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Microwave absorbing characteristics of Fe₃O₄@SiO₂ core–shell polyaniline-based composites

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Abstract

In this study, Fe₃O₄@SiO₂ core–shell/polyaniline composites were successfully prepared by mechanical and chemical methods. The crystalline structure, morphology, magnetic and microwave absorption property of the Fe₃O₄@SiO₂ core–shell polyaniline-based composites were investigated with X-ray diffraction, scanning electron microscope, permagraph and vector network analyzer, respectively. The results indicate the composites of 4 wt% Fe₃O₄@SiO₂ core–shell fillers a potential candidate for X-band electromagnetic absorbing material. The frequency bands for reflection loss below −10 dB (90% microwave absorption) are obtained from 8.0 to 12.2 GHz at the thickness of 2 to 5 mm. This enhancement could be attributed to the addition of Fe₃O₄@SiO₂ core–shell as a filler.

1. Introduction

In recent years, rapid development in telecommunication devices such as military electronic systems, computers, and mobile phones has already attracted extensive concerns due to the electromagnetic interference (EMI) issues [1, 2]. Now people are aware that the EMI environment and pollution are harmful to their health and degrade the quality of our lives [3–7]. Thus, the development of a variety of materials that can eliminate or absorb electromagnetic (EM) waves effectively becomes urgent and reduces the harmful EMI. To overcome this problem, the designing and fabrication of microwave absorbers are a very important subject in modern society. As a kind of typical microwave absorbers, magnetic and dielectric materials are required to fulfill the characteristics of the abundant resource, low cost, easy preparation, lightweight, relatively low density, high efficiency, and frequency range response [8–15].

Some results of studies on Fe₃O₄, SiO₂, and polyaniline materials as microwave absorbers have been published in many papers [16–18]. Xiang Liu et al. investigated the Fe₃O₄/C composites as a excellent microwave absorptionability with optimum reflection loss (RL) of −18.73 dB at 15.37 GHz [19]. Pouria Sardarian et al. prepared Fe₃O₄/BaTiO₃/MWCNT nanocomposite system by a hydrothermal sol-gel method which resulted in maximum absorption for the high-frequency band (16.7–18 GHz) with 80%–93% absorption [20]. Biao Zhao et al. reported Ni–SiO₂ composite micropherses, which show a minimum RL as low as −40.0 dB (99.99% absorption) at 12.6 GHz with a matching thickness of 1.5 mm [21]. Bin Zhang et al. has successfully designed Fe₃O₄/Polyaniline Core/Shell at which an optimum reflection loss of −37.4 dB at 15.4 GHz with a Polyaniiline shell thickness of 100 nm [22].

Up to now, the exploration of Fe₃O₄ and SiO₂ materials with different applications and compositions, such as Fe₃O₄/C composites [19], TiO₂@SiO₂/NiFe₂O₄ composite [23], Fe₃O₄/TiO₂, Fe₃O₄/SnO₂ [24], Fe₃O₄/ZnO, Fe₃O₄/Fe₂O₃/SiO₂, Fe₃O₄/C core/shell, Fe₃O₄@SiO₂@ZnO core-shell, etc., have been used as main attractive candidate materials of the newest microwave absorbers for increased microwave absorption. Currently, many core–shell composition containing Fe₃O₄ cores (e.g., Fe₃O₄/Polyaniline Core/Shell [22], Fe₃O₄/C core/shell [19], and Fe₃O₄@SiO₂@ZnO core–shell [25]) indicate the microwave absorption ability

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than shell materials. Several researchers have achieved some results in making a core–shell based on Fe3O4 as a core for microwave absorbing application. Almost all of them use chemical methods to make Fe3O4 nanometer structure [26–28]. So that the Fe3O4 nanometer structure is produced in small amounts.

In this work, to make light-weight microwave absorbers, Fe3O4@SiO2 core–shell polyaniline-based composites were prepared by mechanical and chemical methods. Fe3O4@SiO2 core–shell material is a filler and polyaniline as the matrix. Fe3O4 as a core material is produced from iron sand which is milled to obtain a smaller particle size. SiO2 as shell material is obtained from large amounts of rice husks. The complex permittivity and permeability of Fe3O4@SiO2 core–shell polyaniline-based composites with 0, 2, 4, and 6 wt% of Fe3O4@SiO2 core–shell as a filler are investigated and the microwave absorbing characteristics are evaluated. The minimum RL and corresponding frequency at different thicknesses have been resulted in detail.

2. Experimental methods

2.1. Materials
The iron sand, rice husks, hydrochloric acid (HCl, 70%), sodium hydroxide (NaOH, 96%), ammonium peroxodisulfate are all commercially local available market. Distilled water is also used for the preparation of the solutions. the synthesized polyaniline powder is ready to use.

2.2. Synthesis of Fe3O4 fine particles from iron sand
Synthesis of Fe3O4 fine particles using mechanical milling method. The iron sand is milled by SPEX M8000 high-energy ball milling (HEBM) to obtain smaller size and then separated magnetically. The magnetic material in the form of Fe3O4 was milled in stages 0, 5, 20, and 560 min to obtain Fe3O4 fine particles. The Fe3O4 fine particles were dispersed in distilled water by ultrasonic for the coating process.

2.3. Synthesis of SiO2 from rice husk.
Isolation of silica from rice husks begins with ashes of rice husks, then the ash of the rice husks is added with 3% HCl with a ratio of 10 mL of 3% HCl for 1 gram of rice husk. While heated and stirred with a hot plate stirrer for 2 h then the mixture is re fluxed for 6 h. The mixture was then cooled to room temperature and filtered using Whatman filter paper No. 42. The filtered residue is then washed with demineralized water to neutral pH. The residue with a neutral pH was then dried at 105 °C for 4 h to get white silica.

2.4. Preparation of sodium silicate solution
The obtained silica is then washed and weighed as much as 10 grams. 82.5 ml of 4 M NaOH was added to 10 grams of fine silica in a moon flask then refluxed for 5 h. The solution is then filtered and the filtrate is taken. The resulting filtrate is a sodium silicate solution which is then used to make the core–shell.

2.5. Synthesis of core–shell Fe3O4@SiO2
core–shell Fe3O4@SiO2 was synthesized by reflux method. 2 grams of Fe3O4 nanoparticles were dissolved in 400 ml of demineralized water. A total of 40 ml of synthesized sodium silicate solution was added dropwise to the mixture. The pH of the solution is lowered with concentrated HCl until it reaches pH 6. After the pH reaches 6 then the mixture is refluxed for 6 h. The mixture was then cooled to room temperature and filtered using Whatman paper No. 42. The resulting residue is washed using demineralized water repeatedly to a neutral pH. The resulting Fe3O4@SiO2 core–shell was dried at room temperature for 12 h.

2.6. Synthesis of polyaniline
Aniline monomer 5 ml was added to 50 ml of 1 M HCl under stirring until homogeneous. In a separate beaker, 6 grams of ammonium peroxodisulfate are dissolved in 50 ml of 1 M HCl until homogeneous. Into the aniline solution, ammonium peroxodisulfate solution is added dropwise under stirring conditions until the solution turns green. The polymerization process was continued for 2 h until a dark green solution was formed. The resulting solution was then stored at about 10 °C for 24 h. The solution was then filtered with Whatman paper no. 42 and washed with demineralized water. The filtered residue is dried at room temperature until completely dry. The green solid formed is polyaniline.

2.7. Synthesis of Fe3O4@SiO2 core–shell polyaniline-based composites
Fe3O4@SiO2 core–shell polyaniline-based composites were synthesized by the oxidation method. core–shell Fe3O4@SiO2 core–shell was added to 100 HCl 1 M then aniline monomer was added dropwise into the solution under stirring conditions. Stirring was continued for 10 min. Then ammonium peroxodisulfate as an oxidizing agent was dissolved in 50 ml 1 M HCl in a separate beaker (mole ratio with aniline 1: 1). Into the aniline solution, ammonium peroxodisulfate solution was added dropwise. The polymerization process is carried out for 3 h.
The crystalline phase of the milled Fe₃O₄ powder and SiO₂ was analyzed by XRD, and the pattern of the sample is shown in figure 1. According to the reference patterns of international crystal diffraction data (ICDD) #98-065-4110 (Fe₃O₄), the crystal structure of the sample is polycrystalline that consists of the Fe₃O₄ phase (figure 1(a)). This represents that the milled sample has been successfully prepared for the core material. Meanwhile, the structural morphologies of the samples were monitored by scanning electron microscopy (SEM) using a high resolution microscope (SEM). The lattice parameters of the Fe₃O₄ phases were calculated based on the Scherrer formula using the following equations [32-33]:

\[ RL \ (dB) = 20 \log \left( \frac{(Z_{in} - 1)}{(Z_{in} + 1)} \right) \]

\[ Z_{in} = \left( \frac{\mu}{\varepsilon} \right) \tanh \left( \frac{-j2\pi ft}{c} \sqrt{\mu \varepsilon} \right) \]

where \( Z_{in} \), \( \mu \), \( \varepsilon \), \( f \), and \( c \) are the characteristic impedance, complex permeability, complex permittivity, X-band frequency, light velocity, and thickness of the samples, respectively.

2.8. Characterization

The crystalline structures of the fine particles Fe₃O₄ and SiO₂ were characterized by x-ray powder diffraction of the powder samples using a PanAnalytical x-ray diffractometer (XRD) using Cu-Kα radiation (wavelength \( \lambda = 1.54 \) Å). The morphologies were observed using a scanning electron microscope (SEM) operating at an accelerating voltage of 15 kV. Magnetic measurements were performed using a Permagraph Electromagnet EP3 with an external field of 1 tesla. The reflected signal (S₁₁ or S₂₂) and transmitted signal (S₁₂ or S₂₁) of the samples were measured by A Rohde-Schwarz ZVA 67 vector network analyser (VNA) at a frequency of 8.0–12.2 GHz. The s-parameters (S₁₁ and S₂₂) and Nicolson-Ross-Weir (NRW) theoretical calculations are being used for resulting the complex permeability (\( \mu = \mu′ - j\mu″ \)) and permittivity (\( \varepsilon = \varepsilon′ - j\varepsilon″ \)) [29-31]. The reflection loss (RL) of samples were calculated by using the values of \( \mu \) and \( \varepsilon \) based on the following equations through the formula using the following equations [32, 33]:

\[ RL \ (dB) = 20 \log \left( \frac{(Z_{in} - 1)}{(Z_{in} + 1)} \right) \]

\[ Z_{in} = \left( \frac{\mu}{\varepsilon} \right) \tanh \left( \frac{-j2\pi ft}{c} \sqrt{\mu \varepsilon} \right) \]

3. Results and Discussion

3.1. Phase identification analysis

The crystalline phase of the milled Fe₃O₄ powder and SiO₂ was analyzed by XRD, and the pattern of the sample is shown in figure 1. According to the reference patterns of international crystal diffraction data (ICDD) #98-065-4110 (Fe₃O₄), the crystal structure of the sample is polycrystalline that consists of the Fe₃O₄ phase (figure 1(a)). This represents that the milled sample has been successfully prepared for the core material. Meanwhile, the pattern of SiO₂ shows that the sample is in amorphous form (figure 1(b)). We observed five crystal orientations of the Fe₃O₄ phase, namely, (141), (122), (202), (322), and (282). A High Score Plus software computer program was used to calculate the lattice parameters of the Fe₃O₄ phases [34]. The lattice parameters of the Fe₃O₄ phases were \( a = 5.919 \) Å, \( b = 16.735 \) Å, and \( c = 5.942 \) Å, which are not much different from the literature (International Centre for Diffraction Data, ICDD no. 98-065-4110). The crystallite sizes of the Fe₃O₄ phases can be calculated from the XRD patterns with different full widths at half maximum (FWHMs) for each peak by the Scherrer method (\( d = 0.9 \frac{\lambda}{\beta \cos \theta} \)), where \( \lambda \) is the wavelength of the Cu-Kα, radiation (1.54 Å), \( d \) is the crystallite size, \( \beta \) is the FWHM of the peak, and \( \theta \) is the diffraction angle [35]. The resulted crystallite size is shown in table 1. The crystallite size of the sample was in the nanometer range (about less than 40 nm).

The structural morphologies of the samples were monitored by scanning electron microscopy (SEM) with two magnifications. Based on the SEM results, it can be seen that Fe₃O₄ after the milling process for 560 min...
there has been a change in particle size. This indicates that the preparation of Fe3O4 nanoparticles has been successful in this method. The results of XRD measurements can be confirmed that Fe3O4 after milling has a crystal size of less than 40 nanometers. In the Fe3O4@SiO2 core–shell synthesis, it can be shown in figures 2(e)–(f) that the colour changes to be whiter. This SiO2 coating process has occurred and Fe3O4@SiO2 core–shell particles tend to agglomerate.

3.2. Magnetic properties
The magnetic hysteresis loops of the Fe3O4 sample are displayed in figure 3. The remanent magnetization (Mr), the saturation magnetization (Ms) and coercivity force (Hc) values of the Fe3O4 sample are 0.25 tesla, 0.05 tesla, and 6 kA/m tesla, respectively.
3.3. Electromagnetic characteristics

It is well known that the complex permeability \((\mu = \mu' - j\mu'')\) and permittivity \((\varepsilon = \varepsilon' - j\varepsilon'')\) can be used to characterize the excellent microwave absorbing properties, which should have high the real \((\mu')\) and imaginary \((\mu'')\) parts of permeability, large imaginary \((\varepsilon'')\) and small real \((\varepsilon')\) parts of permittivity at microwave frequency [21].

As shown in figure 4 for polyaniline sample without filler of \(\text{Fe}_3\text{O}_4@\text{SiO}_2\) core–shell. The \(\mu'\), \(\mu''\), \(\varepsilon'\), and \(\varepsilon''\) values of all samples show fluctuation in the 8.2–12.2 GHz range. The \(\mu'\) values of 2 wt%, 4 wt%, and 6 wt% \(\text{Fe}_3\text{O}_4@\text{SiO}_2\) core–shell fillers showed the tendency to decrease in the 9.0–12.2 GHz range. Generally, \(\mu''\) represents magnetic energy dissipation [24, 36]. The \(\mu''\) value of 2 wt%, 4 wt%, and 6 wt% \(\text{Fe}_3\text{O}_4@\text{SiO}_2\) core–shell fillers also exhibit decreasing in the 8.2–12.2 GHz range, which indicates a weak magnetic loss ability of
microwave energy. As shown in figures 4(c) and 4(d), the \( \varepsilon' \) value of 2 wt%, 4 wt%, and 6 wt% Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell fillers are significant and tend to decrease in the 8.0–12.2 GHz range. The imaginary part (\( \varepsilon'' \)) of 2 wt%, 4 wt%, and 6 wt% Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell filler showed constant at about 8.0–12.2 GHz, while electromagnetic fields are applied in the X-band frequency. The dielectric loss can be explained by the imaginary part of permittivity (\( \varepsilon'' \)). Figure 4 shows the imaginary parts (\( \varepsilon'' \)) of all samples. It can be noticed that the \( \varepsilon'' \) values of 4 wt% and 6 wt% Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell fillers increase with the increasing frequency and show higher than those of others.

3.4. Microwave absorption properties

To evaluate the microwave absorption characteristic of the Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell polyaniline-based composites, their reflection loss (RL) values were calculated according to the complex permeability (\( \mu = \mu' - j\mu'' \)) and permittivity (\( \varepsilon = \varepsilon' - j\varepsilon'' \)) values with the given frequency (\( f \)) and sample thickness (\( t \)) using equations (1) and (2). Now, to closely investigate and obtain impedance matching conditions, the effect of various sample thickness on absorption properties for composite materials in X band frequency range, the RL values have been shown in figure 5(a)–(d). The RL values are calculated using various sample thickness ranging from 1.0 to 5.0 mm. Based on the RL values of the Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell polyaniline-based composites with 4 wt% (figure 5(c)) and 6 wt% fillers (figure 5(d)) for each thickness, there is optimum result for a given absorbing ability. The optimum sample shows the minimum RL of 4 wt% Fe\(_3\)O\(_4\)@SiO\(_2\) core–shell polyaniline-based composite with a thickness of 1.0–5.0 mm reached \(-14.42\) dB (over 95% absorption) at 8.74 GHz, and the bandwidth of the reflection loss less than \(-10\) dB (over 90% absorption) was 4.2 GHz.

Now, to closely investigate and obtain impedance matching conditions, the effect of various sample thickness on absorption properties for composite materials in the 8.0–12.2 GHz frequency range, the 2D map colour filling patterns of RL has been shown in figure 6(a). The RL values are calculated using various sample thickness ranging from 1.0 to 5.0 mm. In this study, to find impedance matching conditions of the samples, the graphical map method is commonly applied [37]. Based on the RL values of the Fe\(_3\)O\(_4\)@SiO\(_2\)core–shell
polyaniline-based composite with 4 wt% filler for each thickness, there is a relative bandwidth of \( W = f_{\text{up}}/f_{\text{low}} \), where \( f_{\text{up}} \) and \( f_{\text{low}} \) are the upper- and lower frequency limits of the bandwidth for a given absorbing ability, in this case, \(-10\) dB, respectively. Therefore, based on the curve of \( W \) versus \( t \), the maximum relative bandwidth (\( W_{\text{max}} \)) and the corresponding optimum thickness (\( t_{\text{m}} \)) can be obtained, as shown in figure 6(b). Thus, the \( W_{\text{max}} \) values of the sample are 1.52 with an optimum thickness of 2.0 mm (a bandwidth of 4.2 GHz) and 1.95 mm (a bandwidth of 3.69 GHz) with the absorption bandwidth below \(-10\) dB. Figure 6(c) shows the minimum reflection loss (\( RL_{\text{min}} \)) values of the sample are obtained as \(-14.42\) dB at 8.74 GHz.

The magnetic loss ability is highly correlated with hysteresis loss, the eddy current effect, domain-wall resonance, exchange resonance and natural resonance. In our case, the exchange, natural, and domain wall resonance which are only existed in the MHz frequency range, could be excluded. Thus, the contribution of the magnetic loss of \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) as a filler is hysteresis loss and the eddy current effect that correlated with the irreversible magnetization because of a strong magnetic field and the penetrating electromagnetic wave into the magnetic materials. The eddy current effect can be expressed by \( \mu'' \approx 2\pi\mu_s(\mu'\sigma d^2)/3 \), where \( \mu_s, \sigma \) and \( d \) are

![Figure 6. The Fe3O4@SiO2 core–shell polyaniline-based composites. (a) The 2D map colour filling patterns of RL characteristics with various sample thickness, (b) the dependence of \( f_{\text{up}}, f_{\text{low}} \) and \( W = f_{\text{up}}/f_{\text{low}} \) on thickness \( t \) and (c) reflection characteristics at the optimum thickness \( t_{\text{m}} \) for 4 wt% \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) core–shell fillers. (d) Eddy current loss \( (C_e) \) curve of 0 wt%, 2 wt%, 4 wt%, 6 wt% \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) core–shell fillers.]

| Composition                        | Minimum RL value (dB) | Optimum thickness (mm) | Optimum frequency (GHz) | Effective bandwidth (RL < \(-10\) dB) (GHz) | References |
|------------------------------------|-----------------------|------------------------|--------------------------|---------------------------------------------|------------|
| \( \text{Fe}_3\text{O}_4/\text{C}/\text{paraffin composites} \) | \(-18.73\)            | 2.5                    | 15.37                    | 5.4                                         | [19]       |
| \( \text{Fe}_3\text{O}_4/\text{SiO}_2/\text{graphene composite} \) | \(-27.1\)             | 1.5                    | 12.2                     | 2.3                                         | [24]       |
| \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) microspheres | \(-17.55\)            | 4.5                    | 13.7                     | 1.6                                         | [25]       |
| \( \text{Fe}_3\text{O}_4@\text{SiO}_2@\text{ZnO microspheres} \) | \(-18.89\)            | 1.5                    | 13.5                     | 2.5                                         | [25]       |
| \( \text{Fe}_3\text{O}_4/\text{PANI core/shell microspheres} \) | \(-32.5\)             | 2.0                    | 15.6                     | 5                                           | [23]       |
| \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) core–shell polyaniline-based composite | \(-14.42\)            | 2.0                    | 8.74                     | 4.2                                         | This work |

![Figure 6. The Fe3O4@SiO2 core–shell polyaniline-based composites. (a) The 2D map colour filling patterns of RL characteristics with various sample thickness, (b) the dependence of \( f_{\text{up}}, f_{\text{low}} \) and \( W = f_{\text{up}}/f_{\text{low}} \) on thickness \( t \) and (c) reflection characteristics at the optimum thickness \( t_{\text{m}} \) for 4 wt% \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) core–shell fillers. (d) Eddy current loss \( (C_e) \) curve of 0 wt%, 2 wt%, 4 wt%, 6 wt% \( \text{Fe}_3\text{O}_4@\text{SiO}_2 \) core–shell fillers.]

![Table 2. Microwave absorption characteristics of some previously studied the typical Fe3O4@SiO2 core–shell fillers.](https://example.com/table2.png)
Fe₃O₄@SiO₂ core-shell electromagnetic absorbing material indicates that the optimum sample shows the minimum RL of 4 wt% shown in References Setia Budi ORCID iDs The data that support the Data availability statement This research is supported by PenelitianDasar UnggulPerguruan Tinggi (PDUPT) 2020 (30/SP2H/DRPM/LPPM/III/2020) researchgrant of Kemenristek/BRIN Republik Indonesia.

4. Conclusions

In summary, the Fe₃O₄@SiO₂-core-shell polyaniline-based composites consist of polyaniline matrix and fillers of Fe₃O₄@SiO₂-core-shell powders with various weight content have been synthesized. The potential candidate for electromagnetic absorbing material indicates that the optimum sample shows the minimum RL of 4 wt% Fe₃O₄@SiO₂-core-shell filler reached ~ -14.42 dB (over 90% absorption) at 8.74 GHz with a thickness of 1.0 – 5.0 mm. The bandwidth of the reflection loss of less than – 10 dB (over 90% absorption) was 4.2 GHz.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Qiu J, Wang Y and Gu M 2007 Microwave absorption properties of substituted BaFe₁₂O₁₉/TiO₂ nanocomposite multilayer film, J. Mater. Sci. 42 166–9
[2] Luo H, Feng W, Liao C, Deng L, Liu S, Zhang H and Xiao P 2018 Peaked dielectric responses in TiₓCₓ, MXene nanosheets enabled composites with efficient microwave absorption J. Appl. Phys. 123 104103
[3] Zhao B, Zhao W, Shao G, Fan B and Zhang R 2015 Morphology-control synthesis of a core–shell structured NiCu alloy with tunable electromagnetic-wave absorption capabilities ACS Appl. Mater. Interfaces 7 12951–60
[4] Zhao B, Fan B, Shao G, Zhao W and Zhang R 2015 Facile synthesis of novel heterostructure based on SnO₂ nanorods grown on submicron Ni walnut with tunable electromagnetic wave absorption capabilities ACS Appl. Mater. Interfaces 7 18815–23
[5] Zhao B, Liu J, Guo X, Zhao W, Liang L, Ma C and Zhang R 2017 Hierarchical porous Ni@boehmite/nickel aluminum oxide flakes with enhanced microwave absorption ability Phys. Chem. Chem. Phys. 19 9128–36
[6] Pattanayak S S, Laskar S H and Sahoo S 2021 Microwave absorption performance enhancement of corn husk-based microwave absorber J. Mater. Sci.: Mater. Electron. 32 1150–60
[7] Wang J, Shi Z, Wang X, Mai X, Fan R, Liu H, Wang X and Guo Z 2018 Enhancing dielectric performance of poly (vinylidene fluoride) nanocomposites via controlled distribution of carbon nanotubes and Barium titanate nanoparticles Eng. Sci. 479–86
[8] Xiang J, Hou Z, Zhang X, Gong L, Wu Z and Mi J 2018 Facile synthesis and enhanced microwave absorption properties of multiferroic NiₓCoₓZnₓFe₄O₁₀/BaTiO₃ composite fibers J. Alloys Compd. 737 412–20
[9] Yang C C, Gung Y J, Shih C C, Hung W C and Wu K H 2011 Synthesis, infrared and microwave absorbing properties of (BaFe₁₂O₁₉ + BaTiO₃)/polyaniline composite J. Magn. Magn. Mater. 323 933–8
[10] Fang J, Shang Y, Chen Z, Wei W, Hu Y, Yue X and Jiang Z 2017 Rice husk-based hierarchically porous carbon and electromagnetic wave attenuation J. Mater. Chem. C 5 4695–705
Liu Y, Cherkasov N, Gao P, Fernández J, Lees M R and Rebrov E V 2017 The enhancement of direct amide synthesis reaction rate over

Lyu L, Yan X, Liu J, Khan M A, Sheriff S, Vupputuri S, Das R, Sun L and David P 2020 Ef

Budi S, Yusmaniar, Juliana A, Cahyana U, Purwanto A, Imaduddin A and Handoko E 2018 Preparation of high surface area and high

Wang Y, Gao X, Zhang W, Luo C, Zhang L and Xue P 2018 Synthesis of hierarchical CuS

Zhao B, Deng J, Zhao C, Wang C, Chen Y G, Hamidinejad M, Li R and Park C B 2020 Achieving wideband microwave absorption

Widanarto W, Ekaputra A I, Effendi M, Cahyanto W T, Ghoshal S K, Kurniawan C, Handoko E and Alaydrus M 2020 Neodymium ions

Liu X, Ma Y, Zhang Q, Zheng Z, Wang L and Peng D 2018 Applied surface science facile synthesis of Fe3O4

Pattanayak S S, Laskar S H and Sahoo S 2021 Microwave absorption study of dried banana leaves-based single-layer microwave

Handoko E, Sugiharto I, Marpaung M A, Randa M, Alaydrus M and Sofyan N 2018 Double layer microwave absorption characteristics of barium hexaferrite/silica composite for X-band frequencies Mater. Sci. Eng. 929 109–15

Widanawito, Effendi M, Krishna S, Kurniawan C, Handoko E and Alaydrus M 2020 Bio-silica incorporated barium ferrite composites: evaluation of structure, morphology, magnetic and microwave absorption traits Curr. Appl. Phys. 20 638–42

Widanawito, Ekaputra A, Efendi M, Cahyanto W T, Ghoshal S K, Kurniawan C, Handoko E and Alaydrus M 2020 Neodymium ions activated barium ferrite composites for microwave X-band absorber applications: synthesis and characterisations Composites Communications 19 51–5

Handoko E, Sugiharto I, Budi S, Randa M, Jalil Z and Alaydrus M 2018 The effect of thickness on microwave absorbing properties of barium ferrite powder J. Phys. Conf. Ser. 1080 012002

Handoko E et al 2019 Complex permittivity, permeability and microwave absorption studies of double layer magnetic absorbers based on BaFe12O19 and BaFe12O19/SiO2 Mater. Sci. Forum 966 302–7

Budi S, Yusmaniar, Juliana A, Cahyana U, Purwanto A, Imaduddin A and Handoko E 2018 Preparation of high surface area and high conductivity polypyrrole nanoparticles using chemical oxidation polymerization technique J. Phys. Conf. Ser. 983 012162

He J, Deng L, Liu S, Yan S, Luo H, Li Y, He L and Huang S 2017 Enhanced microwave absorption properties of Fe3O4-modified flaky Fe3O4@SiO2 J. Magn. Magn. Mater. 444 49–53

Wang Y, Gao X, Zhang W, Luo C, Zhang L and Xue P 2018 Synthesis of hierarchical CuS/SGO/PANI/Fe3O4 quaternary composite and enhanced microwave absorption performance J. Alloys Compd. 757 372–81

Kim D Y, Chung Y C, Kang T W and Kim H C 1996 Dependence of microwave absorbing property on ferrite volume fraction in MnZn ferrite-rubber composites IEEE Trans. Magn. 32 553–8