Complex permeability, permittivity and microwave absorption properties of barium hexaferrite synthesized from natural iron sand

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Abstract. In this paper, the barium hexaferrite was successfully prepared by a conventional ceramic method and the precursors of BaCO3 and natural iron sand from Puger Beach, Jawa Timur-Indonesia. To develop a microwave absorbing material, the complex permeability, permittivity, and microwave absorption ability were investigated using a vector network analyzer (VNA) in the frequency range of 8.2–12.4 GHz. The results showed that barium hexaferrite presented an excellent broadband absorption (>90%, RL <-10dB) and a suitable absorber with high broad bandwidth and attenuation in the microwave frequency range.

1. Introduction
Barium hexaferrite is one of the typical permanent magnets that have high saturation magnetization and curie temperature [1-6]. High saturation magnetization is important for a good microwave absorbing material. As we know, barium hexaferrite also has the complex permeability ($\mu = \mu' - j\mu''$) and permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$), which play an important role in determining the microwave absorbing abilities of the magnetic materials [5,7,8]. Therefore, according to the reported literature, magnetic materials with excellent absorbing properties should have high the real part $\mu'$ and the imaginary part $\mu''$ of the permeability, small real part $\varepsilon'$ and large imaginary part $\varepsilon''$ of permittivity at microwave frequency [9]. Some considerations are necessary for microwave absorbing material, such as small thickness, low density, high mechanical strength, good chemically stability, easy preparation, and low cost. Hence, barium hexaferrite is promising for the development of microwave absorbers [2,6,10,11].

Some research works on barium hexaferrite as microwave absorbers have been reported in many papers. $\text{BaFe}_{12}\text{O}_{19}$ substituted with $\text{Cu}^{2+}-\text{Ti}^{4+}$ and $\text{Zn}^{2+}-\text{Ti}^{4+}$ showed the highest reflection losses (RL) of −34 dB at 10 GHz [12]. The $\text{BaFe}_{11.8}\text{Mg}_{0.1}\text{Al}_{0.1}\text{O}_{19}$ produced an optimal RL of −63.85 dB at a frequency of 10.90 GHz [13]. The nanosized barium ferrite particles reached the RL of −30 dB and the
bandwidth of 11.2 GHz [14]. Barium hexaferrite/silica composite resulted in an optimum RL (less than –15 dB) in the frequency range of 9–12.4 GHz [15]. furthermore, the raw materials play an important role in preparing and synthesizing the microwave absorbing materials. Therefore, this work is to synthesize M-type barium hexaferrite BaFe_{12}O_{19} by using natural iron sand as a precursor material. The microwave absorption properties of barium hexaferrite are reported in detail.

2. Experimental methods

2.1. Materials and preparation
M-type barium hexaferrite BaFe_{12}O_{19} samples were prepared by a conventional ceramic method. The natural iron sand that consists of Fe_{3}O_{4} as main content was milled by vibration ball mill for 1 hour and separated with permanent magnet for collecting Fe_{3}O_{4} powders. The mixtures of BaCO_{3} (99.9 % pure, Merck) and Fe_{3}O_{4} had been sintered for the formation of the BaFe_{12}O_{19} phase at 1100 °C for 5 hours.

2.2. Characterizations
The microwave absorption properties were investigated by using the vector network analyzer (VNA) system Keysight PNA-L N5232A in the frequency range of 8.2 − 12.4 GHz. The WR 90 sample holder was used to measure the complex permeability, permittivity, and reflection loss (RL) in (dB) versus frequency. The complex permeability and permittivity were calculated by using the Agilent Technologies Materials Measurement software with the S-parameters (S_{21} and S_{11}) as input datasets.

The RL values were investigated by calculating through the equations
\[
RL (\text{dB}) = 20 \log \left[ \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right]
\]
and
\[
Z_{in} = Z_0 \frac{\mu}{\varepsilon} \tanh \left( \frac{-j2\pi f d}{c} \right) \sqrt{\mu\varepsilon},
\]
where Z_{0}, Z_{in}, f, c, \mu, \varepsilon and d are the impedance of free space, input impedance, measured frequency, the velocity of EM waves in free space, complex permeability, complex permittivity, and thickness of barium hexaferrite, respectively [16,17].

3. Results and discussion

3.1. Complex permeability and permittivity
The real and imaginary values of the complex permeability and permittivity curves in the range from 8.2 GHz to 12.4 GHz are shown in Fig. 1a. The real part of permittivity (\varepsilon') remains almost constant in the frequency range of 8.2 − 10.5 GHz. While for the imaginary part of permittivity (\varepsilon'') and permeability (\mu'') tend to increase, and the real part of permeability (\mu') slightly decreased over the whole frequency range. Furthermore, the average value for the real and imaginary parts of permeability and the imaginary part of permittivity (\varepsilon'') of the sample is high.

![Image](image_url)

**Figure 1.** (a) Real and imaginary parts of the complex permeability and permittivity and (b) the dielectric (tan \(\delta_E = \varepsilon''/\varepsilon'\)) and magnetic loss tangent (tan \(\delta_M = \mu''/\mu'\)) of barium hexaferrat
Based on the datasets in Fig. 1a, we calculate the dielectric and magnetic tangent losses that represent electromagnetic loss capacity. The calculated results are shown in Fig. 1b. Therefore, the complex permeability and permittivity are the essential parameters that were used to determine the excellent microwave absorption properties of the microwave absorbers [18]. It can also be showed that the sample exhibits higher magnetic loss than dielectric loss with the increase of frequency. It presents that the magnetic loss plays a crucial role in the microwave absorption in the whole frequency range, which indicates that the barium hexaferrite has potential microwave attenuation capabilities.

3.2. Microwave absorption properties
To find the microwave absorption properties of barium hexaferrite in this work, we calculate the reflection loss (RL) in decibels (dB) using some variables of the $Z_{\text{in}}$, $Z_{\text{out}}$, $f$, $c$, $\mu$, $\varepsilon$ and $d$. Fig. 2 shows the RL curves of barium hexaferrite with various thicknesses (0.150, 0.155, 0.160, 0.165, 0.170, 0.175, 0.180 and 0.185 mm). According to the resulted RL values with different thicknesses, it can be noticed in Fig. 2a that the absorption enhances with increasing the sample thickness up to 0.175 mm. The results showed that the RL valued less than −20 dB (99% absorption) and was obtained in the frequency range of 9.12–10.97 GHz, 9.0–10.97 GHz, 8.95–10.97 GHz, 8.87–10.46 GHz, 8.78–10.46 GHz, 8.70–10.46 GHz, 8.62–10.46 GHz, 8.53–10.38 GHz for 0.150, 0.155, 0.160, 0.165, 0.170, 0.175, 0.180 and 0.185 mm thickness, respectively. The results also showed maximum broadband with RL values less than −10 dB (90% absorption) in the whole frequency range and all thicknesses of the sample (see Fig. 2b).

![Figure 2](image)

**Figure 2.** (a) The reflection loss and (b) a three-dimensional (3D) RL image map of barium hexaferrite with different thicknesses in the frequency range of 8.2–12.4 GHz.

4. Conclusions
Barium hexaferrite BaFe$_{12}$O$_{19}$ samples were successfully prepared by a conventional ceramic method with using BaCO$_3$ and Fe$_3$O$_4$ from the separated natural iron sand. The microwave absorption properties resulted in higher magnetic loss than the dielectric loss in the microwave frequency range. The resulted RL values of the sample presented a proper broadband absorption (>90%, RL <−10dB) in the frequency range of 8.2 – 12.4 GHz. Therefore, barium hexaferrite BaFe$_{12}$O$_{19}$ is a suitable absorber with high broadband and attenuation at microwave frequencies.

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