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To cite this article before publication: Erfan Handoko et al 2018 Mater. Res. Express in press https://doi.org/10.1088/2053-1591/aac4d7

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Magnetic and microwave absorbing properties of \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) (\( x = 0.0; 0.2; 0.4; 0.6 \)) nanocrystalline

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\(^2\)Dept.of Chemistry. Universitas Negeri Jakarta. Jalan Rawamangun Muka 13220. Jakarta Indonesia
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Abstract. We have investigated the magnetic and microwave absorbing properties of barium hexaferrite \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) (\( x = 0.0; 0.2; 0.4; 0.6 \)) nanocrystalline prepared using solid state reaction method. The powder of these ferrites were resulted by high energy ball mill for 1 hour and mixed with epoxy resin to be converted into a microwave absorbing composite. The results show barium hexaferrite structures for \( \text{Ba(Fe,Co,Zn)O}_{19} \) have been formed. The coercive force (Hc) decreases rapidly with the substitution of Co and Zn in the structure of \( \text{Ba(Fe,Co,Zn)O}_{19} \). It’s indicate that the Co-Zn in the structure of \( \text{Ba(Fe,Co,Zn)O}_{19} \) contributes to magnetic and microwave absorption properties. The minimum reflection loss value of -29.98 dB was observed at 10.8 GHz with a matching thickness of 1 mm for \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) (\( x = 0.6 \)) nanocrystalline. As results, the magnetic absorbing properties improve significantly by Co-Zn incorporation.

Keywords: \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \), solid state reaction method, refelection loss, microwave absorbing

1. Introduction

Research on barium hexaferrite \( \text{BaFe}_{12}\text{O}_{19} \) has attracted considerable attention from many researchers since the last decade. As a permanent magnet with a hexagonal M-type and space group of P63/mmc, it has superior magnetic properties such as high coercive force, high Curie temperature and high saturation magnetization. In addition, barium hexaferrite has other advantages such as chemically stable, corrosion resistant and low production cost [1-4]. Furthermore, the crystalline structure, crystallite size, magnetic and microwave absorption properties of doped barium hexaferrite were reported[5,6]. Due to its superiority in magnetic properties, the barium hexaferrite has a potential application as recording media, rotors and microwave absorbing materials. Recently, barium hexaferrite has been developed for telecommunication and military applications [7]. Furthermore,
substitution of Fe$^{3+}$ with other metals such as Mg–Ti[5], Co–Ti[8,9], Mn–Co[10], Ru–Co[11], Zn–Ti, Cu–Ti, and Ni–Ti[8] have been demonstrated. M. H. Shams and et al reported that the substitution of Mg and Ti ions on BaFe$_{9}$Mg$_{1.5}$Ti$_{1.5}$O$_{19}$ structure cause the decrease of coercive force value from 258.7 kA/m (undoped) to 6.1 kA/m (doped) with reflection losses less than -10 dB[5]. Meanwhile, other metals combinations i.e. Mn-Ti, Zn-Ti, Co-Ti, Cu-Ti and Ni-Ti which substituted on barium hexaferrite structure has changed the magnetic properties[8]. Among of these, Zn-Ti as non-magnetic ions believed could enhance the magnetic moment of barium hexaferrite. As consequences, the barium hexaferrite has high magnetic saturation due to Zn$^{2+}$ ions replacement at 4f energy level [8]. On the other hand, Co-Ti on barium hexaferrite structure decreased coercive force and magnetic saturation[8].

In this work, Co-Zn substituted barium hexaferrite with composition BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0; 0.2; 0.4; 0.6) nanocrystalline on different composition have been synthesized by two steps route i.e. solid state reaction and mechanical milling. In order to analyze structure, morphology, magnetic properties, and microwave absorber properties we characterized the sample by using XRD, SEM, permagraph, and VNA, respectively. Furthermore, the results will be discussed and analyzed systematically.

2. Experimental Methods

2.1. Preparations

Starting materials were powder of BaCO$_3$, Fe$_2$O$_3$, Co$_3$O$_4$ and ZnO with analytical grade. All of these materials were provided by Sigma Aldrich and Merck Co. Ltd. Barium hexaferriteBaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0; 0.2; 0.4; 0.6) were synthesized by stoichiometric mixtures of BaCO$_3$, Fe$_2$O$_3$, Co$_3$O$_4$, ZnO by solid state reaction method, and sintered at 1100 °C for 3 hours. The powder of these barium hexaferrite were prepared by SPEX M8000 high energy ball mill for 1 hour. Then, the magnetic powders were mixed with epoxy resin to be converted in to a microwave absorbing composite and placed on to a sample holder with width of 22.8 mm, height of 10.1 mm and thickness of 2.1 mm.

2.2. Characterizations

The powders of BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0; 0.2; 0.4; 0.6) were characterized using x-ray diffraction (XRD) Phillips Co-Kα with 40 kV and 30 mA and scanning electron microscopy FE-SEM FEI Inspect F50 for analyzing their structures and crystallite size. Hysteresis curves recorded by Permagraph techniques type Electromagnet EP 3 from magnet physik Dr. Steingroever GmbH with maximum external field of 1 tesla for magnetic properties analysis. The composite of BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0; 0.2; 0.4; 0.6) with epoxy resin were then measured using vector network analyzer (VNA) Keysight PNA-L N5232A to analyse microwave absorbing properties in the frequency range between 8.2 and 12.4 GHz (X-band). According to transmission line theory, reflection loss (RL) ability were calculated and simulated on the electromagnetic data through the NRW formula of following equations[12],[13].

\[
\text{Reflection Loss (dB)} = 20 \log \left( \frac{|Z - 1|}{|Z + 1|} \right)
\]

\[
Z = \sqrt{\mu/\varepsilon} \tanh \left( -j 2\pi f d/c \right) \sqrt{\mu/\varepsilon}
\]

According to the equation (1) and (2), Z is characteristic impedance of samples, ε is complex relative permittivity (ε = ε' - jε") and μ is complex relative permeability (μ = μ' - jμ"), f is frequency of the electromagnetic wave, c is the light velocity and d is the thickness of the samples.

3. Results and discussion

3.1. Crystal structure
The samples were characterized using x-ray diffraction (XRD) Phillips Co-Kα with 2θ interval 20–80° for analyzing the structure. Figure 1 shows XRD patterns of the BaFe_{12-2x}Co/ZnO_{19} powder, with various compositions of x (x = 0.0; 0.2; 0.4; 0.6). According to the reference pattern of international crystal diffraction data (ICDD) number #98-015-7056, the crystal structure of samples BaFe_{12-2x}Co/ZnO_{19} are polycrystalline with single phase. This indicates that Co and Zn ions have been successfully substituted for Fe ions. As seen from the figure 1, we observed ten peaks of the crystal orientations (hkl) of BaFe_{12-2x}Co/ZnO_{19} are (012), (008), (017), (114), (023), (025), (026), (127), (024), and (220). At the (hkl) of (017) and (114), clearly observed that the peaks of BaFe_{12-2x}Co/ZnO_{19} decrease by Co-Zn incorporations. We also observed there are change of lattice parameter of the BaFe_{12-2x}Co/ZnO_{19}. The changes in the lattice parameter can be caused Co - Zn substituted ions. By this substitution, cause strain of the crystal structure change. The value of lattice parameter can be seen in the table 1. It can be seen that the small lattice parameter values contribute to the decrease of the unit cell volume and its crystallite size. The crystallite size values of each peak from XRD patterns with different Full Width at Half Maximum (FWHM) of BaFe_{12-2x}Co/ZnO_{19} (x = 0.0; 0.2; 0.4; 0.6) can be calculated by using Scherer method (d = 0.9/λβcosθ) [14], where d is the crystallite size, λ is the wavelength of the CoKα radiation, θ is the diffraction angle, and β is FWHM of the peak. As seen from the table 2, the crystallite size of BaFe_{12-2x}Co/ZnO_{19} in the range of 35-50 nm. This result confirmed that the substitution of Co and Zn ions into BaFe_{12-2x}Co/ZnO_{19} structure affected crystallite size (Figure 1b).

Figure 2 shows the SEM photographs of barium hexaferrite BaFe_{12-2x}Co/ZnO_{19} (x = 0.0; 0.2; 0.4; 0.6) powders. It can be observed that the barium hexaferrite particles have irregular spherical shapes with the dimension less than 2 µm. The grains size of barium hexaferrite varied from 40 to 70 nm (table 2). The mean of crystalline size of magnetic particles from the line broadening of the XRD peaks as shown in table 2 was evaluated to be about 64.9 nm, 69.4 nm, 58.3 nm, and 44.9 nm for x = 0.0, x = 0.2, x = 0.4, and x = 0.6, respectively. From the above results (Figure 2a, 2b, 2c and 2d), we can investigate that the decreasing of particle size of barium hexaferrite linearly depend on Co-Zn incorporation. Furthermore, as seen from the SEM images, the particle size of BaFe_{12-2x}Co/ZnO_{19} powder for x = 0.0, x = 0.2, x = 0.4, and x = 0.6 in the range of 1.8-2.5 µm, 1.2-1.7 µm, 1.1-1.6 µm, 0.5-1.0 µm, respectively. The particle size of 460 nm is believed as single domain particle of barium hexaferrite [15]. Therefore, we predicted that, the BaFe_{12-2x}Co/ZnO_{19} with x = 0.6 has single domain particle. This is closely related to the domain wall motion resonance that depends on the grain size [15]. Meanwhile, spin rotation relaxation play important role in the high-frequency region of gigahertz, which is depend only on the grain size of samples. As results, the domain of wall motion resonance and also spin rotation relaxation is closely relates to the increased value of magnetic permeability associated with absorption ability of magnetic materials.

3.2. Magnetic Properties

Figure 3 shows the hysteresis loop of barium hexaferrite BaFe_{12-2x}Co/ZnO_{19} (x = 0.0; 0.2; 0.4; 0.6) as measured by a permagraph device under external field of 1 tesla. As can be observed from the figure, the magnetic saturation (Ms) and coercivity force (Hc) values, and magnetic remanence (Mr) tend to constant (see table 2). The values of the coercivity force was change for doped samples. It can be caused by substitution of Fe^{3+} ion by Co^{2+}, and Zn^{2+}. In undoped barium hexaferrite (about 229.9 kA/m), it has a high value of coercivity force which associated to the strong uniaxial anisotropy along the c-axis. The reduction of coercivity force (Hc) for doped barium hexaferrite (see table 2) is predicted due to the change of the easy axis of magnetization from the c-axis. This is because Fe^{3+} ions are located on the 4f sites. Furthermore, the substitution of Co-Zn ions on 4f sites affects the net magnetization.
3.3. Microwave Absorbing Properties

Absorbing materials are characterized by their electric permittivity and magnetic permeability. The complex relative permeability and permittivity are generally written as $\mu = \mu' - j\mu''$ and $\varepsilon = \varepsilon' - j\varepsilon''$, respectively [16],[17]–[23]. Figure 4 shows the value of the complex relative permeability and permittivity of barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ ($x=0.0; 0.2; 0.4; 0.6$) which are measured in the frequency range of 8.2–12.4 GHz using a vector network analyzer (VNA).

The real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the complex permittivity of barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ ($x=0.0; 0.2; 0.4; 0.6$) are shown in figure 4c and 4d. As seen from the figure, the $\varepsilon'$ and $\varepsilon''$ values of $x=0.4$ are larger than $x=0.0$, $x=0.2$, and $x=0.6$. The $\varepsilon'$ ($x=0.4$) value tends to be constant and there is polarization that occurs when given electromagnetic fields in the frequency range of 8.2–12.4 GHz. It’s indicate that barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for $x=0.4$ has ability to store the microwave energy. The $\varepsilon'$ for $x=0.2$ and $x=0.6$ tends to decrease with increasing frequency. However, for $x=0.2$ at the frequency of 11.64 GHz, the $\varepsilon'$ significantly increase. It is indicating that the ability to store microwave energy is optimum at 11.64 GHz. The imaginary ($\varepsilon''$) part of the complex relative permittivity of barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for $x=0.2; 0.4; 0.6$ exhibit fluctuation in frequency of 8.2–12.4 GHz and the $\varepsilon''$ values are less than zero in the range of 8.36–12.40 GHz, 8.20–10.21 GHz and 10.55–12.40 GHz for $x=0.2$, $x=0.4$ and $x=0.6$, respectively. These are indicating that no dissipation of the electromagnetic energy in the BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ so there is no loss of microwave energy [23].

The real ($\mu'$) and imaginary ($\mu''$) parts of complex relative permeability of barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ ($x=0.0; 0.2; 0.4; 0.6$) are shown in the figure 4a and 4b. As can be seen from the figure, the $\mu'$ ($x=0$ and $x=0.6$) values relatively constant in the range frequency of 8.2–12.4 GHz (Figure 4a). Moreover, the $\mu'$ ($x=0.6$) value is more than $\mu'$ ($x=0$). The $\mu'$ values show the decline tendency in the frequency of 10.97–11.98 GHz and 8.20–9.62 GHz for $x=0.2$ and $x=0.4$, respectively. Generally, $\mu''$ represents magnetic energy dissipation. The imaginary ($\mu''$) part of complex relative permeability of barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for $x=0.2; 0.4; 0.6$ also exhibit fluctuation in frequency of 10.21–12.40 GHz, 8.20–10.21 GHz and 10.55–12.40 GHz range for $x=0.2$, $x=0.4$ and $x=0.6$, respectively. These results indicate that the strong magnetic loss in the present samples[24].

One of parameter of absorbing material is the attenuation constant ($\alpha$). It’s correlate with the electromagnetic wave absorptin efficiency. Furthermore, the attenuation constant ($\alpha$) determines the dissipation properties of the absorbing materials[21]–[23].

$$\alpha = \sqrt{\frac{\pi f}{c}} \times x \sqrt{\left(\mu \varepsilon' - \mu' \varepsilon\right) + \sqrt{\left(\mu \varepsilon' - \mu' \varepsilon\right)^2 + \left(\mu \varepsilon'' + \mu' \varepsilon''\right)^2}} \tag{3}$$

where $f$ is the frequency and $c$ is the velocity of light.

The attenuation constant $\alpha$ of BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for $x=0.0; 0.2; 0.4; 0.6$ in the range frequency of 8.2–12.4 GHz can be seen in the figure 5. It can be observed that the $\alpha$ for $x=0.4$ has the largest attenuation constant amount of the four samples.

In order to analyze the microwave absorption properties, we have calculated the reflection loss (RL) according to the complex relative permeability ($\mu = \mu' - j\mu''$) and permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) with a given frequency ($f$) and sample thickness ($d$), through the following equation 1 and 2. The lower the RL value indicates the absorption abilities of microwave absorbing materials.

For magnetic materials, high permeability and high resonance frequency are both required to enhance microwave absorbing properties. The resonance frequency ($f_r$) and static permeability ($\mu_s$) of the
magnetic materials can be expressed by the equations: $2\pi f_i = \gamma H_a$ and $H_a = H_c = 0.64|K_1/M|$ [15].

where $\gamma = 2.8$ GHz kOe$^{-1}$ is the gyromagnetic ratio and $H_a$ is the crystalline anisotropic field, $H_c$ is coercivity force and $K_1$ is the crystalline anisotropic coefficient [22]–[25]. It is well known that undoped M-type barium hexaferrite have a resonance frequency of 50–60 GHz[29]. Therefore, $f_i$ can be shifted to a lower applicable frequencies ~ 8–13 GHz by substituting Fe$^{3+}$ with other metal ions.

In this study, the magnetic saturation ($M_s$) and coercivity force ($H_c$) of doped barium hexaferrite change (see figure 3) by Co-Zn incorporation. Substitution of Fe$^{3+}$ ion by Co$^{2+}$ and Zn$^{+}$ cause the values of coercivity force decreased and the magnetic saturation ($M_s$) increased. Therefore, the improved RL values of barium hexaferrite can be related to the enhancement of permeability and due to domain wall motion.

Figure 6 shows the RL curves of magnetic samples with a thickness of 1.0 mm. The BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.4) shows stronger microwave absorbing properties than the BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0, 0.2) and BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.6). The minimum RL of The BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.4) is -16.94 dB at 8.7 GHz. According to the equations 1 and 2, the various thickness of samples will affect the values of RL and the position of maximum absorption. Therefore, the reflection loss (RL) of the barium hexaferrite BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for x = 0.0; 0.2; 0.4; 0.6 samples are calculated with the different thicknesses. The minimum RL indicates the minimal reflection of the electromagnetic wave power for the particular thickness.

As seen in the figure 6, the BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0) at 12.4 GHz with the thickness layer of 3.0 mm has the minimum RL of -7.97 dB and 59.2% absorption. Meanwhile, the BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.2, 0.4, and 0.6) have the RL more than -10 dB, and 68.3% absorption. The minimum RL of -27.21 dB (95.6% absorption), for x = 0.2, -16.94 dB (85.7% absorption) for x = 0.4 and -29.98 dB (96.8% absorption) for x = 0.6 are resulted at 11.05 GHz for 1.5 mm thickness, 8.7 GHz for 1.0 mm thickness and 10.8 GHz for 1.0 mm thickness, respectively. Nevertheless, according to the attenuation constant $\alpha$ as shown in the figure 5, the $\alpha$ (x=0.4) value has the largest absorption abilities of microwave absorbing materials. Therefore, three-dimensional (3D) image of barium hexaferrite (x = 0.4) with the thickness in the range of 1.0–3.0 mm are depicted in figure 7.

Figure 8 shows the illustration of microwave absorption mechanism of the barium hexaferrite. It can be explain that first, the magnetic particles which consists of nano-grains cause the production of microwave multiple reflection and scattering[13][14]. The interaction between microwave and particles (with $\mu$ and $\varepsilon$) attenuated microwave energy. Second, the charged particles accumulation polarized magnetically and electrically due to external electromagnetic wave.

4. Conclusions

We have synthesized barium hexaferrite BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.0; 0.2; 0.4; 0.6) nanocrystalline prepared using solid state reaction method and characterized. The powder of these ferrites were resulted by high energy ball mill for 1 hour and mixed with epoxy resin to be converted into a microwave absorbing composite. According to the characterization results, the barium hexaferrite structures for Ba(Fe$_{12}$Co$_x$Zn$_x$)$_{12}$O$_{19}$ have polycrystalline structure. The coercive force (Hc) decreases rapidly with the substitution of Co and Zn in the structure of Ba(Fe$_{12}$Co$_x$Zn$_x$)$_{12}$O$_{19}$. It’s indicate that the Co-Zn in the structure of Ba(Fe$_{12}$Co$_x$Zn$_x$)$_{12}$O$_{19}$ contributes to magnetic and microwave absorption properties. The minimum reflection loss value of -29.98 dB was observed at 10.8 GHz with a matching thickness of 1 mm for BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ (x = 0.6) nanocrystalline. As conclusion the magnetic absorbing properties improve significantly by Co-Zn incorporation.

Acknowledgment

Financial support from hibah PTUPT Kemenristek-dikti 2018 is gratefully acknowledged.
References


Table captions

Table 1. The lattice parameter and average crystallite size of barium hexaferrites $\text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19}$ ($x = 0.0; 0.2; 0.4; 0.6$)

Table 2. Peak position and crystallite size of barium hexaferrites $\text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19}$ ($x = 0.0; 0.2; 0.4; 0.6$)

Table 3. Magnetic values of barium hexaferrites $\text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19}$ ($x = 0.0; 0.2; 0.4; 0.6$)
Figure captions

Figure 1. XRD pattern (a) and crystallite size (b) of barium hexaferrites \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) \( (x = 0.0; 0.2; 0.4; 0.6) \)

Figure 2. The SEM photographs of barium hexaferrites \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) \( x = 0.0 \) (a); 0.2 (b); 0.4 (c); 0.6 (d)

Figure 3. Room temperature hysteresis loops of \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) \( x = 0.0; 0.2; 0.4; 0.6 \) nanocrystalline.

Figure 4. The (a) real and (b) imaginary parts of complex permeability and the (c) real and (d) imaginary parts of complex permittivity for barium hexaferrites \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) \( x = 0.0; 0.2; 0.4; 0.6 \)

Figure 5. Attenuation constant versus frequency of the barium hexaferrite \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) for \( x = 0.0; 0.2; 0.4; 0.6 \).

Figure 6. Absorption characteristics of barium hexaferrite \( \text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19} \) for (a) \( x = 0.0 \), (b) \( x = 0.2 \), (c) \( x = 0.4 \), (d) \( x = 0.6 \).

Figure 7. Three-dimensional representation of RL values for \( x = 0.4 \) of the barium hexaferrite.

Figure 8. Microwave absorption mechanism of the barium hexaferrite
Table 1. The lattice parameter and average crystallite size of barium hexaferrites BaFe_{12-2x}Co_{x}Zn_{x}O_{19} (x = 0.0; 0.2; 0.4; 0.6)

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Table 2. Peak position and crystallite size of barium hexaferrites BaFe_{12-2x}Co_{x}Zn_{x}O_{19} (x = 0.0; 0.2; 0.4; 0.6)

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Table 3. Magnetic values of barium hexaferrites BaFe_{12-2x}Co_{x}Zn_{x}O_{19} (x = 0.0; 0.2; 0.4; 0.6)

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<tr>
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<th>M_r (T)</th>
<th>H_c (kA/m)</th>
<th>M_s (T)</th>
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Fig. 1. XRD pattern (a) and crystallite size (b) of barium hexaferrites BaFe_{12-2x}Co_xZn_xO_{19} (x = 0.0; 0.2; 0.4; 0.6)
Fig. 2. The SEM photographs of barium hexaferrites $\text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19}$ $x = 0.0$ (a); 0.2 (b); 0.4 (c); 0.6 (d)

Fig. 3. Room temperature hysteresis loops of $\text{BaFe}_{12-2x}\text{Co}_x\text{Zn}_x\text{O}_{19}$ ($x = 0.0; 0.2; 0.4; 0.6$) nanocrystalline.
Fig. 4. The (a) real and (b) imaginary parts of complex permeability and the (c) real and (d) imaginary parts of complex permittivity for barium hexaferrites BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ ($x = 0.0; 0.2; 0.4; 0.6$)
Fig. 5. Attenuation constant versus frequency of the barium hexaferrite BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for $x = 0.0$; $0.2$; $0.4$; $0.6$.

Fig. 6. Absorption characteristics of barium hexaferrite BaFe$_{12-2x}$Co$_x$Zn$_x$O$_{19}$ for (a) $x = 0.0$, (b) $x = 0.2$, (c) $x = 0.4$, (d) $x = 0.6$. 
Fig. 7. Three-dimensional representation of RL values for $x = 0.4$ of the barium hexaferrite

Fig. 8. Microwave absorption mechanism of the barium hexaferrite