Thicknes optimization of a double-layered microwave absorber combining magnetic and dielectric particles

Affandi Faisal Kurniawan, Mohammad Syaiful Anwar, Khoirotun Nadiyyah, M Mashuri, T Triwikantoro and D Darminto

1 Advanced Materials Research Group, Department of Physics, Institut Teknologi Sepuluh Nopember, Sukolilo, Surabaya 60111, Indonesia
2 Department of Physics Education, Universitas PGRI Semarang, Semarang 50232, Indonesia
* Authors to whom any correspondence should be addressed.

E-mail: affandifaisal@upgris.ac.id and darminto@physics.its.ac.id

Keywords: iron rock, double-layer absorber, graphenic, genetic algorithm, thickness optimization

Abstract
The purpose of this study is to optimize the thickness of the double-layered microwave absorber for obtaining the highest absorption. The graphenic-based carbon compounds and Fe3O4 magnetic particles were combined to fabricate the double-layered absorber. The thickness was optimized by employing a genetic algorithm (GA) to obtain high reflection loss (RLmin) values. These samples at a thickness of 2 mm were measured for reflection loss (RL) with a Vector Network Analyzer (VNA). Input variables, such as relatively complex permeability and relatively complex permittivity, were obtained using a conversion program that uses Nicolson-Ross-Weir (NRW) method from VNA S-parameter values (S11 and S21) data. By entering the permeability and permittivity of the complex relative to GA, the thickness can be optimized to produce high RLmin value. Optimization of the double-layer thickness of 12 absorbers produces the optimum thickness of d1 = 5.99 mm and d2 = 0.87 mm among the materials combination, which results in a high RLmin (~44.69 dB). This optimization is very important for designing double-layer radar absorbing material (RAM) which results in high RLmin values.

1. Introduction
In recent years, electromagnetic radiation pollution or electromagnetic interference (EMI) has become an increasingly serious, and worldwide problem because of the use of electromagnetic waves in the rapidly developing navigation, telecommunications, aviation activities, and also in the increasing use of various electronic devices [1–3]. The EMI not only disrupts the electronic systems but also is potentially hazardous for human health [3–5]. Therefore, electromagnetic wave absorbing materials are being investigated extensively to solve the EMI problem [6]. Electromagnetic wave absorber is a material that can effectively weaken the intensity of electromagnetic waves by causing magnetic loss, and dielectric loss [7]. Different types of materials have been used for microwave absorption, such as magnetic, and dielectric dampers [8]. The level of microwave absorption of these materials depends on complex permittivity, and permeability values for the particular frequency range in question [8].

The growing demand for RAM makes continuous effort to improve RAMs’ microwave absorption properties necessary [8]. Microwave absorber can effectively absorb electromagnetic wave energy, and convert electromagnetic energy into heat [9–14]. Magnetite nanoparticles, such as Fe3O4, are considered as suitable microwave-absorbing material because of the magnetic loss they cause, their easy synthesis, and because they are environmentally friendly, non-toxic, and low cost [10, 11, 15–20]. One effective way of improving the material’s absorption of electromagnetic waves is to combine Fe3O4 with dielectric materials, such as reduced graphene oxide (rGO) [10, 21]. The recently tested graphene derivative (rGO) [6, 15] as a new carbon material, is very...
interesting because of its lightweight, extraordinary electrical conductivity, extraordinary chemical properties, physical properties, and mechanical properties [10, 22].

Multi-layer absorber is the focus of current research [23, 24]. It can give the best microwave-absorbing performance, and therefore, meet the requirements of an ideal microwave-absorbing material ($RL_{\text{min}} < -20 \, \text{dB}$) [24]. Several studies have been conducted on design methods and techniques for RAMs, such as design optimization using the simplex method, simulated annealing method, particle swarm optimization (PSO) [24–26]. According to the previous study [27], heuristic methods developed to date are evolutionary computation, simulated annealing, taboo search, GA, PSO, ant colony optimization (ACO), and others. Promising heuristic methods to solve optimization problems are GA, and PSO. However, for the modeling processes, the GA approach is superior to PSO [28]. GA has several advantages. This algorithm involves very little mathematical calculations to solve a problem. The evolutionary operators used in it make this algorithm very effective in global search. It has high flexibility to hybridize with other search methods to improve their effectiveness [29].

Based on the above description, in this research absorber was designed to increase $RL_{\text{min}}$. The design, among others, considers material selection (a combination of magnetic, and dielectric materials), the combinations of the arrangement of materials of the double-layer absorber, the design of the structure (multi-layer), and the selection of the thickness of each absorber to obtain a high $RL_{\text{min}}$ value. The purpose of this study was to optimize the thickness of the double-layer absorber with the GA method based on the transmission line model.

2. Methods

2.1. Sample preparation and characterization

Fe$_3$O$_4$ powder (sample a) was obtained from the rocks of Tanah Laut (South Kalimantan, Indonesia). The rocks were ground to a coarse powder using mortar, and pestle. The coarse powder was sieved through mesh 200 to obtain fine powder consisting of uniform-sized particles that had a large surface area so that the powder is evenly distributed. The methods for the preparation of fine rGO samples (sample b) with uniform-sized particles were chemical exfoliation processes, and mechanical exfoliation processes, which have been discussed in other research [22]. In this research, the chemical exfoliation process was used. The rGO powder which had previously been heated to 400 °C was mixed with 100 ml of 1 M HCl solution. The variation used in this research is the mole ratio between 1 M HCl solution, and rGO powder, which is 1:5 (sample c), and 1:10 (sample d). Further, Fe$_3$O$_4$, and rGO were considered, respectively, as magnetic, and dielectric particles. Then, the samples were characterized by VNA.

2.2. Design and Optimization of Double-Layer of RAM

A schematic diagram of a conductor backed double-layered absorber to form composite, consisting of combinations: magnetic–dielectric (pure), magnetic–dielectric (with treatment), and dielectric (pure)–dielectric (with treatment) materials. They have intrinsic properties $\mu_r$ (relatively complex permeability), $\varepsilon_r$ (relatively complex permittivity), $\eta$, $\gamma$, and $d_i$ (thicknesses) for the layer-$i$ that is close to the metal plate, and $\mu_i$, $\varepsilon_i$, $\eta$, $\gamma$, and $d_i$ for the layer-$i$ as the front-facing outward as shown in figure 1. Layer-1, and layer-2 are the absorption layers, and the matching layer, respectively [30, 31]. The input impedance on the surface of the air-absorbent, and the calculation of the $RL$ for the sample system were computed as follows [32]:

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

Figure 1. Schematic diagram of double-layer RAM (Dallenbach layer).
The design of the optimization of RAM on the double-layer (Dallenbach layer) on GA was divided into four stages. The first stage was to determine the optimization parameters, input variables, and output variables [33]. The optimization parameters used in this study were population size (PopSize), probability of crossing over ($P_c$), and mutation probability ($P_m$). Optimization parameters used in this study were Grefenstette (1), Grefenstette (2), and De Jong as shown in Table 1. The input variable is the condition chosen for optimization. Input variables in this study include the number of generations (makgen), fitness threshold (fithreshold), frequency, and the speed of light. Permeability ($\mu = \mu' - j\mu''$), and permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) values are obtained from VNA data, namely real $S_{11}$ (real reflection coefficient), imaginary $S_{11}$ (imaginary reflection coefficient), real $S_{21}$ (transmission coefficient real), and imaginary $S_{21}$ (imaginary transmission coefficient) are converted using the NRW conversion method in the MATLAB program. While the output variables to be sought in this study were the thickness of the material in each layer ($d_1$, and $d_2$).

The second stage was to determine fitness function [33]. The fitness function is defined as an individual evaluated based on a certain function as a measure of his performance [33]. Optimization using the GA method required the incorporation of a mathematical model into the fitness function. In this study, the reflection loss equation of double-layer RAM (equation (2)) was used as a mathematical model to be optimized. Because the dimension of reflection loss was predetermined limitation. A boundary mathematical model was needed to include these variables in the fitness function. This mathematical model is known as constrained optimization.

The third stage was the standard GA techniques [33] (figure 2). The sequence of steps was, first to determine the population; before determining the initial population, the first step is to determine the number of individuals in the population. For example, the number of individuals is N. After that, it will generate an initial population that has N individuals randomly [34]. The second step is to evaluate with binary encoding: an encoding where each gene can only be 0 or 1, and linear fitness ranking, namely a mechanism that aims to scale fitness values. The third step was reproduction through elitism: a process that aims to keep the individual with the highest fitness value from being lost during evolution, it is necessary to make one or more copies. Next, beyond roulette-wheel selection: this method aims to map the individuals in a circle segment sequentially so that each individual segment has the same size as its fitness size [35]. Furthermore, thru cross-over, specifically the cross-over of two chromosomes causes one chromosome to lead to a fine solution [36]. Herein after, by the way of mutation, in other words functions to replace the missing genes from the population as a result of the selection process [35]). Finally, general replacement, namely all individuals (e.g. N individuals in a population) of a generation are replaced at once by N new individuals resulting from crossovers, and mutations.

The fourth stage was the simulation, and optimization of the results [33]. Display optimization simulation of double-layered RAM showed the value of fitness during the optimization process from beginning to end as were needed to follow the course of the optimization process, and the results achieved. Meanwhile, the results achieved are the thickness of each material in the double-layered RAM. Meanwhile, the optimization results are displayed in the intermediate graph simulation (frequency of reflection loss).

| Optimization parameter | Popsizes | $P_c$ | $P_m$ |
|------------------------|---------|------|------|
| Grefenstette (1)       | 30      | 0.95 | 0.005|
| Grefenstette (2)       | 80      | 0.45 | 0.01 |
| De Jong                | 100     | 0.6  | 0.001|

$$RL = 20 \log \left( \frac{\sqrt{\mu_2/\varepsilon_2} [a] - 1}{\sqrt{\mu_2/\varepsilon_2} [a] + 1} \right)$$

Where:

$$a = \frac{\sqrt{\mu_1/\varepsilon_1} \tanh \gamma_1 d_1 + \sqrt{\mu_2/\varepsilon_2} \tanh \gamma_2 d_2}{\sqrt{\mu_2/\varepsilon_2} + \sqrt{\mu_1/\varepsilon_1} \tanh \gamma_1 d_1 \tanh \gamma_2 d_2}$$

$$\gamma_1 = \frac{2\pi f}{c} \sqrt{\mu_1 \varepsilon_1}$$

$$\gamma_2 = \frac{2\pi f}{c} \sqrt{\mu_2 \varepsilon_2}$$
2.3. Composite preparation and double-layer reflection loss characterization

The absorber materials selected in this research were sample a, sample b, sample c, and sample d. The method of preparing the samples has been discussed by another researcher [22]. For example, the two selected material combinations are sample b for layer-1 (absorption layer) and sample a for layer-2 (matching layer) (see figure 1), so the combination is called b-a (interface-a). Because the matching layer is sample a, it is called interface-a. The thickness of sample b is called \( d_1 \), and the thickness of sample a is \( d_2 \). Meanwhile, if the layer-2 is sample c, it is called interface-c, and so on there are 12 different combinations of the double-layer RAM design are tabulated in table 2.

![Figure 2. The standard GA technique flow chart.](image)

| Air-absorber interface layer | Sample combination 1-II layer |
|-----------------------------|-------------------------------|
| a-interface                 | b-a                           |
|                             | c-a                           |
|                             | d-a                           |
| b-interface                 | a-b                           |
|                             | c-b                           |
|                             | d-b                           |
| c-interface                 | a-c                           |
|                             | b-c                           |
|                             | d-c                           |
| d-interface                 | a-d                           |
|                             | b-d                           |
|                             | c-d                           |

Table 2. A combination of double-layer absorber design.
3. Results and discussion

3.1. Reflection loss measurement of single-layer absorber

Reflection loss of single-layer for all samples is shown in figure 3. Table 3 shows a relatively small $RL_{\text{min}}$ value, and the experimental bandwidth of all single-layer absorber samples. Thickness ($d$) of each sample is 2 mm. From figure 3, absorber layer bandwidth is defined as the frequency width $f_2 - f_1$ where the sample $RL_{\text{min}}$ is more than −5 dB. The relatively small $RL_{\text{min}}$ indicates that with a single-layer dielectric or magnetic absorber it is difficult to achieve the impedance match and broad frequencies of wave absorption [37, 38].

The design of a microwave absorber depends on the basic electromagnetic parameters such as relative complex permeability, relative complex permittivity, thickness, and frequency of microwave operation. It also depends on the material structure (multi-layer structure, core–shell structure, etc), material selection, and combination of selected materials [32, 38, 39]. The multi-layer structure (double-layer) can be manipulated to produce a high $RL_{\text{min}}$ by finding the appropriate thickness at the desired frequency with GA.

3.2. Calculation of reflection loss from double-layer design

Figures 4(a), and (b) show permittivity in relation with frequency. Real permittivity ($\varepsilon'$) is the ability to absorb microwave energy, while imaginary permittivity $\varepsilon''$ is the ability to release microwave energy [40]. The negative sign in the value of imaginary permittivity indicates that the energy was released. Figures 4(a), and (b) show that $\varepsilon'$ and $\varepsilon''$ have two peaks in each sample. The two peaks are at $\sim 8.5$–$9.0$ GHz, and $\sim 10.50$–$11$ GHz. The two frequencies $\varepsilon'$, and $\varepsilon''$, respectively, are the smallest the largest values are samples b, c, d, and a. The largest and smallest frequencies, $\varepsilon'$ and $\varepsilon''$, are a (pure magnetic material), and b (pure dielectric material). Samples c, and d are dielectric materials with treatment. The chemical, and mechanical exfoliation treatments of samples c, and d increase the values of $\varepsilon'$, and $\varepsilon''$ at both frequency peaks. The real $\mu'$, and imaginary $\mu''$ of the relative permeability are shown in figures 4(c), and (d). Magnetic energy storage is represented by $\mu'$, and $\mu''$ represents magnetic energy dissipation [40]. As shown in figure 4(c), the value $\mu'$ shows a significant upward trend for all samples in the frequency range $\sim 9.3$–$10.3$ GHz, and the frequency range $\sim 11.5$–$12$ GHz, giving rise to two peaks in that frequency range. Meanwhile, the value of $\mu''$ indicates a significant downward trend for all samples in the frequency range of $\sim 9.5$–$10.5$ GHz and $\sim 11.5$–$12$ GHz, giving rise to two valleys in that frequency range (figure 4(d)).

![Figure 3. Reflection loss of single-layer for all samples.](image)

Table 3. Reflection loss of the experiment results of all samples single-layer absorber.

| No | Sample | Reflection loss (dB) | Bandwidth (GHz) |
|----|--------|---------------------|-----------------|
| 1. | a      | −6.16               | 0.72            |
| 2. | b      | −10.62              | 1.36            |
| 3. | c      | −8.38               | 1.02            |
| 4. | d      | −7.93               | 1.06            |
The dielectric loss tangent (tan $\delta_e$), and magnetic loss tangent (tan $\delta_m$) of material are quantitative loss of electrical energy, and magnetic energy due to different physical processes, such as electrical conduction, dielectric relaxation, dielectric resonance, and loss from non-linear processes [41]. Figure 5(a) shows dielectric loss tangent (tan $\delta_e = \varepsilon''/\varepsilon'$) of samples a, b, c, and d as a function of frequency. The spectra of (tan $\delta_e$) of samples a, b, c, and d show constant values at frequencies from 8 to 9 GHz, and then each sample increases sharply to reach maximum values at frequencies of $\sim$9 GHz. At frequencies of $\sim$9.5 GHz, tan $\delta_e$ of all samples decreased sharply, and again showed a constant value at a frequency of $\sim$9.5–10.5 GHz.
Furthermore, tan δ of all samples increased slightly at a frequency of 10.5–12 GHz. Trends in spectra tan δ on figure 5(a) corresponds to the spectral trend ε′′ in figure 4(b). Tangent magnetic loss spectra tan δ_m can be seen in figure 5(b), which also shows that tan δ_m spectral trend for all samples tends to be similar to the tan δ_e spectra in figure 5(a). The tan δ_m spectra for all samples it reaches maximum values at ~ 10 GHz, and ~11.7 GHz frequencies. The tan δ_m spectra trend in figure 5b also tends to be similar to the spectral trend μ'' in figure 4(d). Figures 5(a), and (b) show that the value of tan δ_e for samples b, c, and d is greater than the value tan δ_m, which indicates that dielectric loss is the main factor affecting electromagnetic absorption of samples b, c and d [42, 43].

Analogous to this, figures 4(a), and (b) show that the value of sample a is a tan δ_m > tan δ_e, which indicates that magnetic loss is a major factor in electromagnetic absorption. Figures 3(c), and (d) show that samples have a better wave absorption effect when the value of tan δ_e is greater than the value of ε'' [38]. From figure 5(b) shows that sample a has a larger magnetic loss for wave absorption material. Figure 5(a) shows that the dielectric material samples b, c, and d have a tangent loss of dielectric loss values of ~10 dB, ~−80 dB, and ~−30 dB respectively. The mechanical, and chemical exfoliation process by heating at 400 °C of rGO (samples b, and c) can increase the value of the dielectric loss tangent. Sample c has a tangent value of dielectric loss greater than sample d because of the influence of the mole ratio between 1 M HCl solution, and the rGO powder. Figure 5(b) shows that the magnetic material sample (sample a) has a magnetic loss tangent value greater than those of the dielectric materials (samples b, c, and d).

Equation 2 is used to calculate the reflection loss value of the double-layer design by varying the combinations in the double-layer as shown in table 2. Input parameters of equation 2 such as μ_{21}, μ_{22}, ε_{t1}, and ε_{t2} are obtained from the NRW conversion method available in the MATLAB program while d_1, and d_2 values are obtained from the thickness optimization results of each double-layer variation by the GA in MATLAB.

From the optimization of double-layer microwave absorber for interfaces a, b, c, and d as done in section 2, the double-layered absorber design shows the value of −20 dB < RL_{min} < −45 dB. The frequency positions for different design combinations of the double-layer, and can be used in making absorbers for the desired frequency as shown in table 3, and figure 6. Table 3 also shows the thickness obtained from the optimization results (d_1 and d_2) using GA on the double-layer material absorber. The reflection loss values (RL_{min}) for the double-layer combination (interfaces a, b, c, and d) from the thickness optimization results with GA are plotted in figures 6(a)–(d).

The complex permeability, and permittivity of RAM (figure 4) play an important role in determining the properties of reflection. One way to reduce the reflection is by the condition of electromagnetic waves entering
into the absorbent material with the greatest level (suitable characteristic impedance) [44]. According to [44], to achieve the condition of impedance matching the ratio between material, and free space should be $\mu' / \varepsilon' = 1$. According to equation (1), if dielectric loss is present, a high value of permeability is needed so that matching impedance is reached [44]. By combining the impedance requirements that match attenuation, to reduce reflection, magnetic material should have a low $\varepsilon''$ value, a high $\mu''$ value, and corresponding values $\varepsilon'$, and $\mu'$ in the ratio $\mu' / \varepsilon' = 1$ [44]. Conversely, dielectric materials should have a high value of $\varepsilon''$, low value of $\mu''$, and these values of $\varepsilon'$ and $\mu'$ should be in the ratio $\mu' / \varepsilon' = 1$.

Figure 6 shows the high $RL_{\text{min}} (<-20 \text{ dB})$ for various variations of the double-layer absorber when compared to the single-layer absorber for samples a, b, c, and d (figure 3). From figure 5, the ideal absorber layer

![Figure 6](image_url)

**Figure 6.** Plots of $RL_{\text{min}}$ of conductor backed double-layer microwave absorber with optimized thickness for design combinations (a) interface a, (b) interface b, (c) interface c, (d) interface d.
because it is a dielectric double-layer absorber. Twelve composite materials used in this study are considered to be good RAM because they can absorb microwaves in X-band. It should be noted that the optimization of the thickness of the double-layer microwave absorber with GA of all samples can produce a higher reflection loss value for the double-layer absorber. Sample 8 has a high absorption at 9.12 GHz (figures 4(c), and (d)). This is consistent with the theory of the combination of impedance matching with attenuation to reduce reflection (in the previous paragraph).

Meanwhile, the largest bandwidth is sample 11, where the composition of the absorption layer is sample b, and the total thickness is 6.86 mm, show the greatest $RL_{\text{min}}$ ($-44.69$ dB) with a bandwidth of $0.32$ GHz. Sample 8 is the best absorber among the above combinations. Sample 8 has a high $RL_{\text{min}}$ because it is a dielectric double-layer absorber with high values of $\varepsilon''$ (samples b, and c), and low values of $\mu''$ (samples b, and c) at a frequency of 9.12 GHz (figures 4(c), and (d)). This is consistent with the theory of the combination of impedance matching with attenuation to reduce reflection (in the previous paragraph).

Meanwhile, the largest bandwidth is sample 11, where the composition of the absorption layer is sample b, and the matching layer is sample d with $t_T$ 2.23 mm. Meanwhile, sample 2 (dielectric-magnetic absorber) has high values of $\varepsilon''$ (sample c), and $\mu''$ (sample a) at $10.84$ GHz (figures 4(c), and (d)) so it does not fit the impedance matching combination theory with attenuation to reduce reflection (see the previous paragraph). From table 4, samples 1, and 4, samples 2, and 7, samples 3, and 10, samples 5, and 8, samples 6, and 11, and samples 9, and 12 show that the order in which materials are stacked also plays an important role in determining the final nature of RAM, by affecting the amplitude, and position of the resonant peak [46, 47]. From table 3, and 4, it can be seen that the optimization of double-layer absorber thickness with GA of all samples can produce a higher $RL_{\text{min}}$ value (> −20 dB) from the single-layer absorber but reduces the bandwidth. From table 4, and figure 6 it can be seen that the results of the optimization of the thickness of the double-layer absorber with GA can produce RAM with the required properties, because the thickness variation, the combination of materials with different properties, and the order in which the materials are stacked can improve the RAM absorption quality.

4. Conclusion

The double-layer microwave absorber with a combination of samples b, and c with the thickness $d_1 = 5.99$ mm, and $d_2 = 0.87$ mm respectively (total thickness of 6.86 mm), at a frequency of 9.12 GHz resulted in the largest $RL_{\text{min}}$ ($-44.69$ dB) in this study. Optimization of the thickness of the double-layer microwave absorber with the GA of the twelve composite materials in this study can produce high $RL_{\text{min}}$ value ($< -20$ dB) which is much higher than a single-layer microwave absorber. Twelve composite materials used in this study are considered to be good RAM because they can absorb microwaves in X-band. It should be noted that the optimization of the thickness of the double-layer with GA is necessary to produce high $RL_{\text{min}}$, and is very important step before conducting an effective and efficient experiment.

Acknowledgments

This research was partly supported by a doctoral program scholarship (awardee number 20161141020717) from ‘Lembaga Pengelola Dana Pendidikan Beasiswa Unggulan Dosen Indonesia Dalam Negeri’ (LPDP BUDI-DN), the 4th-year support was provided by the Indonesian Ministry of Finance (AFK), and by ‘Hibah Konsorsium Lembaga Pengelola Dana Pendidikan Beasiswa Unggulan Dosen Indonesia Dalam Negeri’.
Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Affandi Faisal Kurniawan https://orcid.org/0000-0003-1446-1177
T Triwikantoro https://orcid.org/0000-0003-2782-4934
D Darminto https://orcid.org/0000-0002-6269-9246

References

[1] Bi G, Zhu M, Zhang Q, Li Y and Wang H 2011 Synthesis and electromagnetic wave absorption properties of multi-walled carbon nanotubes decorated by BaTiO3 nanoparticles J. Nanosci. Nanotechnol. 11 1030–6

[2] Hou C, Li T, Zhao T, Zhang W and Cheng Y 2012 Electromagnetic wave absorbing properties of carbon nanotubes doped rare metal/pure carbon nanotubes double-layer polymer composites Mater. Des. 33 413–8

[3] Huang X, Chen Z, Tong L, Feng M, Pu Z and Liu X 2013 Preparation and microwave absorption properties of BaTiO3@MWCNTs core/shell heterostructure Mater. Lett. 111 24–7

[4] Feng Y B, Qiu T and Shen C Y 2007 Absorbing properties and structural design of microwave absorbers based on carbonyl iron and barium ferrite J. Magn. Magn. Mater. 318 8–13

[5] Mu G, Shen H, Qiu J and Gu M 2006 Microwave absorption properties of composite powders with low density Appl. Surf. Sci. 252 2278–84

[6] Huang X, Zhang J, Rao W, Sang T, Song R and Wong C 2016 Tunable electromagnetic properties and enhanced microwave absorption ability of flaky graphite/cobalt zinc ferrite composites J. Alloys Compd. 662 409–14

[7] Mashuri M, Baqiya M A, Triwikantoro T, Yahya E, Darminto D, Iskandar F and Abdullah M 2011 AIP Conference Proceedings Epoxy Resin Matrix Nanocomposites with core–shell Structure of NiZnFerrite/ Ag and NiZnFerrite/ PANi as Fillers for Microwave Absorber in Ka-band The 4th Nanoscience And Nanotechnology Symposium (NNS2011): an Int. Symp. 1415 (Bali, Indonesia) 238

[8] Kumar N, Singh S and Singh D 2017 Development of double layer microwave absorber using genetic algorithm IOP Conf. Ser.: Mater. Sci. Eng. 234 012009

[9] Adebayo L L, Soleimani H, Yahya N, Abbas Z, Wahaab F A, Ayinla R T and Ali H 2020 Recent advances in the development of Fe3O4–based microwave absorbing materials Curr. Opin. Chem. Eng. 34 1249–68

[10] Zhang K, Zhang Q, Gao X, Chen X, Wang Y, Li W and Wu J 2018 Effect of absorbers’ composition on the microwave absorbing performance of hollow Fe3O4 nanospheres decorated CNTs/graphene/C composites J. Alloys Compd. 748 706–16

[11] Feng A, Jia Z, Zhao Y and Lv H 2018 Development of Fe/Fe3O4@C composite with excellent electromagnetic absorption performance J. Alloys Compd. 745 547–54

[12] Wu G, Cheng Y, Yang Z, Jia Z, Wu H, Yang L, Li H, Guo P and Lv H 2018 Design of carbon sphere/magnetic quantum dots with tunable phase compositions and boost dielectric loss behavior Chem. Eng. J. 333 519–28

[13] Lu S, Chen Y, Wu X, Wang Z and Li Y 2014 Three-dimensional sulfur/graphene multifunctional hybrid sponges for lithium-sulfur batteries with large areal mass loading Sci. Rep. 4 1–4

[14] Lv H, Ji G, Liu W, Zhang H and Du Y 2015 Achieving hierarchical hollow carbon@Fe3O4@Fe3O4 nanospheres with superior microwave absorption properties and lightweight features J. Mater. Chem. C 3 1032–41

[15] Liu P, Huang Y, Yang Y, Yan J and Zhang X 2016 Sandwich structures of graphene@Fe3O4@PANI decorated with TiO2 nanosheets for enhanced electromagnetic wave absorption properties J. Alloys Compd. 662 63–8

[16] Tong G, Liu Y, Cui T, Li Y, Zhao Y and Guan J 2016 Tunable dielectric properties and excellent microwave absorbing properties of elliptical Fe3O4 nanorings Appl. Phys. Lett. 108 072905

[17] Chen X, Huang Y and Zhang K 2018 Cobalt nanofibers coated with layered nickel silicate coaxial core–shell composites as excellent anode materials for lithium ion batteries J. Colloid Interface Sci. 513 788–96

[18] Liu J, Cheng I, Che R, Xu J, Liu M and Liu Z 2013 Double-Shelled Yolk–Shell Microspheres with Fe3O4 Cores and SnO2 Double Shells as High-Performance Microwave Absorbers J. Phys. Chem. C 117 489–95

[19] Deng J, Wen S, Deng J and Wu D 2015 Extracting copper from copper oxide ore by a zwitterionic reagent and dissolution kinetics Int. J. Miner. Metall. Mater. 22 241–8

[20] Wang K, Wang G, Wang G, He Z, Shi S, Wu L and Wang G 2018 The construction of carbon-coated Fe3O4 yolk-shell nanocomposites based on volume shrinkage from the release of oxygen anions for wide-band electromagnetic wave absorption J. Colloid Interface Sci. 511 307–17

[21] Guo X, Bai Z, Zhao B, Zhang B and Chen J 2016 Microwave absorption properties of CoNi nanoparticles anchored on the reduced graphene oxide J. Mater. Sci. Mater. Electron. 27 8408–15

[22] Kurniawan A F, Anwar M S, Nadiyyah K, Mashuri M, Triwikantoro T and Darminto D 2019 Mechanical exfoliation of reduced graphene oxide from old coconut shell as radar absorber in X-Band Microw. Opt. Technol. Lett. 58 168–75
[26] Yu-Bo T, Yue D, Zhai-Bin X, Sha S and Tao P 2013 Frequency characteristics of electromagnetic bandgap structure with bow-tie cells and its optimal design based on particle swarm optimization IEEE Trans Electromag. Technol. 63–8
[27] Deepa S N and Sugumaran G 2011 MPSO based model order formulation technique for SISO continuous systems World Acad. Sci. Eng. Technol. 51 838–43
[28] Jones K 2005 Comparison Of Genetic Algorithm And Particle Swarm Optimisation International Conference on Computer Systems And Technologies - Compusystech 2005
[29] Gen M and Cheng R 1996 Genetic Algorithms and Engineering Design (Hoboken, NJ: Wiley)
[30] Wu H, Wang L, Guo S and Shen Z 2012 Double-layer structural design of dielectric ordered mesoporous carbon/polymer composites for microwave absorption Appl. Phys. A 108 439–46
[31] Ni Q-Q, Melvin G H and Natsuki T 2015 Double-layer electromagnetic wave absorber based on barium titanate/carbon nanotube nanocomposites Ceram. Int. 41 9885–92
[32] Gogoi J P and Bhattacharyya N S 2014 Expanded graphite—Phenolic resin composites based double layer microwave absorber for X-band applications J. Appl. Phys. 116 204101
[33] Bramantyo N 2006 Aplikasi algoritma genetika untuk optimasi desain resonator hemiholtz ganda menggunakan Matlab 7.0 Undergraduate Thesis Universitas Sebelas Maret Surakarta.
[34] Putra I M S 2018 Penerapan Algoritma Genetika Dan Implementasi Dalam Matlab (Bali, Indonesia: Universitas Udayana Bali)
[35] Kusumawati S and Purwono H 2005 Peneledaasian Masalah Optimasi dengan Teknik Teknik Heuristik (Yogyakarta: Graha Ilmu)
[36] Suyanto 2005 Algoritma Genetika dalam Matlab (Penerbit ANDI Yogyakarta)
[37] Bregar V B 2004 Advantages of Ferromagnetic Nanoparticle Composites in Microwave Absorbers IEEE Trans. Magn. 40 1679–84
[38] Huo J, Wang I and Yu H 2009 Polymers for electromagnetic wave absorption J. Mater. Sci. 44 3917–27
[39] Michielsen E, Sajer J-M, Ranjithan S and Mittra R 1993 Design of lightweight, broad-band microwave absorbers using genetic algorithms IEEE Trans. Microwave Theory Techn. 41 1024–31
[40] Handoko E, Iwan S, Anggoro B S, Mangasi A M, Randa M, Zulkarnain J, Kurniawan C, Sofyan N and Alaydrus M 2018 Magnetic and microwave absorbing properties of BaFe12−2xCoxZnxO19 (x = 0.0; 0.2; 0.4;0.6) nanocrystalline Mater. Res. Express 5 064003
[41] Sebastian M T 2010 Dielectric Materials for Wireless Communication (Amsterdam: Elsevier)
[42] Ma W, Yang R, Yang Z, Duan C and Wang T 2019 Synthesis of reduced graphene oxide/zinc ferrite/nickel nanohybrids: as a lightweight and high-performance microwave absorber in the low frequency J. Mater. Sci.: Mater. Electron. 30 18496–505
[43] Fu M, Jiao Q and Zhao Y 2013 Preparation of NiFe2O4 nanorod–graphene composites via an ionic liquid assisted one-step hydrothermal approach and their microwave absorbing properties J. Mater. Chem. A 1 5577
[44] Zhang B, Feng Y, Xiong J, Yang Y and Lu H 2006 Microwave-absorbing properties of de-aggregated flake-shaped carbonyl-iron particle composites at 2-18 GHz IEEE Trans. Magn. 42 1778–81
[45] Nikmanesh H, Haghgoohifard S and Hadi-Sichani B 2019 Study of the structural, magnetic, and microwave absorption properties of the simultaneous substitution of several cations in the barium hexaferrite structure J. Alloys Compd. 775 1101–8
[46] Folgueras I, de C, Alves M A and Rezende M C 2010 Dielectric properties of microwave absorbing sheets produced with silicone and polyaniline Mat. Res. 13 197–201
[47] Kaur H and Aul G D 2012 A review based on effects of change in thickness and number of layers on microwave absorbing Materials 3 5 https://www.ijsr.net/search_index_results_paperid.php?id=20132033