Effect of temperature on magnetic and dielectric properties of Mg-Cd-Ga ferrites for high-frequency-range antennas

Gongwen Gan, Dainan Zhang*, Jie Li, Gang Wang, Yan Yang, Xueying Wang, Huaiwu Zhang
State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu, 610054, Chengdu, China

*Corresponding author e-mail: gangongwen@gmail.com

Abstract. Mg ferrites with magnetic and dielectric properties are widely used composites to stabilize spinel structure. This study investigates the effect of sintering temperature (900°C, 915°C, 930°C, 945°C, 960°C) on the magnetic and dielectric properties and low-loss characteristics of Mg0.7Cd0.3Fe1.92Ga0.08O4 composites with 5 wt.% Bi2O3 additive. The change in temperature enhances magnetization (saturation magnetization Ms from 24.37 emu/g to 33.12 emu/g), hence increasing permeability. The real permeability (μ’) of Mg-Cd-Ga ferrites was examined to be monotonically increasing from 15 H/m to 19 H/m. And the real part of permittivity (ε’) was fine-tuned by increasing temperature. As a result, at 920°C, μ’ and ε’ are closely equivalent ranging from 1 MHz to, this characteristics can be used for miniaturization and good radiation behaviors antennas. In addition, very low magnetic (tanδμ~3*10⁻²) and dielectric (tanδε~5*10⁻³) tangent enable excellent radiation efficiency at operation.

1. Introduction
Wing-footed progress of modern wireless communication makes more demands of high speed and high performance for transmitting and receiving antennas working from HF (3-30 MHz) to VHF (300MHz) [1] [2] [3] [4]. In addition, miniaturization is another factor that should be taken into consideration, comparing to conventional antennas with both large physical and relatively bad radiation efficiency [5]. Based on these requirements, to explore how to achieve miniaturization and good radiation behaviors of those antennas is being widely researched. In general, one method to realizing miniaturization is to reduce the sizes of substrates and radiation unit simultaneously by tailoring the intrinsic properties of such materials [6] [7] [8] [9]. Hence, it is vital to improve the properties of substrate materials. To improve dielectric constant of materials is a favorable way. However, surface wave will be excited and trapped into the substrates, as a result, mutual coupling between arrays will deteriorate radiation performance [10]. On this condition, the appearance of dielectric materials with magnetic properties is a favorable way because of two factors. One is the existence of magnetization can eliminate surface wave and realizing miniaturization, as the below equation describes [11]:

\[ l = \frac{C}{22f\sqrt{\mu\varepsilon}} \] (1)
In which \( l \) is patch size in patch antennas. \( C \) is velocity of light, \( f_r \) is resonance frequency. \( \mu \) and \( \varepsilon \) are real parts of permeability and permittivity of substrate materials. Another is that \( \mu \) and \( \varepsilon \) are in close relationship to the bandwidth (\( BW \)) of an antenna, according to the equation [12]:

\[
BW \approx \frac{96h}{\sqrt{2\lambda(4+17\mu\varepsilon)}} = \frac{96h}{\sqrt{2\lambda(4+17\mu\varepsilon})}
\]  

(2)

Where \( \lambda \) is wavelength and \( h \) are the substrate thickness. It illustrates that \( BW \) is mainly determined by \( \mu \) over \( \varepsilon \). So matching impedance between antennas and propagating medium would be inevitable on account of the intrinsic impedance (\( Z \)) of antenna substrate is derived from the following equation [13]:

\[
Z = \eta_0 \frac{\mu}{\varepsilon} = \eta_0 \sqrt{\frac{\mu}{\varepsilon}}
\]  

(3)

Here, \( \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \) is intrinsic impedance of propagating medium. Herein, if \( \mu \) exceeds \( \varepsilon \) by too much, \( Z \) will be mismatching from \( \eta_0 \). As a result, modest quotient of \( \mu \) and \( \varepsilon \) should be design to make a trade-off between wide bandwidth and low reflection loss. However, to obtain such materials is hard. Many researches have been performed for this purpose. V.G. Harris and his group researched Co–Ti substituted low loss M-type hexaferrite composites with tailored magnetic and dielectric properties, then equal \( \mu' \) and \( \varepsilon' \) were obtained [14]. A. Saini et al. put forward ceramic ferrites with equal \( \mu' \) and \( \varepsilon' \) by using Ni0.5Zn0.3Co0.2Fe2O4 and BaFe12O19 composition, a decrease in reflection loss (-35 dB to -28 dB) and an increase in bandwidth (1.6 %–6 %) were achieved [15].

Mg-based ceramic ferrites having mixed spinel structure with admirable magnetic and dielectric behaviors are proposed for antenna substrate application, due to the magnetic and dielectric properties are tunable by changing the cations, i.e. some concentration of Mg\(^{2+}\) and Fe\(^{3+}\) cations being substituted by other cations, (Cd\(^{2+}\), Cu\(^{2+}\), Ga\(^{3+}\), Sm\(^{3+}\), and Co\(^{3+}\) [16]. Generally, in Mg ferrites, Mg/Fe cations distribute at both the tetrahedral (A) and octahedral (B) site, the proportion of Mg/Fe cations at some site depend on experimental purpose and condition [17], in special, the substituted cations that tailor magnetic and dielectric properties through changing the interactions between A-site and B-site, i.e., Fe\(^{3+}\)(B)–O–Fe\(^{3+}\)(A), Fe\(^{3+}\)(B)–O–Mg\(^{2+}\)(B), Fe\(^{3+}\)(A)–O–Mg\(^{2+}\)(B), Fe\(^{3+}\)(B)–O–Fe\(^{3+}\)(B) and Fe\(^{3+}\)(B)–O–Mg\(^{2+}\)(A) [18].

The objective of this research is investigating the effect of sintering temperature on Mg-Cd-Ga ferrites with small amount of Bi\(_2\)O\(_3\) for the application of antenna substrates. In specific, spinel Mg\(_{0.7}\)Cd\(_{0.3}\)Fe\(_{1.92}\)Ga\(_{0.08}\)O\(_4\) ferrites sintered at various temperature points (900℃, 915℃, 930℃, 945℃, 960℃) are proposed with 5 wt.% Bi\(_2\)O\(_3\) addictive to realize the proper magnetic and dielectric properties.

2. Experimental

Spinel Mg\(_{0.7}\)Cd\(_{0.3}\)Fe\(_{1.92}\)Ga\(_{0.08}\)O\(_4\) ferrites were synthesized using the conventional solid-state reaction technology. The original oxidates powders MgO (AR grade, ≥99%), CdO (AR grade, ≥99%), Ga\(_2\)O\(_3\) (AR grade, ≥99%) and Fe\(_2\)O\(_3\) (AR grade, ≥99%) were calculated and then weighed in a stoichiometric proportion. They were then mixed and ball milled in a planetary ball mill for 10 h. The mixtures were desiccated and pre-sintered at 1100℃ for 6 h in a muffle furnace for the formation of initial phase. The pre-sintered powders were then milled for 10 h with 5 wt.% Bi\(_2\)O\(_3\) added. The mixtures were dried and prilled by adding 10 wt.% polyvinyl alcohol (PVA). Then the prilled particles were pressed to slices, and thick rings in a fixed size by applying pressure of 10 MPa. Finally, the massive materials were calcined at 900℃, 915℃, 930℃, 945℃, 960℃ for 6 h.

The crystal phase was measured by X-ray diffraction (DX-2700, Haoyuan Co.) with CuKa radiation (\( \lambda=1.54059 \) Å) at a 0-20 geometric angle range of 10° to 80°, using a scanning speed of 0.3°/min and an
angle step of 0.05°/s. Bulk density was detected by applying an auto density tester (GF-300D, AND Co.) using Archimedes’ principle. Microstructure of all ferrites were taken employing a scanning electron microscopy, (JEOL, JSM-6490). Complex permeability and permittivity were measured by a HP-42391B RF impedance analyzer with the frequency ranging from 1 MHz to 1.5 GHz. The magnetic hysteresis loop of the synthesized ferrites was recorded employing a vibrating sample magnetometer (VSM), (MODEL, BHL-525).

3. Results and discussion
A The structural details including crystalline phase, cell parameters and strain of processed samples are characterized by X-ray diffraction. The XRD patterns for all samples are shown in Figure 1. It shows that all the samples crystalline with multiphase including the main phase indexed to MgFe₂O₄ peaks having the diffraction reference of the JCPDS card No. 22-1086 [19] and a second phase of Bi₂₄Fe₂O₃₉ (BFO) peaks with relatively low intensity peaks indexed to JCPDS card No. 42-0201. It indicates that the dielectric BFO is from Bi³⁺ and dissociative Fe³⁺ [20]. Generally, the whole phases indicate that the needed samples with magnetic and dielectric properties are obtained. Additionally, all the peaks in the XRD patterns are observed to slightly shift towards higher 2θ angle with increasing temperature, as shown with the enlarged scope of the most intense peaks around 30° of MgFe₂O₄ peak in Figure 1 (b). It means that higher temperature results in smaller lattice constant [21], which is calculated by the following equation [11]:

\[ a = d_{hkl}(h^2+k^2+l^2)\]

Where \( h, k, l \) are the Miller indices of the planes with inter-planar spacing \( 'd_{hkl}' \). Then the crystallite size \( (D) \) of the ferrites is calculated by the Debye-Scherrer relationship [11]:

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]

In which \( \lambda \) is the X-ray wavelength, \( \theta \) is the Bragg’s angle, \( \beta \) is the radiation full width at half maximum. According to this equation, the calculated crystallite size is also listed in Table 1.

![Figure 1](https://example.com/figure1.png)

Figure 1. XRD patterns of Mg₀.₇Cd₀.₃Fe₁.₉₂Ga₀.₀₈O₄ samples sintered at various temperatures.

Structural parameters including lattice constant, calculated theoretical density (TD) and measured density (ED) shown in Table I, it can be observed that good matching between the theoretical and experimental results. For as-prepared Mg-Ga-Cd ferrites, it is found that lattice constant increases with increasing temperature as shown with the change of lattice constant and relative density (RD) with
increasing temperature in Figure 2. It shows monotonically increasing trend for TD and ED of the samples with increasing temperature. It is attributed to the positive relationship between density and lattice constant. At the same time, the RD can be derived from the TD and ED using the equation:

\[ RD = \frac{ED}{TD} \]

From the results, it is found that the observed RD keeps over than 91%, meaning that the ferrites were fabricated with proper densification.

**Table 1.** Effect of sintering temperature on structural parameters in Mg\(_{0.7}\)Cd\(_{0.3}\)Fe\(_{1.92}\)Ga\(_{0.08}\)O\(_4\) composites.

| Temperature (℃) | Lattice constant (Å) | Theoretical density (g/cm\(^3\)) | Experimental density (g/cm\(^3\)) |
|-----------------|----------------------|---------------------------------|---------------------------------|
| 900             | 8.3352               | 4.795                           | 4.471                           |
| 920             | 8.3637               | 4.832                           | 4.536                           |
| 940             | 8.4232               | 4.865                           | 4.579                           |
| 960             | 8.4591               | 4.968                           | 4.721                           |

**Figure 2.** Variation of lattice constant and relative density of Mg\(_{0.7}\)Cd\(_{0.3}\)Fe\(_{1.92}\)Ga\(_{0.08}\)O\(_4\) ferrites sintered at different temperatures.

For the sake of understanding the influence of various sintering temperatures on the microstructure especially particle sizes and densification of Mg\(_{0.7}\)Cd\(_{0.3}\)Fe\(_{1.92}\)Ga\(_{0.08}\)O\(_4\) ferrites, SEM images are studied, as shown in Figure 3. It illustrates that particle size increases with increasing temperature, and the average grain size ranges from 0.42 μm to 1.88 μm, through a linear statistical method. Additionally, more dense and uniform structure is observed as temperature goes up. As shown in Figure 3 (a), low densification with some porosity is obvious, Figure 3 (b)-(d) display a significant change in densification with less pores and larger grains. It indicates that grain growth is promoted with the increase of sintering temperature. In general, increasing sintering temperature makes contribution to the formation of better microstructure, which has significant effect on magnetic and dielectric perofrmances.
Figure 3. Surface morphology of Mg$_{0.7}$Cd$_{0.3}$Fe$_{1.92}$Ga$_{0.08}$O$_4$ ferrites sintered at different temperatures where (a) 900℃, (b) 920℃, (c) 940℃, and (d) 960℃.

Magnetization measurement are performed and the parameters containing saturation magnetization ($M_s$) and coercivity ($H_c$) of Mg$_{0.7}$Cd$_{0.3}$Fe$_{1.92}$Ga$_{0.08}$O$_4$ ferrites are shown in Figure 4. Figure 4 (a) displays the hysteresis loops for Mg-Ga-Cd ferrites sintering at various temperatures, it indicates typical soft magnetization performance for all the ferrites in spite of varying sintering temperatures. It is attributed to the intrinsic magnetic behavior and proper microstructure with moderate particle size and denser arrangement. The change in $M_s$ and $H_c$ are shown in Figure 4 (b), it shows a monotonically upwards trend of $M_s$ with increasing temperature. The maximum value of $M_s$ is as high as 33.12 emu/g as the sintering temperature increase up to 960℃, while the minimum value of $M_s$ is 24.37 emu/g at 900℃. The increase in magnetization can be concluded as enhanced magnetic super exchange interactions between tetrahedral site and octahedral site [22], and unidirectional spin on the particle surface [23] [24]. Then increasing temperature results in promoted spin magnetic moment, causing higher $M_s$. Higher temperature also affects the inter-sub lattice exchange energy between Mg-O-Ga or Mg-O-Fe. In addition, the energy between Mg-O-Fe is stronger than the Fe–O–Fe interaction energy. As a result, the observed increased $M_s$ indicates the increase in inter-sub lattice exchange energy with increasing temperature. Figure 4 (b) also displays a decrease trend of coercivity ($H_c$), with the maximum value of 139.17 Oe at 900℃ and the minimum value of 97.23 Oe at 960℃. It is attributed the decrease in anisotropy constant as temperature increases [25]. The change in $M_s$ and $H_c$ agrees well with the theoretical equation [26]:

$$H_c = \frac{0.96K_1}{M_s}$$

Where $K_1$ is a constant. The equation indicates a negative correlation between $M_s$ and $H_c$. 
Figure 4. Magnetization of Mg$_{0.7}$Cd$_{0.3}$Fe$_{1.92}$Ga$_{0.08}$O$_4$ ferrites sintered at different temperatures. (a) Hysteresis loops, (b) saturation magnetization and coercivity.

The complex permeability and permittivity of Mg-Cd-Ga ferrites sintered at different temperatures with 5 wt.% Bi$_2$O$_3$ addictive are shown in Figure 5. From Figure 5 (a), it is observed the real part ($\mu'$) of permeability increases from H/m to H/m with increasing sintering temperature with the frequency ranging from approximately 1 to 90 MHz. In the meantime, one sample has higher $\mu'$ value will possess lower resonant frequency, which is due to the Snoek’s law [27]. In regard of the imaginary part ($\mu''$) of permeability, it shows very low magnitude order to $10^{-1}$, over the discussed frequency range. Hence, low magnitude order of magnetic loss tangent $\tan\delta_\mu$ ($\frac{\mu''}{\mu'}$) as low as $10^{-2}$ for all samples are attained. It can be explained by the uniform and dense microstructure from relatively low temperature sintering by adding Bi$_2$O$_3$ sintering aids.

To further discuss the effect of sintering temperature on permeability, two aspects should be mentioned: spin rotation and magnetic domain wall motion, for the complex permeability can be described by the relationship [28]:

$$\mu = 1 + \chi_{\text{spin}} + \chi_d$$

(8)

Where $\chi_{\text{spin}}$ and $\chi_d$ donate magnetic susceptibility for spin rotation and domain wall motion, respectively. In our work, $\chi_{\text{spin}}$ determines $\mu$ because of weak domain wall motion (small $\chi_d$ value) on account of small grain size [29]. That is to say the relationship can be simplified as [30]:

$$\mu = 1 + \chi_{\text{spin}} = \frac{4\pi M_s}{H_d + H_a}$$

(9)

Where $H_d$ and $H_a$ are the demagnetizing field and the magnetic anisotropy field, respectively. Thus, the experimental $\mu$ and $M_s$ display the similar change trend in theory.

Figure 5 (b) displays permittivity as a function of frequency of Mg-Cd-Ga ferrites sintered at different temperatures. It is found that real part ($\varepsilon'$) of permittivity for all samples jogs range from 15 F/m to 19 F/m, as sintering temperature increase from 900 to 960°C. And the magnitude order of imaginary part ($\varepsilon''$) for all samples is as low as $10^{-2}$, so the very low magnitude order ($10^{-4}$-$10^{-3}$) of dielectric loss tangent ($\tan\delta_\varepsilon$) ($\frac{\varepsilon''}{\varepsilon'}$) is achievable. The details of complex permittivity can be explained as two aspects. One is Bi$_2$O$_3$ sintering aids that forms Bi$_{12}$Fe$_2$O$_{39}$ having dielectric property determines $\varepsilon'$. The second is the dense microstructure and proper particle size, causing relatively low $\tan\delta_\varepsilon$. 

Figure 5 (a) shows the saturation magnetization and coercivity for Mg-Cd-Ga ferrites sintered at different temperatures with 5 wt.% Bi$_2$O$_3$ sintering aids. Figure 5 (b) shows the permittivity of Mg-Cd-Ga ferrites sintered at different temperatures with 5 wt.% Bi$_2$O$_3$ sintering aids.
To further discuss the performance of various temperature sintered Mg-Cd-Ga ferrites for the application in the antenna, two parameters including \( Z \) factor and \( BW \) factor in formula (1) and (2) of the samples are discussed at 50 MHz and the results are shown in Table II and Figure 6. It is observed that \( M_{\gamma 0.7Cd0.3Fe1.92Ga0.08O4} \) ferrites sintered at various temperatures show low \( Z \) and the composites sintered at 920°C reveal broad operating frequency band. The best eligible samples with \( Z=0.93, BW=0.0028 \) and long operating frequency for all samples can be obtained at 920°C.

### Table 2. Comparison of various Ga\(^{3+}\) ions concentration of \( M_{\gamma 0.8Cd0.2Fe2-xGa_{x}O4} \) composites.

| Temperature (℃) | \( \mu' \) | \( \varepsilon' \) | Z factor | BW factor | Operating frequency |
|-----------------|-----------|----------------|----------|-----------|------------------|
| 900             | 15        | 21             | 0.65     | 0.0021    | 1-200 MHz        |
| 920             | 18        | 21             | 0.93     | 0.0028    | 1-200 MHz        |
| 940             | 18        | 24             | 0.87     | 0.0024    | 1-150 MHz        |
| 960             | 19        | 30             | 0.80     | 0.0020    | 1-150 MHz        |

Figure 6. \( Z \) and \( BW \) of \( M_{\gamma 0.7Cd0.3Fe1.92Ga0.08O4} \) ferrites sintered at various temperatures.

### 4. Conclusion
Spinel \( M_{\gamma 0.7Cd0.3Fe1.92Ga0.08O4} \) ferrites sintered at various temperature were mainly investigated as candidates for the miniaturization and high performance of high frequency antenna substrates. The synthesized ferrites were measured and discussed through crystalline structure, microstructure, magnetic...
and dielectric behaviors. Consequently, increasing sintering temperature caused increasing lattice parameters, the super exchange interactions between A and B site are enhanced. Based on this, the magnetization and permeability were enhanced. In addition, adding 5 wt.% Bi2O3 achieve denser microstructure and more uniform grains with increasing sintering temperature. Hence, excellent dielectric properties with moderate $\varepsilon'$ and relatively low loss tangent were achieved. Finally, matching impedance (Z=0.93) factor and wideband characteristic factor ($BWR=2.8 \times 10^{-3}$) for the Mg0.7Cd0.3Fe1.92Ga0.08O4 ferrites operating over 1-200 MHz were achieved at. In conclusion, miniaturization, broad operating frequency and wideband were obtained. In addition, enhanced magnetization ($M_s=33.12$ emu/g, $H_c=97.23$ Oe) and low magnitude order of magnetic (tan$\delta_\mu\sim10^{-2}$) and dielectric (tan$\delta_\varepsilon\sim10^{-4}-10^{-3}$) tangent illustrated inspiring application prospect of the proposed materials in high-frequency antenna substrates.

Acknowledgments

This work was supported by Major Science and Technology projects in Sichuan Province Nos. 2019ZDZX0026, and by the Key projects of Sichuan Province No. 2020YFG0106, and by Foundation for University Teacher of Education of China No. ZYGX2019J011.

References

[1] Q. Li, S. Yan, X. Wang, Y. Nie, Z. Feng, Z. Su, Y. Chen, V.G. Harris, Dual-ion substitution induced high impedance of Co<inf>2</inf>Z hexaferrites for ultra-high frequency applications, Acta Mater. (2015). doi: 10.1016/j.actamat.2015.07.038.

[2] J. S. Colburn, Patch antennas on externally perforated high dielectric constant substrates, IEEE Trans. Antennas Propag. (1999). doi: 10.1109/8.817654.

[3] K. Buell, H. Mosallaei, K. Sarabandi, A substrate for small patch antennas providing tunable miniaturization factors, in: IEEE Trans. Microw. Theory Tech., 2006. doi: 10.1109/TMTT.2005.860329.

[4] L. B. Kong, Z. W. Li, G. Q. Lin, Y. B. Gan, Magneto-dielectric properties of Mg-Cu-Co ferrite ceramics: II. Electrical, dielectric, and magnetic properties, J. Am. Ceram. Soc. 90 (2007) 2104–2112. doi: 10.1111/j.1551-2916.2007.01691.x.

[5] A. Thakur, P. Thakur, J. H. Hsu, Novel magnetodielectric nanomaterials with matching permeability and permittivity for the very-high-frequency applications, Scr. Mater. 64 (2011) 205–208. doi: 10.1016/j.scriptamat.2010.09.045.

[6] P. M. T. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo, S. A. Tretyakov, Magnetodielectric substrates in antenna miniaturization: Potential and limitations, IEEE Trans. Antennas Propag. (2006). doi: 10.1109/TAP.2006.884303.

[7] K. Borah, N.S. Bhattacharyya, Magnetodielectric composite with ferrite inclusions as substrates for microstrip patch antennas at microwave frequencies, Compos. Part B Eng. 43 (2012) 1309–1314. doi: 10.1016/j.compositesb.2011.11.067.

[8] O. S. Kim, O. Breinbjerg, Lower bound for the radiation Q of electrically small magnetic dipole antennas with solid magnetodielectric core, IEEE Trans. Antennas Propag. (2011). doi: 10.1109/TAP.2010.2096394.

[9] G. Yang, N. X. Sun, Magnetoelectric composites for miniature antennas, in: Compos. Magnetoelectrics, 2015. doi: 10.1016/b978-1-78242-254-9.00010-x.

[10] A. Hoorfar, A. Perrotta, An experimental study of microstrip antennas on very high permittivity ceramic substrates and very small ground planes, IEEE Trans. Antennas Propag. (2001). doi: 10.1109/8.929638.

[11] A. Saini, K. Rana, A. Thakur, P. Thakur, J. L. Mattei, P. Queffelec, Low loss composite nano ferrite with matching permittivity and permeability in UHF band, Mater. Res. Bull. 76 (2016) 94–99. doi: 10.1016/j.materresbull.2015.12.002.

[12] R. C. Hansen, M. Burke, Antennas with magneto-dielectrics, Microw. Opt. Technol. Lett. 26 (2000) 75–78. doi: 10.1002/1098-2760(20000720)26: 2<75: AID-MOP3>3.0.CO; 2 - W.
[13] Y. Lin, X. Liu, H. Yang, F. Wang, C. Liu, Low temperature sintering of laminated Ni0.5Ti0.5NbO4-Ni0.8Zn0.2Fe2O4 composites for high frequency applications, Ceram. Int. (2016). doi: 10.1016/j.ceramint.2016.04.042.

[14] Y. Peng, X. Wu, Z. Chen, W. Liu, F. Wang, X. Wang, Z. Feng, Y. Chen, V.G. Harris, BiFeO 3 tailored low loss M-type hexaferrite composites having equivalent permeability and permittivity for very high frequency applications, J. Alloys Compd. 630 (2015) 48–53. doi: 10.1016/j.jallcom.2015.01.026.

[15] J. Huang, P. Du, L. Hong, Y. Dong, M. Hong, A percolative ferromagnetic-ferroelectric composite with significant dielectric and magnetic properties, Adv. Mater. (2007). doi:10.1002/adma.200601217.

[16] S. Joshi, M. Kumar, S. Chhoker, A. Kumar, M. Singh, Effect of Gd3+ substitution on structural, magnetic, dielectric and optical properties of nanocrystalline CoFe2O4, J. Magn. Magn. Mater. 426 (2017) 252–263. doi: 10.1016/j.jmmm.2016.11.090.

[17] Z. J. Zhang, Z. L. Wang, B.C. Chakoumakos, J. S. Yin, Temperature dependence of cation distribution and oxidation. State in magnetic Mn-Fe ferrite nanocrystals, J. Am. Chem. Soc. (1998). doi:10.1021/ja973085l.

[18] H. Leaderman, National Bureau of Standards, Kobunshi. (1957). doi:10.1295/kobunshi.6.190.

[19] Q. Li, S. Bao, Y. Liu, Y. Li, Y. Jing, J. Li, Influence of lightly Sm-substitution on crystal structure, magnetic and dielectric properties of BiFeO 3 ceramics, J. Alloys Compd. (2016). doi: 10.1016/j.jallcom.2016.05.023.

[20] L. Ju-Fen, K. Xiao-Yu, M. Ai-Jie, Theoretical studies of the optical and EPR spectra for Fe3+ ion in the MF3:Fe3+ (M=Al, Ga) systems, J. Lumin. (2010). doi:10.1016/j.jlumin.2009.10.011.

[21] G. Gan, H. Zhang, Q. Li, J. Li, X. Huang, F. Xie, F. Xu, Q. Zhang, M. Li, T. Liang, G. Wang, Low loss, enhanced magneto-dielectric properties of Bi 2 O 3 doped Mg-Cd ferrites for high frequency antennas, J. Alloys Compd. (2018). doi: 10.1016/j.jallcom.2017.12.002.

[22] N. Yadav, A. Kumar, P.S. Rana, D.S. Rana, M. Arora, R.P. Pant, Finite size effect on Sm3+ doped Mn<inf>x</inf>Zn<inf>1-x</inf>Fe<inf>2</inf>O<inf>4</inf> (0≤x≤0.5) ferrite nanoparticles, Ceram. Int. 41 (2015) 8623–8629. doi: 10.1016/j.ceramint.2015.03.072.

[23] A. Verma, R. Chatterjee, Effect of zinc concentration on the structural, electrical and magnetic properties of mixed Mn-Zn and Ni-Zn ferrites synthesized by the citrate precursor technique, J. Magn. Magn. Mater. (2006). doi: 10.1016/j.jmmm.2006.03.033.

[24] S. H. Song, C.C.H. Lo, S.J. Lee, S.T. Aldini, J.E. Snyder, D.C. Jiles, Magnetic and magnetoelastic properties of Ga-substituted cobalt ferrite, in: J. Appl. Phys., 2007. doi: 10.1063/1.2712941.

[25] R. C. Kamble, P.A. Shaikh, S.S. Kamble, Y. D. Kolekar, Effect of cobalt substitution on structural, magnetic and electric properties of NiFeO 3 ferrite, J. Alloys Compd. (2009). doi: 10.1016/j.jallcom.2008.11.101.

[26] T. Nakamura, Snoek’s limit in high-frequency permeability of polycrystalline Ni-Zn, Mg-Zn, and Ni-Zn-Cu spinel ferrites, J. Appl. Phys. (2000). doi: 10.1063/1.373666.

[27] K. Sun, H. Liu, Y. Yang, Z. Yu, C. Chen, G. Wu, X. Jiang, Z. Lan, L. Li, Contribution of magnetization mechanisms in nickel-zinc ferrites with different grain sizes and its temperature relationship, Mater. Chem. Phys. (2016). doi: 10.1016/j.matchemphys.2016.03.002.

[28] K. Kawano, M. Hachiya, Y. Iijima, N. Sato, Y. Mizuno, The grain size effect on the magnetic properties in NiZn ferrite and the quality factor of the inductor, J. Magn. Magn. Mater. (2009). doi: 10.1016/j.jmmm.2009.03.015.

[29] H. Jia, W. Liu, Z. Zhang, F. Chen, Y. Li, J. Liu, Y. Nie, Monodomain MgCuZn ferrite with equivalent permeability and permittivity for broad frequency band applications, Ceram. Int. (2017). doi: 10.1016/j.ceramint.2017.01.129.

[30] W. Liu, S. Yan, Y. Cheng, Q. Li, Z. Feng, X. Wang, R. Gong, Y. Nie, Monodomain Design and Permeability Study of High-Q-Factor NiCuZn Ferrites for Near-Field Communication Application, J. Electron. Mater. (2015). doi: 10.1007/s11664-015-3978-z.