the previous case. Also, the sample at a thickness of 2 mm has a reflective loss of about -11 dB and a bandwidth of about 2 GHz. It can be seen from the results that with the presence of only 10% weight of polypyrrole powder in the field, Bandwidth increased significantly owing to increased interfacial polarization and increased dielectric loss due to the presence of polypyrrole. After applying the polymer shell on the magnetic particles with different percentages, reflection loss, and especially bandwidth, improved at lower thicknesses. In the best case, i.e. in the 1: 2 ratio state, at the thickness of 2 mm, the sample has a reflective loss of about -14.2 dB and a bandwidth of 3.5 GHz, while only for this sample, the composite is also capable of absorbing electromagnetic waves at the thickness of 1.5 mm, with the reflection loss of -1.1 dB and the bandwidth of 2.5 GHz. It is apparent that applying more polymer shell on magnetic particles causes the polymer shell hinder the operation of magnetic particles, and the impedance mismatch resulting from the excessive increase of electrical conductivity parameters leads to more reflection of the striking wave, hence weakening the amount of absorption.



(a) (b)

(c) (d)

(e) (f)

Figure 3: Simulation of electromagnetic wave absorption behavior of samples prepared in X band, (a) SrFe10Al2O19, (b) SrFe10Al2O19@FeCo, (c) SrFe10Al2O19@FeCo/PPy, (d) SrFe10Al2O19@FeCo@PPy (1:1), (e) SrFe10Al2O19@FeCo@PPy (1: 2), (f) SrFe10Al2O19@FeCo@PPy (1: 3).

Loss of hysteresis and resonance of the amplitude wall are negligent in this frequency range. Considering the effect of Foucault's currents and ferromagnetic resonance, in cases where the magnetic loss is because of the eddy currents, then $\boldsymbol{C_0}$, obtained from the relation $\boldsymbol{C_0 = \mu''(\mu')^{-2}f^{-1}}$, will have a constant value as frequency alters, which is a measure of the effect of the shell. Regarding the samples containing the core-shell structure of SrFe10Al2O19@FeCo@PPY at 1: 1 and 1: 2 ratios, the value of $\boldsymbol{C_0}$ is an almost constant over the entire frequency range, which is due to the occurrence of eddy current-related loss phenomenon. In fact, this phenomenon is prevailing among other existing phenomena (Figure 5).

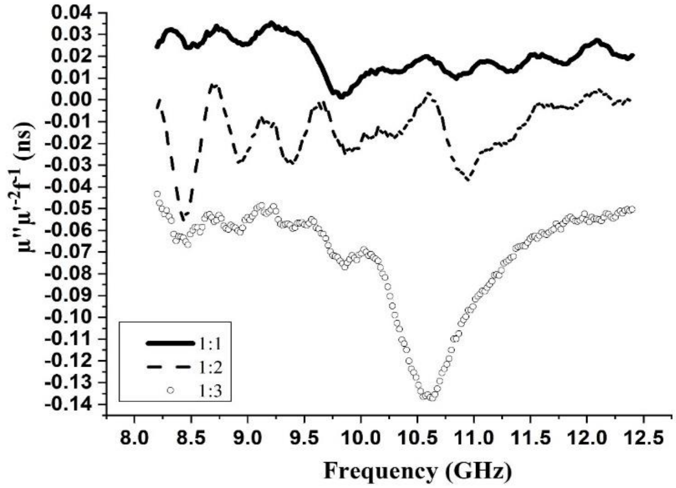


Figure 5: Simulation of $\mu''(\mu')^{-2}f^{-1}$ by frequency with samples containing polymer shell

Matching thickness for n coefficients of 1 for the samples are illustrated in Figure 6. The simulated values are in good agreement with matching thickness of the match. The maximum reflection loss occurs during the maximum impedance matching between the open air and the absorber. The large gap between the impedance of the absorber layer and the open air increases the reflection from the absorber surface and hence a smaller portion of the wave is introduced to the absorber. Therefore, less wave is absorbed by the loss or even cancellation mechanisms upon return to the surface. Therefore, the inverse condition, i.e. greater impedance matching, leads to optimized reflection loss.

Absorption of the composite sample is possibly owing to the magnetic dissipation of the two magnetic components and the electrical loss of the electrical component within the composite. The presence of polypyrrole on the particle surface leads to higher impedance matching of the sample and thus more reflection loss. On the other hand, the structure of the core of the shell contributes to increased reflection loss resulting from the increased interface and consequently increased the space charge polarizations.

It is evident from examining the maximum values of the actual loss with the matching thickness value, that it is completely matches the thickness changes of a quarter of the wavelength, while the best results are observed in for the 1:2 ratio sample.

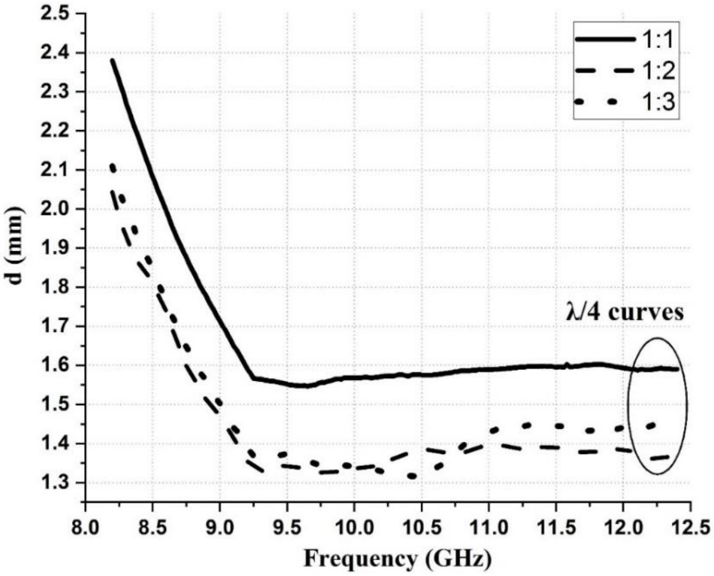


Figure 6: Simulation of frequency matching thickness for samples containing polymer shell.

Figure 7 depicts the results of the actual reflection loss of samples prepared in a 1:2 ratio at different thicknesses. As the thickness decreases from 2 mm to 1 mm, the maximum reflection loss shifts towards higher frequencies. When the sample thickness is 2 mm, the maximum reflection loss is about -22 dB and the bandwidth is about 2.7 GHz. For cases where the thickness is 1.5 mm, the maximum reflection loss was about -25.2 dB and the bandwidth about 2 GHz. According to the results, at both 2 mm and 1.5 mm thicknesses, the sample exhibited good adsorption properties and was in good agreement with the results from simulations.

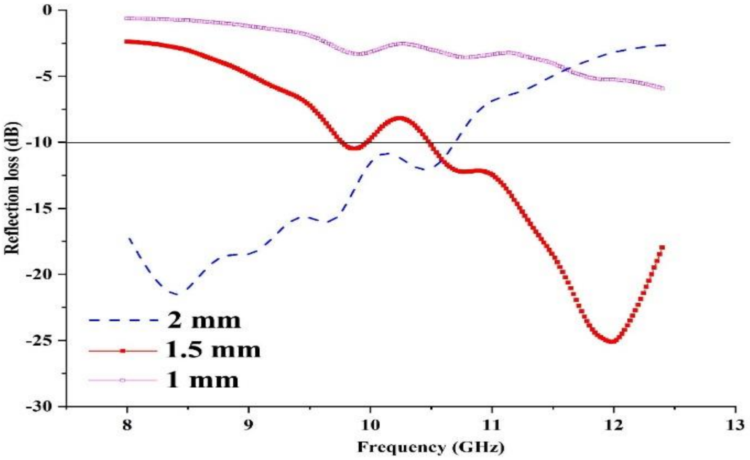


Figure 7: Actual absorption of SrFe10Al2O19@FeCo@PPy (1: 2) sample by frequency, at different thicknesses.

Conclusion

In this study, a composite with the capacity to adsorb electromagnetic waves in the X-band range of radar waves was synthesized. This composite was based on strontium hexaferrite doped with aluminum metal cation as a hard-magnetic core, Fe-Co alloy as a soft magnetic shell on the surface of hard magnetic particles, and ultimately polypyrrole as a polymer shell on the surface of this particle. The composite was synthesized with the purposes of (i) exploiting the property of exchange coupling and increasing the storage capacity of magnetic energy by using hard and soft magnetic composites, and (2) utilizing the composite of polypyrrole as a polymer shell on the surface of magnetically insulated particles and thus improving the dielectric loss of the sample by increasing the amount of interfacial polarization. The increase in dielectric loss of the sample was in common with the increase in polarization rates. Strontium hexaferrite was synthesized by sol-gel method, Fe-Co alloy by reduction method and polypyrrole polymer via in situ polymerization method. According to the X-ray diffraction results, the single-phase combination of strontium hexaferrite and Fe-Co alloy was confirmed and the amorphous presence of polypyrrole on the particle surface was thus approved. The results of magnetic measurements also indicated the exchange coupling between hard and soft particles. Ultimately, the coercive force was increased and the saturation magnetization was decreased by applying a non-magnetic polypyrrole shell. The results of adsorption of samples by applying polypropylene shell on the surface of magnetic particles using different weight ratios indicate high adsorption in 1: 2 weight ratio between magnetic particles and polymer shell, which in the best case at a thickness of 2 mm, the maximum reflectance loss was achieved at -22 dB and the bandwidth at about 2.7 GHz

According to the results of this study, it is recommended that in future works, different magnetic shells be applied to the strontium hexaferrite core and the adsorption properties be studied. Moreover, the effect of other polymers or even the simultaneous use of conductive polymers on the absorption properties should be examined.

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