Manganese–Zinc Ferrite: Synthesis, Structural, Electrical, Dielectric and Magnetic Properties and Emerging Applications—A Comprehensive Review

P. A. Katre[1], D. S. Choudhary[2]
[1,2]*Department of Physics, M. B. Patel College, Sakoli, Bhandara 441802, India*

***Abstract*—Manganese–zinc ferrites (Mn–Zn ferrites), generally represented by the composition $Mn_{1-x}Zn_xFe_2O_4$, are technologically important soft magnetic spinel ferrites owing to their high magnetic permeability, relatively high saturation magnetization, high electrical resistivity, low coercivity and comparatively low power loss. Their properties are strongly governed by cation distribution between tetrahedral (A) and octahedral (B) crystallographic sites, particle size, grain size, porosity, synthesis route, sintering temperature and chemical substitution. During the last several decades, substantial research has been devoted to developing Mn–Zn ferrites with controlled microstructures and improved magnetic and electromagnetic performance. This review critically discusses the crystal chemistry of Mn–Zn ferrites, mechanisms of magnetic interactions, synthesis routes, structural and morphological characterization, electrical and dielectric behavior, magnetic properties, frequency response, doping strategies and technological applications. Particular emphasis is placed on the relationship between Zn concentration and cation distribution, and consequently on saturation magnetization, coercivity, permeability and Curie temperature. Conventional ceramic processing remains attractive for bulk magnetic cores, whereas sol–gel, co-precipitation, hydrothermal, citrate precursor, combustion and microemulsion methods provide better control over nanoscale morphology and chemical homogeneity. The review also discusses the role of rare-earth and oxide dopants in modifying grain growth, electrical resistivity, magnetic losses and high-frequency performance. Recent developments indicate that Mn–Zn ferrites remain promising for power electronics, high-frequency inductors, transformers, electromagnetic interference suppression, microwave absorption, sensors and advanced magnetic devices. Future research should focus on low-temperature processing, additive manufacturing, controlled cation engineering, environmentally responsible synthesis and simultaneous optimization of magnetic and dielectric losses.**

***Index Terms*—Mn–Zn ferrite; spinel ferrite; nanoparticles; cation distribution; magnetic properties; dielectric properties; permeability; high-frequency applications.**

I. INTRODUCTION

Ferrites are a technologically significant family of ceramic magnetic oxides containing iron and one or more divalent or trivalent metallic cations. Their combination of magnetic functionality, electrical resistivity, chemical stability and relatively low eddy-current losses has resulted in extensive use in electronic and electromagnetic devices [1]. Spinel ferrites generally possess the formula MFe_2O_4, where M may be Mn, Zn, Ni, Co, Mg or other suitable cations. The properties of these materials depend strongly on the distribution of cations over tetrahedral and octahedral sites of the spinel lattice [2,3].

Among soft ferrites, manganese–zinc ferrites have received particular attention because they can simultaneously provide high permeability, relatively high saturation magnetization and low coercivity. Consequently, Mn–Zn ferrites are widely considered for magnetic cores, transformers, inductors, electromagnetic interference suppression and other power-electronic components [4–7]. Their electromagnetic behavior is particularly sensitive to composition, grain size, porosity and sintering conditions.

The general composition may be expressed as:
$Mn_{1-x}Zn_xFe_2O_4$, $0 \le x \le 1$
In practical materials, however, deviations from ideal stoichiometry and partial redistribution of Mn^{2+}, Zn^{2+}

and Fe^{3+} ions can occur. Such changes influence superexchange interactions between A and B sites and therefore modify the net magnetization and magnetic anisotropy [8–10].

Recent research has expanded the scope of Mn–Zn ferrites from conventional bulk cores toward nanoparticles, microwave absorbers, magnetic composites, sensors and multifunctional materials. A recent review highlights solid-state, sol–gel, co-precipitation and hydrothermal routes as major approaches for producing Mn–Zn ferrites with controlled properties. The objective of this review is therefore to provide a systematic discussion of the structure–processing–property relationships of Mn–Zn ferrites, emphasizing synthesis, characterization, magnetic and dielectric behavior, composition dependence and technological applications.

1.1 Crystal Structure and Cation Distribution

Mn–Zn ferrites crystallize predominantly in the cubic spinel structure. The spinel unit cell contains oxygen ions arranged approximately in a close-packed framework, with cations occupying two principal interstitial positions: tetrahedral A sites and octahedral B sites [11]. For an ideal normal spinel, divalent ions occupy A sites while Fe^{3+} occupies B sites. However, real ferrites commonly exhibit mixed or partially inverse distributions. Mn^{2+} and Zn^{2+} have different site preferences, and the final distribution depends on synthesis temperature, oxygen partial pressure, composition and thermal history [12–15]. The magnetic interaction in ferrites is dominated by superexchange coupling through oxygen. The A–B interaction is normally stronger than the A–A and B–B interactions. Consequently, the magnetic moments associated with A and B sublattices are oppositely aligned, producing ferrimagnetic behavior.

The net magnetic moment can be approximately expressed as:

$$M = M^B - M^A$$

where M^A and M^B represent the magnetic moments of the tetrahedral and octahedral sublattices, respectively. Zn^{2+} is essentially nonmagnetic and preferentially occupies tetrahedral sites in many Mn–Zn ferrite compositions. Therefore, increasing Zn content can modify the A–B superexchange interaction and substantially change the saturation magnetization [16–18]. Experimental studies using X-ray absorption, neutron diffraction and Mössbauer spectroscopy have demonstrated the importance of cation distribution in explaining these composition-dependent magnetic properties [19–21].

1.2 Effect of Zn Concentration

The Zn concentration is one of the most important variables controlling Mn–Zn ferrite properties. Zinc ions are nonmagnetic, whereas Mn^{2+} and Fe^{3+} contribute magnetic moments. Consequently, substitution of Zn changes both the magnetic sublattice populations and exchange interactions.

Experimental studies have demonstrated that structural parameters such as lattice constant, crystallite size and magnetic properties vary systematically with Zn concentration [22–24]. Because Zn^{2+} has a relatively large ionic radius, its incorporation can increase the lattice parameter.

The lattice parameter can be estimated from X-ray diffraction using:

$$a = d\sqrt{h^2 + k^2 + l^2} \quad (1)$$

where a is the lattice constant and d is the interplanar spacing.

The Zn concentration also influences grain growth, domain-wall mobility and magnetic anisotropy. Zapata et al. demonstrated that Zn concentration affects both microstructure and relaxation frequency in Mn–Zn ferrites produced by solid-state processing [25]. Such effects are important for optimizing ferrites for high-frequency devices.

II. SYNTHESIS OF MN–ZN FERRITES

The synthesis route strongly influences phase purity, crystallite size, particle morphology and magnetic performance. The most commonly reported techniques include:

1. Conventional ceramic/solid-state method
2. Co-precipitation
3. Sol–gel
4. Citrate precursor method
5. Hydrothermal synthesis
6. Combustion synthesis
7. Microemulsion
8. Oxalate/organic precursor methods
9. Mechanical milling
10. Thin-film and plasma-based processing.

A comparison of important approaches is given below.

Synthesis method	Major advantage	Major limitation	Typical application
Solid-state	Simple and scalable	High temperature; larger grains	Bulk cores
Co-precipitation	Low-cost; good chemical homogeneity	Agglomeration	Nanoparticles
Sol–gel	Excellent compositional control	Organic precursors/processing complexity	Nanomaterials
Citrate precursor	Fine particles	Heat-treatment optimization required	Nano/magnetic devices
Hydrothermal	Controlled morphology	Requires pressure vessel	Nanoparticles
Combustion	Rapid synthesis	Difficult combustion control	Nanopowders
Microemulsion	Narrow particle-size distribution	Surfactant removal	Highly controlled nanoparticles

The literature confirms that synthesis conditions can substantially alter magnetic properties even for nominally identical compositions [26–30].

2.1 Conventional Solid-State Method

The conventional ceramic route involves mixing Mn, Zn and Fe oxide or carbonate precursors, followed by calcination, milling, pressing and sintering. It remains one of the most commercially relevant methods because it is inexpensive and readily scalable.

The major disadvantage is that the process generally requires high temperatures and prolonged heat treatment. Grain growth may result in relatively coarse microstructures. Nevertheless, carefully optimized calcination and sintering can provide high density and high permeability.

Studies of Mn–Zn ferrites have demonstrated that calcination and sintering conditions significantly influence magnetic properties and power losses [31].

2.2. Co-Precipitation Method

Co-precipitation is widely used for producing Mn–Zn ferrite nanoparticles. Metal salts are dissolved in an aqueous medium and precipitated using an alkaline solution. The precipitate is subsequently washed, dried and thermally treated.

The main advantages include:

- relatively low processing temperature;
- good chemical homogeneity;
- control of particle size;
- relatively simple equipment;
- suitability for nanoparticle synthesis.

However, particle agglomeration and incomplete precipitation can affect the final product. Careful control of pH, precursor concentration, precipitation temperature and calcination is therefore necessary.

Studies on Mn–Zn ferrite nanoparticles prepared by co-precipitation have demonstrated that composition and processing conditions strongly influence particle size and magnetic parameters [32–34].

2.3 Sol–Gel and Citrate Precursor Methods

Sol–gel processing offers molecular-level mixing of metal precursors. Metal salts are complexed with suitable organic agents and converted into a gel before drying and calcination.

Azadmanjiri et al. reported preparation of Mn–Zn ferrite nanoparticles using a chemical sol–gel combustion route and examined the effect of sintering on their magnetic behavior [35].

The citrate precursor technique is another attractive chemical route. It enables relatively homogeneous mixing of Mn, Zn and Fe ions and can produce nanoscale ferrites at comparatively low temperatures [36,37].

The main advantages are:

- high chemical homogeneity;
- relatively fine crystallite size;
- good compositional control;
- reduced diffusion distance during calcination.

2.4 Hydrothermal Synthesis

Hydrothermal processing has become an important route for producing nanoscale Mn–Zn ferrites. The reaction takes place in a sealed vessel at elevated temperature and pressure, allowing crystalline ferrites to form under controlled conditions.

Makovec et al. demonstrated hydrothermal synthesis of Mn–Zn ferrite powders from oxide precursors [38].

More recently, modified hydrothermal synthesis has produced Mn–Zn ferrite nanoparticles with narrow size distributions and high saturation magnetization;

one study reported a maximum saturation magnetization of approximately 79.6 emu/g.

Hydrothermal processing is particularly attractive where particle morphology and crystallinity need to be controlled simultaneously.

III. STRUCTURAL CHARACTERIZATION

3.1 X-ray Diffraction

XRD is the principal technique for determining the crystal structure and phase purity of Mn–Zn ferrites. The characteristic reflections of cubic spinel ferrites generally include planes such as (220), (311), (400), (422), (511) and (440).

The crystallite size can be estimated using the Scherrer equation:

$$D = K\lambda/(\beta \cos \theta) \quad (2)$$

where:

- D = crystallite size,
- K = shape factor,
- λ = X-ray wavelength,
- β = corrected full width at half maximum,
- θ = Bragg angle.

It is important to distinguish crystallite size from particle size observed by SEM or TEM.

3.2 FTIR Spectroscopy

FTIR spectroscopy is useful for identifying metal–oxygen vibrations associated with tetrahedral and octahedral sites. Ferrites commonly show characteristic absorption bands in the lower wavenumber region associated with M–O vibrations.

Changes in FTIR band position and intensity can indicate changes in cation distribution, lattice distortion and bonding environment.

3.3 SEM and TEM

Scanning electron microscopy provides information about grain morphology, agglomeration and grain size. Transmission electron microscopy provides more detailed information concerning particle morphology and nanoscale crystallinity. The particle morphology is strongly dependent on synthesis route. Hydrothermal and chemical routes can produce relatively uniform nanoparticles, whereas solid-state synthesis generally produces larger particles.

3.4 Magnetic Properties

Magnetic characterization is essential for evaluating Mn–Zn ferrites for technological applications. Vibrating sample magnetometry (VSM) is widely employed to obtain M–H hysteresis loops.

The principal magnetic parameters are:

- saturation magnetization (M_s);
- remanent magnetization (M_r);
- coercivity (Hc);
- squareness ratio (M_r/M_s).

Mn–Zn ferrites generally exhibit soft magnetic behavior characterized by relatively low coercivity.

The coercivity is strongly affected by crystallite/grain size, magnetic anisotropy, internal stress and domain structure [39–42].

Saturation magnetization represents the maximum magnetization achieved when the magnetic domains become substantially aligned with the applied magnetic field.The dependence of M_s on Zn concentration is not necessarily linear. At lower Zn concentrations, replacement of magnetic ions and changes in cation distribution may modify the A–B exchange interaction. At sufficiently high Zn content, dilution of magnetic sublattices can decrease magnetization.Studies of Mn–Zn ferrites have shown substantial variation in saturation magnetization depending on composition and processing conditions [43–45].

Notably, highly optimized nonstoichiometric Mn–Zn ferrites have demonstrated saturation magnetization near 120 emu/g and Curie temperatures around 750 K in specialized high-frequency/microwave-absorption studies.

Coercivity represents the reverse magnetic field required to reduce the magnetization to zero after saturation. For soft magnetic applications, low Hc is desirable because it indicates easy magnetization reversal and lower hysteresis losses.Grain size has a significant influence on coercivity. Ultrafine-grained Mn–Zn ferrites can exhibit changes in magnetization behavior because grain boundaries contribute to magnetic disorder and anisotropy. Experimental work has linked magnetic behavior with grain size and grain-boundary characteristics [46].

The Curie temperature (Tc) is the temperature above which long-range ferrimagnetic order disappears. Tc is controlled by exchange interactions and therefore depends strongly on cation distribution and

composition. Mn–Zn ferrites generally have Curie temperatures suitable for many electronic applications, but the exact value depends on the Mn/Zn/Fe ratio and processing history.Temperature-dependent magnetic characterization is therefore important for selecting Mn–Zn ferrites for high-temperature applications.

3.5 Dielectric Properties

The dielectric properties of Mn–Zn ferrites arise from charge transport and polarization mechanisms associated with localized hopping between ions of different valence states.

A commonly proposed mechanism involves electron hopping between Fe^{2+} and Fe^{3+} ions:

$Fe^{2+} \rightleftharpoons Fe^{3+} + e^{-}$

Similarly, hole hopping and cation redistribution can contribute to electrical conduction.

The dielectric constant generally decreases with increasing frequency because slower polarization mechanisms cannot follow the rapidly changing electric field. This behavior is consistent with the Maxwell–Wagner interfacial polarization model and Koop's phenomenological theory [47]. Thakur et al. reported frequency-dependent dielectric behavior in Mn–Zn nano-ferrites and demonstrated the importance of processing conditions in controlling electrical properties [48].

3.6 Electrical Resistivity

High electrical resistivity is one of the major advantages of ferrites compared with metallic magnetic materials.

High resistivity reduces eddy-current losses, making Mn–Zn ferrites attractive for high-frequency applications. However, resistivity is affected by:

- grain size;
- grain-boundary density;
- Fe^{2+}/Fe^{3+} concentration;
- sintering temperature;
- oxygen stoichiometry;
- dopant concentration.

Doping and grain-boundary engineering can therefore be used to increase resistivity and reduce high-frequency losses.

3.7 Complex Permeability and High-Frequency Behavior

Complex permeability is represented as:

$\mu = \mu' - j\mu''$*

where μ' is the real part associated primarily with magnetic energy storage and μ'' represents magnetic energy loss.

The frequency dependence of permeability is governed by domain-wall motion, spin rotation and magnetic resonance. Tsutaoka et al. investigated frequency dispersion in Mn–Zn and Ni–Zn spinel ferrites and their composites [49].

For high-frequency applications, the objective is generally to obtain:

- high μ';
- low μ'';
- high resistivity;
- low core loss;
- high Curie temperature;
- stable permeability over the operating frequency range.

Sintering temperature is one of the most important processing variables for Mn–Zn ferrites. Increasing temperature generally promotes densification and grain growth. However, excessive grain growth can increase magnetic loss or alter domain-wall behavior. Conversely, insufficient sintering may leave pores and poorly connected grains, reducing permeability. Studies have demonstrated that optimizing calcination and sintering conditions is essential for achieving high-permeability Mn–Zn ferrites [31,50].

Low-temperature processing has therefore emerged as an important research direction. Controlled doping is widely used to tailor Mn–Zn ferrite properties. Dopants can modify:

- lattice parameter;
- grain growth;
- electrical resistivity;
- saturation magnetization;
- coercivity;
- permeability;
- power loss;
- Curie temperature.

Reported dopants include Nb, Ti, Sn, Y, rare-earth ions and other metal oxides.

For example, Nb_2O_5 addition has been investigated for modifying Mn–Zn ferrite properties and reducing

losses [50]. Y^{3+} substitution has also been reported to alter microstructure and electromagnetic properties. Rare-earth doping can modify cation distribution and magnetic behavior. Nd^{3+}-substituted Mn–Zn ferrites, for example, have shown changes in structural parameters and enhanced saturation magnetization attributed to changes in cation distribution.

3.8 Microwave Absorption

Mn–Zn ferrites are attractive microwave-absorbing materials because of their magnetic and dielectric losses.

For an absorber, efficient attenuation requires appropriate impedance matching between the absorber and free space. Recent work on nonstoichiometric Mn–Zn ferrites demonstrated microwave absorption over a broad 0.1–18 GHz range, with a reported maximum reflection loss of approximately 22 dB at 16 GHz for a 1.5 mm matching thickness. These results demonstrate the potential of Mn–Zn ferrites for electromagnetic compatibility and microwave-absorption technologies.

IV. APPLICATIONS OF MN–ZN FERRITES

Mn–Zn ferrites have a broad range of technological applications.

Their high permeability and low magnetic losses make Mn–Zn ferrites useful for transformer cores, particularly in high-frequency power conversion.

Mn–Zn ferrites are widely investigated for inductive components because of their favorable permeability and magnetic-loss characteristics.

Ferrite components can absorb unwanted high-frequency electromagnetic energy and are therefore useful for electromagnetic interference suppression.

The electrical and magnetic response of Mn–Zn ferrites can be modified by external magnetic fields, temperature and chemical environments, supporting sensor applications.

The combination of magnetic and dielectric loss makes Mn–Zn ferrites promising for microwave absorption [44].

Mn–Zn ferrites can be incorporated into polymers and other matrices to create multifunctional magnetic/dielectric composites.

Nanoscale ferrites have also been explored for biomedical applications because their magnetic response can be controlled through particle size and composition. However, biomedical applications require careful assessment of surface chemistry, toxicity, particle stability and biological compatibility.

The performance of Mn–Zn ferrite can be understood through a chain of interdependent parameters:

Composition → Cation distribution → Crystal structure → Grain size → Domain structure → Magnetic properties → Frequency response → Device performance

For example, changing Zn concentration changes cation occupancy. This modifies A–B exchange interactions, which affect magnetization and magnetic anisotropy. Processing conditions then control grain size and porosity, influencing domain-wall motion and permeability.

Therefore, simply optimizing chemical composition is insufficient. The composition–processing–microstructure relationship must be optimized simultaneously.

V. RESEARCH CHALLENGES AND FUTURE PERSPECTIVES

Despite extensive research, several challenges remain.

5.1 Low-temperature processing

Conventional Mn–Zn ferrite fabrication often requires relatively high sintering temperatures. Development of low-temperature routes can reduce energy consumption and suppress excessive grain growth.

5.2 High-frequency loss reduction

Future Mn–Zn ferrites should combine high permeability with reduced magnetic and dielectric losses at increasingly high frequencies.

5.3 Controlled cation distribution

Advanced characterization methods such as Mössbauer spectroscopy, neutron diffraction and synchrotron X-ray techniques can provide better understanding of cation occupancy.

5.4 Nanostructure control

Precise control of particle size, morphology, surface chemistry and agglomeration remains essential for nanoparticle applications.

5.5 Additive manufacturing

Recent work indicates that Mn–Zn ferrite components can potentially be fabricated using advanced

manufacturing approaches. A 2026 study investigated binder-jet-printed Mn–Zn ferrite toroids and reported improvements in density, saturation magnetization and permeability following infiltration.

5.6 Environmentally sustainable synthesis

Future research should reduce solvent consumption, energy demand and hazardous precursor use while maintaining high material performance.

VI. CONCLUSIONS

Mn–Zn ferrites remain among the most technologically important soft magnetic spinel ferrites. Their combination of high permeability, relatively high saturation magnetization, high resistivity and low coercivity provides advantages for magnetic and electromagnetic applications. The properties of Mn–Zn ferrites are strongly dependent on cation distribution, Zn concentration, crystallite size, grain structure, porosity and thermal processing. Conventional solid-state synthesis remains important for bulk magnetic components, whereas co-precipitation, sol–gel, citrate precursor, hydrothermal and combustion methods provide improved control of nanoscale materials. XRD, FTIR, SEM/TEM, VSM, Mössbauer spectroscopy and impedance measurements provide complementary information required for establishing structure–property relationships.

Zn substitution plays a particularly important role because Zn^{2+} is essentially nonmagnetic and modifies the distribution of magnetic ions between A and B sites. Consequently, changes in Zn concentration can alter saturation magnetization, coercivity, permeability and Curie temperature. Doping with selected transition-metal, rare-earth and oxide additives provide another effective strategy for tailoring electrical and magnetic behavior. Future development should focus on low-loss high-frequency Mn–Zn ferrites, controlled cation engineering, low-temperature sintering, nanoscale grain-boundary engineering, microwave absorption, additive manufacturing and environmentally sustainable synthesis. The combination of advanced characterization with computational materials design is expected to accelerate the development of next-generation Mn–Zn ferrite components.

REFERENCES

[1] Sugimoto, M., “The past, present, and future of ferrites,” Journal of the American Ceramic Society, vol. 82, pp. 269–280, 1999, doi: 10.1111/j.1551-2916. 1999.tb20058. x.

[2] Sickafus, K. E., J. M. Wills, and N. W. Grimes, “Structure of spinel,” Journal of the American Ceramic Society, vol. 82, pp. 3279–3292, 1999, doi: 10.1111/j.1151-2916. 1999.tb02241. x.

[3] Henderson, C. M. B., et al., “Cation occupancies in Mg, Co, Ni, Zn, Al ferrite spinels: A multi-element EXAFS study,” Journal of Physics: Condensed Matter, vol. 19, Art. no. 076214, 2007, doi: 10.1088/0953-8984/19/7/076214.

[4] Pardavi-Horvath, M., “Microwave applications of soft ferrites,” Journal of Magnetism and Magnetic Materials, doi: 10.1016/S0304-8853(00)00106-2.

[5] Töpfer, J., “Soft ferrite materials for multilayer inductors,” International Journal of Applied Ceramic Technology, vol. 3, pp. 455–462, 2006, doi: 10.1111/j.1744-7402.2006.02110.x.

[6] Miclea, C., et al., “Soft ferrite materials for magnetic temperature transducers and applications,” Journal of Magnetism and Magnetic Materials, vols. 290–291, pp. 1506–1509, 2005, doi: 10.1016/j.jmmm.2004.11.561.

[7] Ji, X., et al., “Microstructure and temperature dependence of magnetic properties of MnZnTiSn ferrites for power applications,” IEEE Transactions on Magnetics, vol. 46, pp. 974–977, 2010, doi: 10.1109/TMAG.2009.2037954.

[8] Calvin, S., et al., “Use of multiple-edge refinement of extended X-ray absorption fine structure to determine site occupancy in mixed ferrite nanoparticles,” Applied Physics Letters, vol. 81, pp. 3828–3830, 2002, doi: 10.1063/1.1520700.

[9] Fatemi, M., et al., “X-ray absorption, neutron diffraction, and Mössbauer effect studies of MnZn-ferrite processed through high-energy ball milling,” Journal of Applied Physics, vol. 85, pp. 5172–5174, 1999, doi: 10.1063/1.369114.

[10] Sakurai, S., et al., "Cation distribution and valence state in Mn-Zn ferrite examined by synchrotron X-rays," Physica B: Condensed Matter, vol. 403, pp. 3589–3591, 2008, doi: 10.1016/j.physb.2008.05.035.

[11] Abbas, M. M., et al., "X-ray diffraction study of the cation distribution in the Mn-Zn ferrites," Solid State Communications, vol. 82, pp. 701–704, 1992, doi: 10.1016/0038-1098(92)90064-G.

[12] Rath, C., et al., "Dependence on cation distribution of particle size, lattice parameter, and magnetic properties in nanosize Mn-Zn ferrite," Journal of Applied Physics, vol. 91, pp. 2211–2215, 2002, doi: 10.1063/1.1432474.

[13] Veena Gopalan, E., et al., "Impact of zinc substitution on the structural and magnetic properties of chemically derived nanosized manganese zinc mixed ferrites," Journal of Magnetism and Magnetic Materials, vol. 321, pp. 1092–1099, 2009, doi: 10.1016/j.jmmm.2008.10.031.

[14] Thota, S., et al., "Cation distribution in Ni-substituted Mn0.5Zn0.5Fe2O4 nanoparticles: A Raman, Mössbauer, X-ray diffraction and electron spectroscopy study," Materials Science and Engineering B, vol. 206, pp. 69–77, 2016, doi: 10.1016/j.mseb.2016.01.002.

[15] Sun, X., et al., "Synthesis and characterization of nanocrystalline zinc manganese ferrite," Journal of the American Ceramic Society, vol. 94, pp. 1490–1495, 2011, doi: 10.1111/j.1551-2916.2010.04265.x.

[16] Arulmurugan, R., et al., "Effect of zinc substitution on Co-Zn and Mn-Zn ferrite nanoparticles prepared by co-precipitation," Journal of Magnetism and Magnetic Materials, vol. 288, pp. 470–477, 2005, doi: 10.1016/j.jmmm.2004.09.138.

[17] Li, Y., et al., "Synthesis and characterization of MnZn ferrite nanoparticles with improved saturation magnetization," Journal of Superconductivity and Novel Magnetism, vol. 30, pp. 2275–2280, 2017, doi: 10.1007/s10948-017-4013-9.

[18] Kogias, G., et al., "New MnZn ferrites with high saturation flux density," Journal of the Japan Society of Powder and Powder Metallurgy, vol. 61, pp. S201–S204, 2014, doi: 10.2497/jjspm.61.S201.

[19] Tsutaoka, T., "Frequency dispersion of complex permeability in Mn–Zn and Ni–Zn spinel ferrites and their composite materials," Journal of Applied Physics, vol. 93, pp. 2789–2796, 2003, doi: 10.1063/1.1542651.

[20] Babayan, N., et al., "Combined effect of demagnetizing field and induced magnetic anisotropy on the magnetic properties of manganese-zinc ferrite composites," Journal of Magnetism and Magnetic Materials, vol. 324, pp. 161–166, 2012, doi: 10.1016/j.jmmm.2011.08.002.

[21] Sláma, J., et al., "Magnetic properties of selected substituted spinel ferrites," Journal of Magnetism and Magnetic Materials, vol. 326, pp. 251–256, 2013, doi: 10.1016/j.jmmm.2012.07.016.

[22] Skołyszewska, B., et al., "Preparation and magnetic properties of MgZn and MnZn ferrites," Physica C, vol. 387, pp. 290–294, 2003, doi: 10.1016/S0921-4534(03)00696-8.

[23] Moulin, J., et al., "Magnetic properties of MnZn ferrite with ultra-fine grain structure," Journal of Magnetism and Magnetic Materials, 2003.

[24] Son, S. H., et al., "Structure and magnetic properties of RF thermally plasma synthesized Mn and Mn–Zn ferrite nanoparticles," Journal of Applied Physics, vol. 93, pp. 7495–7497, 2003, doi: 10.1063/1.1557953.

[25] Zapata, A., et al., "Effect of zinc concentration on the microstructure and relaxation frequency of Mn-Zn ferrites synthesized by solid state reaction," Ceramics International, vol. 39, pp. 7853–7859, 2013, doi: 10.1016/j.ceramint.2013.03.046.

[26] Feng, Y., et al., "Preparation of soft-agglomerated nano-sized ceramic powders by sol-gel combustion process," Materials Science and Engineering B, vol. 162, pp. 53–57, 2009, doi: 10.1016/j.mseb.2009.02.007.

[27] Justin Joseyphus, R., et al., "Synthesis and magnetic properties of the size-controlled Mn-Zn ferrite nanoparticles by oxidation method," Journal of Physics and Chemistry of Solids, vol. 67, pp. 1510–1517, 2006, doi: 10.1016/j.jpcs.2005.11.015.

[28] Razzitte, A. C., et al., "Magnetic properties of MnZn ferrites prepared by soft chemical routes," Journal of Applied Physics, vol. 87, pp. 6232–6234, 2000, doi: 10.1063/1.372664.

[29] Angermann, A., et al., "Nanocrystalline Mn-Zn ferrites from mixed oxalates: Synthesis, stability and magnetic properties," Journal of Alloys and Compounds, vol. 508, pp. 433–439, 2010, doi: 10.1016/j.jallcom.2010.08.083.

[30] Szczygieł, I., et al., "Synthesis and characterization of manganese-zinc ferrite obtained by thermal decomposition from organic precursors," Journal of Thermal Analysis and Calorimetry, vol. 115, pp. 471–478, 2014, doi: 10.1007/s10973-013-3281-2.

[31] Su, H., et al., "Effects of calcining and sintering parameters on the magnetic properties of high-permeability MnZn ferrites," IEEE Transactions on Magnetics, vol. 41, pp. 4225–4227, 2005, doi: 10.1109/TMAG.2005.855327.

[32] Thakur, P., et al., "A review on MnZn ferrites: Synthesis, characterization and applications," Ceramics International, vol. 46, pp. 15740–15763, 2020, doi: 10.1016/j.ceramint.2020.03.287.

[33] Thakur, P., et al., "Preparation and characterization of nanosize Mn0.4Zn0.6Fe2O4 ferrite by citrate precursor method," Ceramics International, vol. 29, pp. 505–509, 2003, doi: 10.1016/S0272-8842(02)00194-3.

[34] Mathur, P., et al., "A study of nano-structured Zn–Mn soft spinel ferrites by the citrate precursor method," Physica Scripta, vol. 77, Art. no. 045701, 2008, doi: 10.1088/0031-8949/77/4/045701.

[35] Azadmanjiri, J., et al., "Preparation of Mn-Zn ferrite nanoparticles from chemical sol-gel combustion method and the magnetic properties after sintering," Journal of Non-Crystalline Solids, vol. 353, pp. 4170–4173, 2007, doi: 10.1016/j.jnoncrysol.2007.06.046.

[36] Winiarska, M., et al., "Manganese-zinc ferrite synthesis by the sol-gel autocombustion method," Industrial & Engineering Chemistry Research, vol. 52, pp. 353–358, 2013.

[37] Thakur, P., et al., "Study of dielectric behaviour of Mn–Zn nano ferrites," Journal of Physics and Chemistry of Solids, vol. 68, pp. 378–382, 2007, doi: 10.1016/j.jpcs.2006.11.028.

[38] Makovec, D., et al., "Hydrothermal synthesis of manganese zinc ferrite powders from oxides," Journal of the American Ceramic Society, vol. 82, pp. 1113–1118, 1999, doi: 10.1111/j.1151-2916. 1999.tb01884.x.

[39] Kalarus, M., et al., "High permeability-high frequency stable MnZn ferrites," Journal of Magnetism and Magnetic Materials, vol. 324, pp. 2788–2792, 2012, doi: 10.1016/j.jmmm.2012.04.011.

[40] Papazoglou, E., et al., "Low sintering temperature MnZn-ferrites for power applications in the frequency region of 400 kHz," Journal of Magnetism and Magnetic Materials, vol. 296, pp. 25–32, 2006, doi: 10.1016/j.jmmm.2005.01.021.

[41] Beatrice, C., et al., "Magnetic loss, permeability, and anisotropy compensation in CoO-doped Mn-Zn ferrites," AIP Advances, vol. 8, 2018, doi: 10.1063/1.4993718.

[42] Yan, M., et al., "Plasma-sprayed MnZn ferrites with insulated fine grains and increased resistivity for high-frequency applications," IEEE Transactions on Magnetics, vol. 40, pp. 3346–3348, 2004, doi: 10.1109/TMAG.2004.831658.

[43] Mathur, P., et al., "Low temperature processing of Mn-Zn nanoferrites," Journal of Materials Science, vol. 42, pp. 8189–8193, 2007, doi: 10.1007/s10853-007-1690-y.

[44] Phong, P. H., et al., "Studies of the magnetic properties and specific absorption of Mn0.3Zn0.7Fe2O4 nanoparticles," Journal of Electronic Materials, vol. 44, pp. 287–293, 2015, doi: 10.1007/s11664-014-3463-0.

[45] Meng, X., et al., "Structure and magnetic properties of Mn(Zn)Fe2−xRExO4 ferrite nano-powders synthesized by co-precipitation and refluxing method," Powder Technology, vol. 229, pp. 270–275, 2012, doi: 10.1016/j.powtec.2012.06.050.

[46] Moulin, J., et al., "Magnetic properties of MnZn ferrite with ultra-fine grain structure," Journal of Magnetism and Magnetic Materials, 2003.

[47] Mohammed, M. M., et al., "Modification of dielectric and mechanical properties of rubber ferrite composites containing manganese zinc ferrite," Materials Research Bulletin, vol. 37, pp. 753–762, 2002, doi: 10.1016/S0025-5408(02)00690-6.

[48] Thakur, P., et al., "Study of dielectric behaviour of Mn–Zn nano ferrites," Journal of Physics and Chemistry of Solids, vol. 68, pp. 378–382, 2007, doi: 10.1016/j.jpcs.2006.11.028.

[49] Tsutaoka, T., "Frequency dispersion of complex permeability in Mn–Zn and Ni–Zn spinel ferrites and their composite materials," Journal of Applied Physics, vol. 93, pp. 2789–2796, 2003, doi: 10.1063/1.1542651.

[50] Kogias, G., et al., "Temperature stable MnZn ferrites for applications in the frequency region of 500 kHz," Ceramics International, vol. 42, pp. 7639–7644, 2016, doi: 10.1016/j.ceramint.2016.01.176.