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The effect of thickness on microwave absorbing properties of barium ferrite powder

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Abstract. We have investigated the effect of thickness on microwave absorbing properties of barium ferrite (BaFe12O19) powder prepared by a solid-state reaction method with a sintering temperature of 1100°C for 5 hours. The sample was analyzed using XRD, SEM, PERMAGRAPH, and vector network analyzer (VNA). The microwave absorbing properties were measured at the frequency in the range of 8.2 – 12.4 GHz. Permeability, permittivity and reflection loss (RL) were calculated at a given thickness based on transmit line theory. The results show the optimal RL of −23.07 dB can be obtained at 10.72 GHz with a thickness of 3.0 mm, bandwidth with RL less than −5 dB and −10 dB can reach 1.2 GHz (10.4–11.6 GHz) and 0.8 GHz (10.6–11.4 GHz), respectively.

1. Introduction

Recently, the microwave absorbing materials have been used in military purposes such as radar-absorbing material (RAM), stealth technology, telecommunication for wireless system and electromagnetic interference (EMI) absorbers [1-2]. The two important things required as microwave absorbing materials are impedance and ability to reduce the incident electromagnetic (EM) wave. The value of the intrinsic impedance of material should be close to the intrinsic impedance of free space. Thus, it is necessary to make the value of magnetic permeability similar to the electrical permittivity [3]. Moreover, the reflection loss (RL) with different sample thicknesses can be calculated to evaluate EM absorption abilities of an absorber [4]. In EM wave absorber technology, barium ferrite (BaFe12O19) has large values of permeability, high resistivity, good magnetic and dielectric properties at microwave frequencies that are suitable and as one of the potential candidates for microwave absorbing materials [5]. The exploration of barium ferrite as a microwave absorber material has stimulated a lot of inventions. However, barium ferrite (BaFe12O19) composition does not work quite well in the giga-hertz frequency range which is known as snoek’s limit [6-8].

In this paper, the effect of layer thickness on microwave absorbing properties of barium ferrite (BaFe12O19) was investigated. The thickness variations to reflection loss (RL) in the frequency range from 8.2 to 12.4 GHz from BaFe12O19 was calculated using the transmit line theory [4-9]. Furthermore, structure and magnetic properties investigation of the BaFe12O19 are also discussed.
2. Experimental
2.1. Materials and synthesis
Barium ferrite was synthesized through a solid-state method using BaCO$_3$ and Fe$_2$O$_3$ as precursors. The mixtures of BaCO$_3$ and Fe$_2$O$_3$ were pulverized by high energy ball mill for 1 hour and pelletized under a pressure of 5 MP to increase the hardness of barium hexaferrite. Furthermore, the mixture was sintered in a furnace at 1100°C for 5 hours. Finally, sintered barium ferrite was crushed for 1 hour to obtain magnetic powders.

2.2. Characterization
Crystal structure identification of barium ferrite (BaFe$_{12}$O$_{19}$) powder was characterized by PANalytical X-ray diffractometer (XRD) using CuKα radiation (λ =1.5418 Å) in the range of 2θ = 20°–70°. scanning electron microscopy (SEM) SEC type SNE4500 M examination was used for analyzing the morphological structure of magnetic powders. Hysteresis loop for magnetic properties was recorded using PERMAGRAPH techniques type Electromagnet EP 3 from magnet physic Dr.Steingroever GmbH and measured at room temperature with an applied field up to 1 tesla. Keysight PNA-L N5232A vector network analyzer (VNA) was used to analyze microwave absorbing properties for X-band (8.2–12.4 GHz) frequencies. The magnetic powders of barium ferrite were mixed with epoxy resin to be converted into a microwave absorbing composite. The mixing weight ratio of ferrite to epoxy resin was 4:1 and placed in a sample holder with a dimension of width 22.86 mm and height 10.16 mm. The reflection (S$_{11}$) and complex transmission (S$_{21}$) coefficients were measured with VNA. To obtain relative complex permeability ($\mu = \mu' - j\mu''$) and permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of barium ferrite (BaFe$_{12}$O$_{19}$), coefficients were used in the Nicolson-Ross-Weir (NRW) algorithm with a thickness of 5 mm [10]. Reflection loss (RL) was calculated using the transmit line theory by the following equations:

$$RL \ (dB) = 20 \ \log \left( \frac{|Z - 1|}{|Z + 1|} \right)$$  
$$Z = \sqrt{\frac{\mu}{\varepsilon}} \ \tanh \left( \frac{-j2\pi fd}{c} \right) \sqrt{\mu_0 \varepsilon_0}$$

According to these equations, relative complex permeability ($\mu = \mu' - j\mu''$) and complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$), f is frequency and d is the thickness of barium ferrite (BaFe$_{12}$O$_{19}$), and c is the light velocity.

3. Results and discussion
3.1. Structure identification
Figure 1 shows the XRD pattern of barium ferrite (BaFe$_{12}$O$_{19}$) powder sintered at 1100°C for 5 hours. Base on XRD pattern, a barium ferrite has successfully formed a single phase with polycrystalline structure. The calculation result using High Score Plus software shows that lattice constant value is $a = b = 5.8882$ Å and $c = 23.1988$ Å. The results are not much different from the indicated literature that is $a = b = 5.8920$ Å and $c = 23.1830$ Å (International Centre for Diffraction Data, ICDD no. 00-084-0757). The result proves that the formation temperature of barium ferrite is about 100°C lower than as indicated in the literature [11].
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3.2. Morphology
SEM micrograph of the barium ferrite is shown in figure 2. After milling, the powder of sintered sample is relatively the same in size. The average of powder size is less than about 10 μm. Therefore, the powder of barium ferrite is suitable to be mixed with epoxy resin for preparation a microwave absorbing material.

Figure 2. The SEM of morphological structure of barium ferrite (BaFe$_{12}$O$_{19}$).

3.3. Magnetic and dielectric properties
Figure 3 shows hysteresis loop of barium ferrite (BaFe$_{12}$O$_{19}$) at room temperature. The values of residual magnetization ($M_r$) at 0.213 T, is coercive field ($H_c$) 235.5 kA/m and saturation magnetization ($M_s$) 0.371 T. The results of magnetic properties indicate a good correlation between the magnetic properties and structural. A high $H_c$ for sample (about 235.5 kA/m) is caused by strong uni-axial anisotropy along the c-axis. The result confirms that the barium ferrite powder is a permanent magnet.

Figure 1. XRD patterns of barium ferrite (BaFe$_{12}$O$_{19}$).
Figure 3. Room temperature hysteresis loop of barium ferrite (BaFe$_{12}$O$_{19}$).

Figure 4(a) shows the real ($\mu'$) and imaginary ($\mu''$) parts of relative complex permeability while figure 4(b) shows the real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of permittivity at the frequency range of 8.2–12.4 GHz of barium ferrite. The relative complex permeability ($\mu = \mu' - j\mu''$) and permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) determine the microwave absorbing properties of the absorbing materials. The real ($\mu'$) and imaginary ($\mu''$) permeability symbolize the storage and the attenuation abilities of magnetic energy, respectively. While the real ($\varepsilon'$) stands for the storage ability and imaginary ($\varepsilon''$) permittivity represents dissipation ability of electric energy [4, 12-14]. According to the relative complex permeability and permittivity of the sample, a microwave absorbing properties can be estimated. As shown in Fig. 4a, the value of $\mu'$ and $\mu''$ are in the range of 0.85–1.02 and 0.01–0.12, respectively. The values of $\mu'$ and $\mu''$ with increasing frequency decreases in the range of about 8.75–9.25 GHz and 9–9.75 GHz, respectively. On the other hand, the value of $\mu'$ and $\mu''$ increases in the range of about 9.25–10.25 GHz and 8.2–9 GHz. The changes of the magnetic tangent loss of barium ferrite indicate that the sample has a magnetic loss to electromagnetic waves in some degree. Figure 4(b) shows the value of $\varepsilon'$ and $\varepsilon''$ in range 4.15–4.42 and 0.08–0.42, respectively. According to the results, it suggests that barium ferrite has good absorption properties due to the magnetic loss and the dielectric loss [15].

Figure 4. (a) The Real ($\mu'$), (b) imaginary ($\mu''$) parts of relative complex permeability, (c) the real ($\varepsilon'$) and (d) imaginary ($\varepsilon''$) parts of permittivity of barium ferrite (BaFe$_{12}$O$_{19}$).
3.4. Microwave absorbing properties

The reflection loss (RL) values of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) were calculated using the transmit line theory by the following equations 1 and 2 based on the real ($\mu'$) and imaginary ($\mu''$) parts of relative complex permeability and the real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of permittivity are shown in figure 4. The figure 5(a) shows RL values of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) at different thickness 0.2 mm, 0.5 mm, 1.0 mm, 2.0 mm and 3.0 mm. It is found that the minimum RL value in barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) is influenced by thickness of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) as shown in table 1.

The microwave absorbing properties of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) were exhibited in figure 5(a). The optimal RL of −23.07 dB can be obtained at 10.72 GHz with thin thickness of 3.0 mm, bandwidth with RL less than −5 dB and −10 dB can reach 1.2 GHz (10.4–11.6 GHz) and 0.8 GHz (10.6–11.4 GHz), respectively. Table 1 shows the electromagnetic absorption properties of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}). It can be found that the thickness of sample is useful for the enhancement of the electromagnetic absorption. The enhanced absorption properties were attributed to the two-dimensional contour (see figure 5(b)) and more interfacial polarization relaxation. The results indicate that a thicker absorber layer has a wider frequency bandwidth.

**Table 1. Electromagnetic Absorption Properties of barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}).**

<table>
<thead>
<tr>
<th>Sample thickness (mm)</th>
<th>Minimum RL (EMI value) (dB)</th>
<th>Frequency range (GHz) (RL &lt; −5 dB)</th>
<th>Effective bandwidth (GHz) (RL &lt; −5 dB)</th>
<th>Frequency range (GHz) (RL &lt; −10 dB)</th>
<th>Effective bandwidth (GHz) (RL &lt; −10 dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>-0.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.5</td>
<td>-3.15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.0</td>
<td>-3.28</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>-3.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>-19.08</td>
<td>8.6–9.5</td>
<td>0.9</td>
<td>8.7–9.2</td>
<td>0.5</td>
</tr>
<tr>
<td>3.0</td>
<td>-12.81</td>
<td>8.5–9.4</td>
<td>0.9</td>
<td>8.9–9.3</td>
<td>0.4</td>
</tr>
<tr>
<td>3.0</td>
<td>-23.07</td>
<td>10.4–11.6</td>
<td>0.8</td>
<td>10.6–11.4</td>
<td>0.8</td>
</tr>
<tr>
<td>3.0</td>
<td>-14.82</td>
<td>10.4–11.6</td>
<td>1.2</td>
<td>10.6–11.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Figure 5.** (a) Reflection loss and (b) two-dimensional contour of the simulated RL values barium ferrite (BaFe\textsubscript{12}O\textsubscript{19}) different thicknesses.
4. Conclusions
Barium ferrite (BaFe$_{12}$O$_{19}$) have been prepared using BaCO$_3$ and Fe$_2$O$_3$ as precursors by solid-state method. XRD characterization shows that barium ferrite phase has successfully formed as a single phase of polycrystalline structure after sintering at 1100°C for 5 hours. SEM measurement shows morphological structure of the powders with relatively same in size less than 10 µm. Magnetic properties show that the sample has a high H$_c$ and as permanent magnet barium ferrite. According to VNA measurement, the real ($\mu'$) and imaginary ($\mu''$) parts of permeability and the real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of permittivity of the magnetic powders of barium ferrite vary at the frequency range of 8.2–12.4 GHz. The optimal RL of −23.07 dB can be obtained at 10.72 GHz with thickness of 3.0 mm.

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