



A Review on Y-Type Hexagonal Ferrite

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Abstract. Ferrites, which are ceramic compounds or mixed crystals of different metallic oxides (Fe_2O_3) and are thought to be made up of cations occupying the spaces between oxygen ions in a close-packed structure. They are classified into two main types based on their magnetic properties: hard ferrites, that possesses high coercivity and soft ferrite, whose coercivity varies very low. They are classified into four different types according to their crystalline structure: spinel ferrites, garnet ferrites, hexaferrites, and orthoferrites. Each group represents a different manner in which atoms are arranged in the crystal lattice. Hexaferrite is a special class in which Y-type ferrites have the chemical formula $\text{Ba}_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}$. In this formula, the symbol “Me” represents a metal ion with a +2 charge. This can be zinc (Zn^{+2}), nickel (Ni^{+2}), cobalt (Co^{+2}), or magnesium (Mg^{+2}). Recent research has focused on containing various combinations of divalent and trivalent ions into Y-type hexaferrites, aiming to manipulate their crystal structure and enhance their electrical and magnetic properties, specifically targeting saturation magnetization and coercivity. Y-type ferrites are gaining importance in both scientific research and practical applications due to their exceptional dielectric loss characteristics and conductivity properties. These materials are increasingly utilized in various technological fields, including electromagnetic interference (EMI) shielding, microwave absorption, and applications in defense and aerospace industries. This study provides an in-depth examination of Y-type ferrites, exploring their synthesis methods, structural characteristics, and magnetic and dielectric properties.

Keywords: Ferrites, Hexaferrite, saturation magnetization, electrical properties.

1 Introduction. Modern communications systems, such as mobile phones and radar technology, depend on ferrite materials for their proper operation. These materials play a crucial role in enabling these technologies to function effectively. However, manufacturers are facing significant challenges in adapting these materials for miniaturized electronics. Scientific studies show that ferrites play an important role in modern communication systems, characterized by the extraordinary ability to behave like electrical insulators and at the same time perform signal transmission for magnetic signals [1]. As the demand for wireless communication devices increases, the researcher's approach for Y-type hexaferrites focuses on more cost-efficient and minimal temperature requirements compared to other hexagonal ferrite techniques to drive technological advancement. Magnetite (Fe_3O_4), which contains Fe^{+3} ions, is a type of iron oxide that belongs to the ferrite family of materials. They exhibit both ferromagnetic behavior and electrical insulation properties. Ferrites are the type of materials that belong to the category of hexagonal ferrites due to their hexagonal structure, while there are different ferrite structures such as spinel's and garnets. Among these hexagonal ferrites is particularly important for advanced technological applications. Research conducted over many decades has discovered numerous distinct properties exhibited among the different classes of hexagonal ferrites. Hexaferrites exist in several different types, each having a unique formula: Y-type with the formula $\text{Ba}_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}$, M-type composed of $\text{BaFe}_{12}\text{O}_{19}$, U-type structured as $\text{Ba}_4\text{Me}_2\text{Fe}_{36}\text{O}_{60}$, W-type made up of $\text{BaMe}_2\text{Fe}_{16}\text{O}_{27}$, X-type with the formula $\text{Ba}_2\text{Me}_2\text{Fe}_{28}\text{O}_{46}$, and Z-type consisting of $\text{Ba}_3\text{Me}_2\text{Fe}_{24}\text{O}_{41}$ [2]. In which Y-type hexaferrites are the first known ferroxplana materials (i.e., materials whose magnetic properties are oriented within a two-dimensional plane) in the hexaferrite family. Z-type and Y-type ferroxplana materials are the most recognized and research-oriented materials. In these ferrites, magnetization naturally occurs along a specific geometric plane (called the basal c-plane or a-b plane) that is perpendicular to the c-axis. This particular orientation of the magnetic easy plane is responsible for their ability to become magnetized spontaneously when at room temperature. Y-type hexaferrites have attracted significant research interest because their planar magnetic anisotropy results in better magnetic permeability in the GHz frequency range compared to hexaferrites with uniaxial magnetic anisotropy. The chemical formula of Y-type ferrite is $\text{Ba}_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}$, where "Me" can be any of several transition

metals with a +2 charge like Ni^{+2} , Cu^{+2} , Zn^{+2} , Mn^{+2} , Co^{+2} [3]. $\text{Ba}_{2-x}\text{Sr}_x\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ (BSZFO) Y-type hexagonal ferrite, where x ranges between 0.0 and 1.5 is specifically investigated by K. Rama Obulesu et al. [4]. Because of its strong planar magnetic anisotropy, this material stands out as a significant very high frequency and ultra-high frequency soft magnetic material. Because of the remarkable magnetic characteristics of Y-type ferrite, it has completely changed the technology of millimeter-wave and microwave devices. This review article provides several synthesis techniques for Y-type hexaferrite and studies the effect on structural, magnetic, microwave, and dielectric properties by various divalent metal ions. Y-type hexaferrites are studied for their potential in tunable microwave devices due to their ability to change magnetic properties under external fields.

1.1 Crystallite Structure of Y-type ferrite:

Ferrite's basic structure is made up of an interconnected arrangement where positively charged metal ions (including Fe^{+3} and Me^{+2}) are combined with divalent oxygen ions (O^{2-}) [5]. Y-type hexaferrites are an important class of magnetic materials with a complicated crystal structure. Their crystal system is rhombohedral, having a space group of R-3m [6]. The basic structure of Y-type ferrite is composed of alternating S and T units that together form a six-layer molecular arrangement. This six-layer pattern is repeated three times to make a complete unit cell, resulting in a c-axis that measures 43.56 Å in length. The structure of the T block does not have mirror symmetry, and therefore, three T blocks are required to properly align the hexagonal and cubic closed-packed layers. This arrangement also determines the periodic positioning of barium atoms, which repeat their pattern after every three T blocks [7]. The Y-type crystal structure is shown below in figure 1 as projected along the b axis. Ba^{+2} represents the large green and O^{2-} is indicated by the little red spheres. The distribution of Fe^{+3} in octahedral sites, whereas Me^{+2} is in tetrahedral sites, is random. Magnetic blocks S and T have collinearly aligned Fe^{+3} magnetic moments [8].

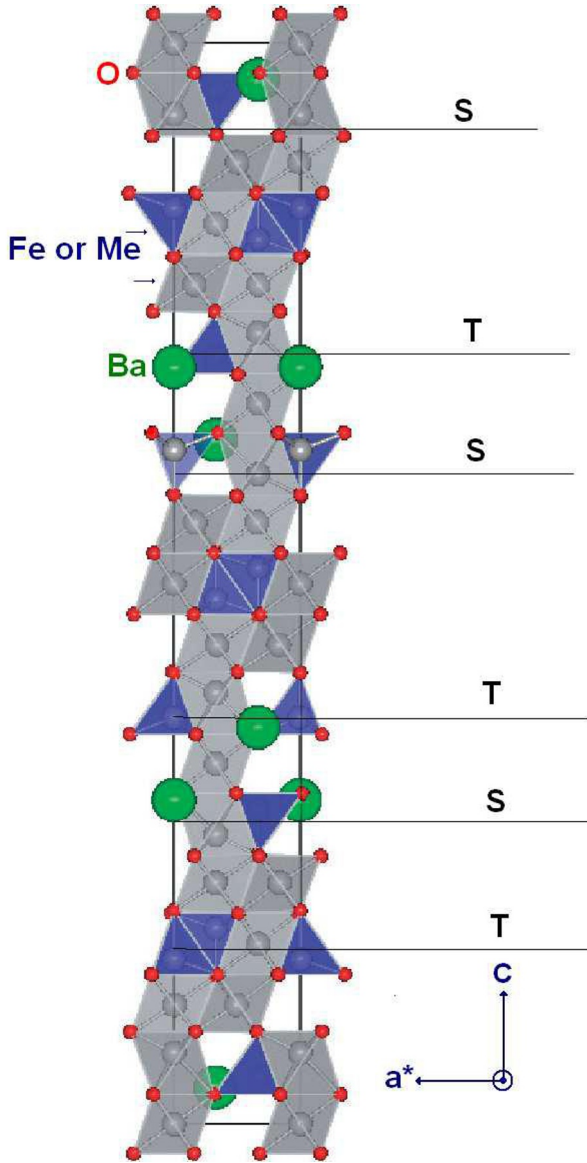


Figure 1. Atomic-scale arrangement illustrating the crystalline structure of Y-type hexaferrite. [8]

1.2 Characteristics of Y-type hexa-ferrite:

Y-type hexaferrite possesses unique magnetic and electrical properties that make it advantageous for many applications. Its crystal structure is defined by the R3m space group [9], with specific lattice constants where 'a' is 5.93 Å and 'c' is 43.33 Å [4]. They produce considerable magnetic permeability (5.0 emug^{-1}) [10] with lower magnetic losses, mainly favorable at high frequencies. High electrical resistivity (5.46 gcm^{-3}) [7] also exists for them, which helps to suppress the eddy current losses. Hexaferrites tend to offer anisotropic magnetic characteristics, which are orientation dependent owing to their crystal structure. Although they exhibit only relatively moderate saturation magnetization ($42 \text{ A m}^2 \text{ kg}^{-1}$) [7], generally much less than spinel ferrites (50.4 emug^{-1}) [11], they retain Curie temperatures typically in the range of 130°C [7], depending on the composition. The ferromagnetic resonance frequencies vary significantly between materials: $\text{Ba}_2\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ (Zn_2Y) shows a range of 1.1-1.4 GHz at room temperature [12], whereas $\text{Sr}_{1.5}\text{Ba}_{0.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ reaches 9.5 GHz [13]. Another interesting characteristic is their typically low magnetostriction, which is advantageous for certain applications. One of their most valuable characteristics is that they can be tuneable in magnetic properties by modifying their chemical compositions for specific application requirements.

1.3 Applications of Y-type hexa-ferrite: Y-type ferrites find widespread applications in various fields such as electronics and telecommunications due to their exceptional magnetic properties at high frequencies [14]. These multifunctional materials are important for microwave technology, where they are commonly employed in circulators, isolators, and phase shifters. Y-type ferrites contribute to the development of compact and efficient antennas, particularly used in mobile devices [2]. Their ability to suppress electromagnetic interference makes them valuable in reducing electronic noise in circuits. Y-type ferrites' unique properties make them particularly well-suited for high-density magnetic recording media. Furthermore, because of their special magnetic properties, Y-type ferrites are used in a variety of radar components. Lastly, due to their high-frequency performance, they are used in some satellite components [6]. The applications of Y-type are shown in figure 2.

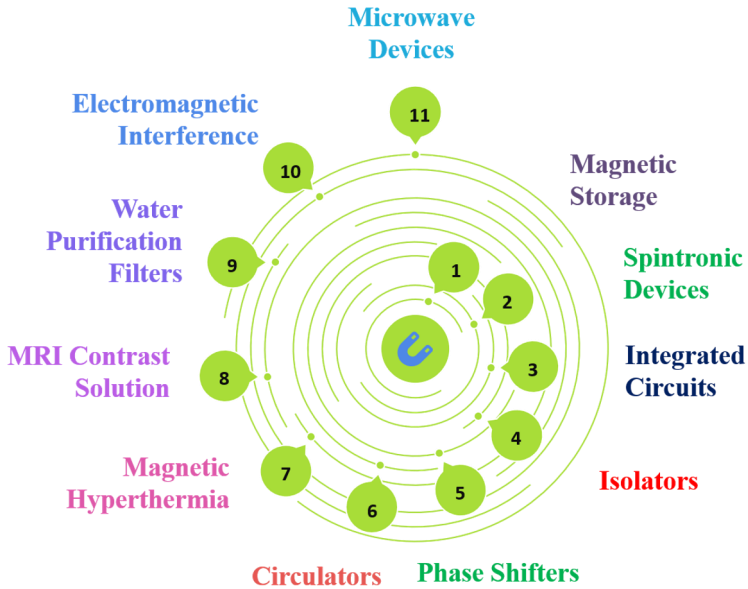


Figure 2. Schematic representation of the diverse applications of Y-type hexaferrite.

2. Synthesis of Y-type ferrite: The Y-type ferrite typically forms at temperatures ranging from 900 to 1200°C, which is the lowest temperature range necessary for its synthesis [6]. Various chemical methods that are employed for the synthesis of Y-type hexagonal ferrites, such as sol-gel combustion [6], coprecipitation [8], hydrothermal [9], solid-state synthesis [5], micro-emulsion [15], and reverse micro-emulsion [6] methods. Many researchers have utilized these methods to produce Y-type hexaferrite for a wide range of applications [6]. Xiaozhi Zhang and Jincang Zhang prepared polycrystalline $\text{Ba}_2\text{Fe}_2^{+2}\text{Fe}_{12}^{+3}\text{O}_{22}$ (Fe_2Y) samples in which both Fe^{+2} and Fe^{+3} were synthesized through sintering and calcination processes conducted in the presence of nitrogen via the solid-state reaction method then magnetic properties were examined [16]. Charalampos A. Stergiou et al. [17] prepared Y-type hexagonal ferrites with the composition $\text{BaSrCo}_{2-x}\text{Ni}_x\text{Fe}_{12}\text{O}_{22}$ using the solid-state method. Their goal was to improve the electromagnetic properties for high-frequency application of magnetic ceramic materials. They modify Y-type hexaferrites through doping to enhance both their magnetic and microwave

properties, making them suitable for high-frequency applications. Using the sol-gel method, Odeh et al. [10] produced a series of single-phase Co_2Y barium hexaferrite where zinc was substituted i.e., $\text{Ba}_2\text{Co}_{2-x}\text{Zn}_x\text{Fe}_{12}\text{O}_{22}$. The research showed that adding more zinc content enhanced magnetic saturation while reducing coercivity. This result opened up new ways for further investigation into the material's dielectric properties. Among various techniques, the sol-gel auto-combustion method stands out for its unique features, such as its simplicity, affordability, and ability to produce highly reactive nanopowders.

2.1 Sol-Gel Method:

In a sol-gel auto-combustion method, a homogenous solution of nitrates of metal is prepared with the help of citric acid as a fueling agent. The pH is adjusted by adding ammonia, leading to the formation of a sol that develops a gel-like structure as the water evaporates. Citric acid acts as a chelating agent, and when the nitrate-citrate gel is burned in air, it undergoes self-propagating combustion. This process produces a loose powder, which is then calcined at $1100\text{ }^\circ\text{C}$ for 4-5 hours, heating at a rate of $10\text{ }^\circ\text{C}/\text{min}$, ultimately yielding pure Y-type hexagonal ferrite [6][5][10]. The sol-gel technique offers several benefits, including a lower annealing temperature and exceptional control over the microstructure [5].

2.2 Co-precipitation Method:

Since the 1960s, the chemical co-precipitation technique required mixing metal nitrates in specific molar ratios with deionized water. The mixture is heated to $70\text{ }^\circ\text{C}$ and stirred magnetically for 15 minutes to create a homogenous solution. A base (NaOH) is then added dropwise until the pH reaches 11. The solution is further heated to $100\text{ }^\circ\text{C}$, used for 2 hours, and left to age at room temperature with continuous stirring for 24 hours. The particles are purified by centrifugation using a 1:1 mixture of methanol-acetone solution and deionized water as washing agents. The particles are then desiccated at $80\text{ }^\circ\text{C}$ for 24 hours in an oven. Finally, they are calcined at $950\text{ }^\circ\text{C}$ for 4 hours and allowed to cool to room temperature in the furnace. This process yields single-phase Y-type hexaferrite nanoparticles [6][8].

2.3 Hydrothermal Method:

In this hydrothermal technique, the presence of NaOH or KOH (as the base), along with nitrates, hydroxides, and Fe:Ba ratios, is essential to facilitate the co-precipitation of metal nitrates in an aqueous solution. The autoclave heat treats the mixture at temperatures of 150°C and 290°C. The obtained metal precipitates are filtered out and washed to remove impurities, followed by drying the particles. The final step involves sintering the dried powder at temperatures between 110°C and 200°C [9]. For the hydrothermal process, the interest has been growing for about 15 years by researchers and scientists [9]. This technique is a synthesis that creates materials in a liquid environment under controlled conditions of elevated pressure and temperature. Its benefits include the ability to control shape formation, energy efficiency, and less pollution during synthesis [6].

2.4 Solid State Method:

The conventional solid-state reaction method is the easiest and most cost-effective. Precursors, namely carbonates (BaCO_3 , SrCO_3) and oxides (Fe_2O_3 , Co_2O_3 , NiO), are first mixed wet for 12 hours. The mixtures were subjected to calcination at 1100°C for 4 hours [5][17]. After the reaction process, the powder was ground, a process that may introduce contamination and defects in the crystal structure and has the potential to alter its magnetic characteristics [5].

2.5 Micro-emulsion Method:

In this method, the metallic salts in specific molar concentrations were mixed together in deionized water [6]. A surfactant, CTAB (cetyltrimethylammonium bromide), was introduced to a metal solution in a ratio of 1:15 (metals to CTAB), which was further magnetically stirred until the solution became clear. Now, ammonia solution as a precipitating agent was added gradually. After that, the precipitates are cleaned with methanol and dried at 150 °C. Finally, annealing is performed in a furnace at 1050 °C for a duration of 8 hours [6][18]. The micro-emulsion technique is a highly flexible approach for the preparation of nanoparticles, providing fine-tuned control over properties such

as particle size, shape, and uniformity. Microemulsions have a wide range of uses and applications in both biological and chemical and scientific fields.

2.6 Reverse Micro-emulsion Method:

The concept of the reverse micro-emulsion method was initially introduced by Schulman [19]. This system is a thermodynamically balanced mixture composed of oil, water, and surfactant, and in some cases, a co-surfactant. The term “reverse” in this describes a specific arrangement of the micro-emulsion component, consisting of water droplets suspended within oil (w/o) using micelles, rather than oil droplets suspended in water (o/w) [6]. M. Abdullah Dar et al. [20] synthesized $\text{Ni}_{0.7}\text{Zn}_{0.3}\text{Fe}_2\text{O}_4$ ferrite nanoparticles using the reverse micro-emulsion method. In this method, cyclohexane as an oil phase, cetyltrimethylammonium bromide (CTAB) as the surfactant, and iso-amyl alcohol as the co-surfactant were added to an aqueous solution of reactants (5.5 wt%) until it became clear. Two separate micro-emulsions were prepared: one containing metal nitrates like $\text{Fe}(\text{NO}_3)_3$, $\text{Ni}(\text{NO}_3)_2$, and $\text{Zn}(\text{NO}_3)_2$, and another with NaOH as the aqueous phase. These emulsions were mixed at 80°C , maintaining a pH of 9. To complete the reaction, the emulsions were stirred for 2 hours, and acetone and isopropanol were added to the solution. The solid product was then separated via centrifugation, cleaned, and heated at 100°C for 12 hours to yield final nanocrystals.

3. Properties of Y-type Hexaferrite:

3.1 Structural properties:

The X-ray analyzes the crystalline structure of Y-type ferrite, even after the initial sintering process [17], and this analysis was conducted at room temperature [10]. XRD is used to determine average crystallite size for the samples through the Scherrer equation (1):

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

Where D represents the crystallite size of the material, k is the Scherrer constant ($k = 0.94$), λ is the wavelength of X-ray radiation used i.e., 1.5405 \AA , β represents full width and half maximum (measured in radians), and θ is the angle and position of the diffraction peak [21].

Y. Alizad Farzin et al. [15] prepared Y-type ferrite doped by both Mg-Ni using the sol-gel method. Their XRD patterns show that the Y-type hexaferrite formed as the main phase at $950 \text{ }^\circ\text{C}$, along with the presence of impurity phases such as $\alpha\text{-Fe}_2\text{O}_3$ and SrO. Sol-gel auto-combustion was used by S.H. Mahmood et al. [21] to create Y-type barium ferrites doped with Co. Their results show temperature-dependent formation of phase in the synthesis of Y-type hexa-ferrites, emphasizing the importance of high sintering temperatures ($> 1000 \text{ }^\circ\text{C}$) for achieving pure single-phase products. Borislava Georgieva et al. [22] synthesized Y-type ($\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$) hexaferrite using two methods: a modified co-precipitation technique (sonochemistry) and sol-gel auto-combustion. The structural and magnetic properties of the resulting materials were investigated. ZnFe_2O_4 appears as a secondary phase in the first method of XRD analysis, whereas the Y-type hexaferrite structure serves as the main phase in all samples. However, the sample prepared through the second method, i.e., sonochemistry, only displays faint ZnFe_2O_4 peaks, indicating minimal presence of the secondary phase. The sample produced via sonochemistry showed stronger and sharper peaks than the sol-gel auto-combustion sample, indicating a high degree of crystallinity.

Some papers emphasizing the influence of ion substitutions on lattice parameters and crystal morphology, such as Y-type ($\text{Ba}_2\text{Co}_{2-x}\text{Zn}_x\text{Fe}_{12}\text{O}_{22}$) hexaferrite prepared by I. Odeh et al. [10] using the sol-gel method, show XRD analysis that described the compositional effects on crystal structure in Y-type hexaferrite. K. Rama Obulesu et al. [4] investigated the structural, magnetic, and microwave dielectric characteristics of Zn_2Y hexagonal ferrite, synthesized using the solid-state reaction technique. X-ray diffraction confirmed that the sample crystallizes into a rhombohedral structure by matching the peaks with the JCPDS reference data. They revealed the effects of Sr substitution on the crystal structure, lattice parameters, and density of Zn_2Y -type hexaferrites, with the presence of a secondary ZnFe_2O_4 phase also noted. Charalampos A. Stergiou et al. [17] developed Y-type hexagonal ferrites for use in microwave absorber

and antenna applications. They observed difficulties when increasing the nickel content and suspected that the impurities were caused by reduced mobility of Ba and Sr ions within the nickel-rich hexagonal ferrite structures. A solution was implanted to achieve pure Y-type crystal structures. These identifications were made using standard JCPDS reference patterns.

Based on a review of the literature, it is evident that synthesis methods and processing conditions play a crucial role in determining the structural properties and phase formation of Y-type hexaferrites. Techniques such as sol-gel, sonochemistry, and solid-state reactions have been widely employed, each offering unique benefits and limitations. Among them, sonochemical synthesis tends to yield samples with higher crystallinity and fewer secondary phases compared to the sol-gel auto-combustion method. Achieving a pure single-phase Y-type hexagonal structure typically requires high sintering temperatures (>1000 °C). Ion substitutions—such as Sr, Co, Ni, Mg, and Zn—can significantly influence the crystal structure, lattice parameters, and magnetic behavior, although they may also promote the formation of secondary phases like ZnFe_2O_4 and $\alpha\text{-Fe}_2\text{O}_3$. X-ray diffraction (XRD) remains a key characterization tool, providing insights into phase purity, structural attributes, and impurity phases. Such understanding is essential for optimizing synthesis parameters to tailor the material properties for targeted applications, particularly in microwave and antenna technologies.

3.2 Morphology:

The scanning electron microscope (SEM) is a highly effective tool within the field of electron microscopy. It allows researchers to examine the structure and composition of ferrites and devices at extremely small scales, down to the nanometer level, providing detailed insights into features with high resolution and requiring electrically conductive samples. The information gathered from a sample can come from varying depths, spanning from 1 nanometer (when using Auger electrons) to 5 micrometers (when using characteristic X-rays). Samples need to conduct electricity well. If a sample is not electrically conductive, it must either be coated with a metal layer before being examined [23]. Energy Dispersive X-ray Spectroscopy (EDS) complements SEM by identify-

ing and quantifying elemental composition, detecting elements with atomic numbers greater than 3 [24].

Morphology refers to the structural properties and external configuration of the surface. In the study of $\text{Sr}_2\text{Cu}_{2-x}\text{Co}_x\text{Fe}_{12}\text{O}_{22}$ hexaferrite samples produced via co-precipitation, Rajshree B. Jotania et al. [8] employed a scanning electron microscope (SEM) for detailed analysis. The SEM micrographs revealed a varied array of particle sizes, from micro to nanoscale, with the presence of agglomeration. The researchers observed that the cobalt content had a significant impact on both the size of the particle and the overall morphology of the hexaferrite samples. G. Murtaza et al. [18] used SEM to determine the morphology and particle size of Y-type hexaferrites with varying Nd-Mn substitution levels. They observed a transition from clearly defined hexagonal structures to more irregular, rounded shapes as substitution levels increased, along with homogeneity at higher substitution levels. I. Odeh et al. [10] analyzed SEM of Zn-substituted hexaferrite samples, focusing on grain morphology (platelet-like), size, and structure changes with different levels of Zn substitution in Y-type. Borislava Georgieva et al. [22] analyze the SEM for the $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ sample, showing irregular shapes as morphology, and the particle size distribution is broad, spanning from 200 to 1000 nanometers. Y-type barium ferrites synthesized with Co doping, using a sintering temperature of 1100 °C for all samples by S.H. Mahmood et al. [25]. They observed that the particles exhibited a platelet-like structure. Interestingly, while the sintering conditions remained constant, they noted that the morphological features of the particles varied depending on the degree of Zn substitution for Co in the ferrite composition.

In conclusion, the morphology of Y-type hexaferrites is strongly influenced by both the type and concentration of ionic substitutions, as well as the synthesis conditions employed. SEM analyses from various studies reveal a broad range of particle sizes—from nanometers to micrometers—and diverse morphologies, including well-defined hexagonal platelets and irregular rounded forms. Substitutions such as Co, Nd-Mn, and Zn have been shown to significantly impact particle shape and size, with cobalt notably increasing grain size and Nd-Mn inducing a shift from hexagonal to rounded structures. Even under identical sintering conditions, variations in substitution levels, such as replacing Co

with Zn, can lead to distinct morphological outcomes. A common observation across synthesis methods is the aggregation of particles, with size distributions typically ranging from 200 to 1000 nm. These insights underscore the necessity of precisely tuning both chemical composition and processing parameters to tailor the morphological features of hexaferrites for targeted applications.

3.3 Magnetic properties of Y-type ferrite:

The Vibrating Sample Magnetometer analyzes magnetic characteristics across various fields and material forms [1]. It can effectively measure various magnetic properties such as magnetically soft (easily demagnetized) and hard (resistant to demagnetization) and works with various material forms, including solid pieces, powdered samples, single crystals, thin films, and liquid substances. Hexaferrites, known for their essential magnetic properties, are important in various technological applications. These materials exhibit ferromagnetic behavior, and Y-type hexaferrites demonstrate ferroelectric polarization under applied magnetic fields due to their spiral magnetic structure. The magnetic properties of these materials are basically a direct consequence of how their crystals are arranged; in fact, the way they arrange themselves will influence their magnetic behavior. The Y-type hexaferrite can be enhanced by the substitution of divalent, trivalent, and tetravalent elements in place of Fe^{+3} ions to achieve desired magnetic properties and also improve performance for microwave applications [1]. The magnetic characteristics of a two-phase nanocomposite magnet are influenced by several factors related to its structure, such as shape, distribution, and grain size. Additionally, the overall magnetic behavior is strongly influenced by two key interactions between the -magnetic components- exchange interactions and dipolar interactions [26]. Y-type hexagonal ferrites ($\text{Sr}_2\text{Cu}_{2-x}\text{Co}_x\text{Fe}_{12}\text{O}_{22}$) were synthesized and characterized, and their structural, magnetic, and dielectric characteristics were examined using the wet chemical co-precipitation process in a review of the structure of several hexaferrite types by Rajshree B. Jotania [8]. They discuss the magnetic properties of cobalt-doped strontium copper hexa-ferrite and highlight how cobalt doping impacts magnetization, leading to a magnetic state transition from ferromagnetic to super-paramagnetic. G. Murtaza et al. [18] synthesized a series of hexaferrites with Nd and Mn substitutions using the micro-emulsion technique, which gives clarity of composition and synthesis method of these hex-

a-ferrites. They observed high saturation magnetization with low coercivity. I. Odeh et al. [10] prepared Y-type hexaferrites with the formula $Ba_2Co_{2-x}Zn_xFe_{12}O_{22}$, examining their synthesis, structure, and both dielectric and magnetic characteristics using the sol-gel method. They revealed that higher amounts of zinc in the material led to an increase in the sample's saturation magnetization.

Table 1. Comparison of Magnetic saturation (M_s), Coercivity (H_c) and Retentivity (M_r) in various ferrites.

Ferrite	Sample	M_s ($emug^{-1}$)	H_c (Oe)	M_r ($emug^{-1}$)	Ref	
Spinels	$NiFe_2O_4$	50.4	--	--	[11]	
	$Ni_{0.7}Zn_{0.3}Fe_2O_4$	6.1	7.9	--	[20]	
	$Ni_{0.7}Zn_{0.3}Fe_2O_4$	31	17	--	[20]	
	$CoFe_2O_4$	44.505	89.58	29.95	[27]	
M-Type	$BaFe_{12}O_{19}$	60.175	860	14.60	[28]	
	$BaCo_xZr_xFe_{12-2x}O_{19}$ ($x=0-1.0$)	56.94- 62.44	630.214- 5428.32	23.39- 33.44	[29]	
Y-Type	Zn_2Y	$SrFe_{12}O_{19}$	55.73	1.06 K	16.23	[30]
		$Ba_2Zn_2Fe_{12}O_{22}$	41	8.39	--	[5]
		$Ba_2Zn_2Fe_{12}O_{22}$	35.2	45	5.0	[10]
		$BaSrFe_{12}O_{22}$	28.8	17.7	--	[5]
		$Ba_{0.5}Sr_{1.5}Zn_2Fe_{12}O_{22}$	38	18	--	[21]
	Co_2Y	$BaSrCo_2Fe_{12}O_{22}$	32.5	74	--	[17]
		$BaSrCoNiFe_{12}O_{22}$	25	49	--	[17]
		$Ba_2Co_2Fe_{12}O_{22}$	31.1	255	14.3	[10]
		Ba_2Co_2 $_xCu_xFe_{12}O_{22}$ ($x=0.0-0.8$)	31.7- 27.74	172-136	1.88- 2.85	[14]
	Mg_2Y	$Ba_2CoZnFe_{12}O_{22}$	38.5	95	10.0	[10]
		Sr_2Co_2	55.53	634	19.11	[15]
		$_xMg_{x/2}Ni_{x/2}Fe_{12}O_{22}$	22.78	31.35	--	[31]
$Ba_2Mg_2Al_{x/2}Cr_{x/2}Fe_{12}O_{22}$		19.85	16.66	1.20	[32]	
Ni_2Y		$BaSrNi_2Fe_{12}O_{22}$	21	31	--	[17]
Cu_2Y		$Sr_2Cu_2Fe_{12}O_{22}$	60.10	--	27.50	[8]
Fe_2Y		$Ba_2Zn_xFe_{12}O_{22}$ ($x=0.5-2.0$)	35.4- 44.7	19-46	1.1-3.4	[3]
	$Ba_2Fe_{2-2x}Fe_{12-3x}O_{22}$	38.5	1k	--	[16]	

Table 1 presents a comparative analysis of the magnetic properties—namely saturation magnetization (M_s), coercivity (H_c), and magnetic retentivity (M_r)—across three major categories of ferrites: spinel, M-type, and Y-type. The saturation magnetization shows notable variation among these categories. Spinel ferrites exhibit a wide range from 6.1 to 50.4 emu/g, while M-type ferrites demonstrate consistently higher values, ranging from 55.73 to 62.44 emu/g. Y-type ferrites display the broadest range, with M_s values spanning from 19.85 to 60.10 emu/g. This indicates that M-type ferrites generally possess the highest magnetic saturation, although Y-type ferrites offer considerable variability depending on composition. Coercivity (H_c) trends further distinguish the ferrite types. Spinel ferrites typically show low coercivity values (7.9 to 89.58 Oe), whereas M-type ferrites display a much wider and significantly higher range (630.2 to 5428.3 Oe), reflecting their strong magnetic anisotropy. Y-type ferrites fall in an intermediate range, generally between 8.39 Oe and a few kilo-Oersteds, depending on the substitution and synthesis conditions. In terms of magnetic retentivity (M_r), data for spinel ferrites is limited, while M-type ferrites offer more comprehensive values. Y-type ferrites, however, show restricted retentivity data, with values largely dependent on compositional modifications. Overall, while spinel ferrites are known for their excellent soft magnetic properties, M-type ferrites stand out in terms of high magnetic performance. Y-type ferrites, despite moderate coercivity and saturation values, offer greater flexibility through compositional tuning. Notably, elemental substitution emerges as a critical factor that significantly alters the magnetic behavior across all ferrite systems, underscoring its importance in tailoring materials for specific applications.

3.4 Microwave properties:

The Vector Network Analyzer (VNA) examines the frequency responses of networks (active and passive) and measures signal power [1], amplitude, and phase at frequencies ranging from a few Hz to many GHz, thus making it critical for radio frequency and microwave engineering applications [32]. Hexagonal ferrites have attracted considerable attention as materials for microwave applications in the frequency of 1- 100 GHz [4]. In 1966, R.A. Braden identified Y-type compounds that exhibited the most promising characteristics for microwave applications [33]. A well-known example of this is

Mg_2Y , referred to as ferroxplana [4]. To study microwave properties, a solid understanding of magnetic properties is essential, as they are closely connected to the use of ferrites in microwave devices. The resonance properties of the material are greatly influenced by its high anisotropy, which is reflected by its substantial anisotropy (H_A). This strong anisotropic field leads to a weak ferromagnetic resonance (FMR) occurring at the unusually high frequency of 5.7 GHz. It is essential to understand the relationship between anisotropy and resonance behavior for evaluating the material sustainability for high-frequency and microwave properties. The magnetic properties of $\text{Ba}_2(\text{Ni}_{1-x}\text{Zn}_x)_2\text{Fe}_{12}\text{O}_{22}$ ceramic are significantly changed by zinc substitution when compared to pure Co_2Y . This results in maintaining high permeability while slightly decreasing the FMR frequency, which can be useful in some applications, as discussed by Robert C. Pullar [34]. Co_2Y fibers in composite form are appropriate for microwave applications because they exhibit multiple resonance peaks and their ability to maintain high permeability below resonance. Additionally, Zn_2Y exhibits two distinct FMR frequencies, the first of which has high permeability, suggesting that it could be used in high-frequency devices or electromagnetic wave absorption. They also investigated how the addition of Zn with Cu significantly altered the magnetic properties of hexaferrites [1]. The change in permeability and FMR behavior were explained by changes in the material's anisotropy and domain wall dynamics, which are crucial factors in determining its overall magnetic performance. Also, the sintering temperature affects the ferromagnetic resonance behavior, as higher temperatures lead to larger grain size. This increase in grain size allowed domain walls to contribute to FMR, resulting in more complex resonance patterns with multiple peaks [17]. Ibrahim Mohammed et al. investigated the significance of remanent magnetization in ferrite materials, particularly for their use in microwave devices [1]. Hexagonal ferrites offer several advantages in electrical and microwave devices, such as the capacity to operate at high frequencies, the removal of conductor losses, strong electrical resistivity, and quick domain realignment. Domain realignment has the advantage of minimizing energy losses. They are especially helpful in microwave and high-frequency devices because of their increased resistivity and decreased dielectric properties [16]. D. Basandrai et al. gives the relationship between radiation loss, reflection loss, and magnetic properties in hexaferrite samples.

$$\text{Reflectionloss}(dB) = 20 \log \frac{(Z - 1)}{(Z + 1)}$$

Where, Z is impedance ratio.

They investigated the effects of doping and the magnetic properties of the hexaferrite on reflection loss analysis, which is evaluated in the X-band frequency range (8-12.3 GHz). For example, materials with higher saturation magnetization exhibited lower reflection loss (R_L), while those with lower M_s had high R_L . This is important for applications in electromagnetic wave absorption or shielding. They obtained a good reflection loss of -37.25 dB, which enables the material to be used in microwaves and communication devices [32]. Braden et al. [33] suggest that the hexagonal ferrite has a potential application in microwave devices operating in the gigahertz range. They obtained anisotropy field values ranging from 0 to 40000 Oe, with resonant line widths varying between 100 and 1200 Oe. These substances seem to have potential technology, particularly for equipment operating at frequencies higher than 10 GHz.

From above, we concluded that Y-type hexagonal ferrites are considered to be highly suitable for microwave applications because of their unique magnetic properties, which include high anisotropy and the ability to operate at high frequencies. Modifications of zinc substitution and adjustment in the sintering temperature would significantly affect the ferromagnetic resonance behavior and permeability in these materials and improve their performance for certain applications. These materials have good resistivity, low dielectric losses, and efficient domain realignment, making them suitable for high-frequency applications. The reflection loss parameters reveal the electromagnetic performance of these ferrites. Doping of Y-type hexagonal ferrites indicates potential for electromagnetic wave absorption and shielding in the X-band range of 8-12.3 GHz. Higher magnetic saturation indicates lower reflection loss values, which are appropriate for microwave and communication devices.

3.5 Dielectric properties:

To prepare for dielectric and impedance measurements, they were conducted using an LCR Hi-tester at room temperature, spanning a frequency range varying from 42 Hz to 5 MHz [35].

For hexaferrites to be used in high-frequency applications, especially as integrated chip components, their dielectric and magnetic characteristics are essential. Permittivity and resistivity are two important properties that are very significant. Permittivity, also known as relative permittivity (ϵ_r) or dielectric constant (ϵ), measures a material's ability to support an electric field. For most applications, both resistivity and permittivity should be high at high frequencies. A researcher examined the impact of cation deficiency on the Y phase formation in hexaferrites, specifically in the compound $\text{Ba}_2\text{Zn}_{0.6}\text{Co}_{0.6}\text{Cu}_{0.8}\text{Fe}_{12-x}\text{O}_{22-1.5x}$. They revealed that in cation-deficient ferrite, resistivity decreases as temperature increases, thus limiting charge variation on iron ions. The deficiencies tend to concentrate at grain boundaries, creating a more resistive surface layer, which hinders electrical conduction. However, at high sintering temperatures, the number of grain boundaries decreases, reducing the insulating effect, and the elevated temperature also promotes the formation of Fe^{+2} ions [7]. Impedance analysis is a technique used to examine several key parameters, such as the dielectric constant (ϵ'), which reflects the material's capacity to store electromagnetic energy, and dielectric loss (ϵ''), which indicates the dissipation of electromagnetic energy within the material relative to the applied field, and the dielectric loss tangent ($\tan \delta$), which indicates the transformation of electrical energy into heat. The ϵ' decreasing with increasing frequency is typical for ferrimagnetic materials. The reduction in ϵ' indicates energy dissipation, which signifies dielectric loss ($\tan \delta$). The AC electrical conductivity (σ_{AC}) exhibits distinct behavior across different frequency ranges, such as remaining constant at low and mid-range frequencies and not being influenced by substitution of Cr^{+3} and Ni^{+2} ions. However, it sharply increases at higher frequencies, which is attributed to electronic polarization caused by electron hopping between ferrous and ferric ions at the octahedral sites [1]. A study examined by Ram Oblu et al. [5] the dielectric constant and dielectric loss of $\text{Ba}_{2-x}\text{Sr}_x\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ samples in terms of measurement at room temperature over the frequency range 8.2 to 12.4 GHz.

With increasing strontium substitution concentration, the dielectric constant increases as the frequency decreases, while dielectric loss rises as the frequency increases. Their findings revealed that the dielectric constant in ferrites is strongly influenced by the presence of Fe^{+2} ions, which are readily formed due to the high Fe^{+3} ions. As higher Fe^{+3} concentration leads to an increased dielectric constant. The rise in dielectric constant with Sr^{+2} ion substitution can be attributed to the polarization mechanism in ferrites. The dielectric properties of polycrystalline ferrites result from both interfacial polarization and intrinsic electric dipole polarization. The intrinsic dipole polarization is caused by electron hopping between Fe^{+2} and Fe^{+3} at the octahedral sites. Due to smaller number of hopping electrons, it lowers the permittivity. The distribution of cations affects the electronic structure and conductivity of Y-type hexagonal ferrite. In Zn_2Y ferrite, Sr substitution alters the relative occupation of Zn^{+2} and Fe^{+3} , increasing permittivity as Sr content rises. Higher dielectric constant and dielectric loss values are found when Sr introduces multivalent states into the system, causing electron hopping and polarization flipping. Additionally, dielectric loss becomes frequency-dependent with the introduction of Sr in the majority of compositions, indicating the start of relaxation behavior. In the X-band frequency range, there is an increase in both the dielectric constant and dielectric loss. Rajshree B. Jotania et al. [8] studied the dielectric constant (ϵ') and found that it decreases as the measurement frequency increases, reflecting an inverse relationship between ϵ' and frequency. This behavior is linked to the polarization process in ferrites. The peaks in the $\tan\delta$ vs. log frequency curve can also be explained by the polarization process in ferrites. As reported by I. Odeh et al. [10] in 2016, the dielectric measurement revealed that all samples exhibit insulating properties, with the alternating current (AC) conductivity decreasing as zinc content increases. However, the AC conductivity rose with increasing direct current (DC) bias. This DC bias effect was noticeable in samples containing less zinc. At a constant applied bias voltage, the real component of the dielectric constant showed a significant decrease as frequency increased. Additionally, the activation energy of the prepared samples was found to be heavily dependent on the zinc concentration. The dielectric characteristics of all samples were experimentally measured over a temperature range of 30°C to 100°C and a frequency range from 13 Hz to 1 MHz.

Y-type hexaferrites are ideal for high-frequency applications due to their dielectric and magnetic properties, such as high permittivity and resistivity. High permittivity and dielectric loss are influenced by ion substitution. On the other hand, due to cation deficiency, AC conductivity rises sharply at higher frequencies, which also affects the resistivity and grain boundary behavior and reduces the conduction. The sintering temperature influences dielectric loss, which is frequency dependent and crucial for X-band applications.

4. Conclusion:

The Y-type hexagonal ferrites ($\text{Ba}_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}$) combine a rhombohedral R-3m structure with planar magnetic anisotropy, which yields high magnetic permeability (5.0 emug^{-1}) and low magnetic loss at gigahertz frequencies. Their relatively moderate saturation magnetization ($42 \text{ A m}^2 \text{ kg}^{-1}$) and high electrical resistivity ($5.46 \text{ } \Omega \text{ cm}$) also inhibit eddy-current losses, making them perfect for miniaturised microwave components. A wide variety of synthesis methods- including sol-gel auto-combustion, co-precipitation, hydrothermal, solid-state, and micro-emulsion techniques which allow precise control of phase purity, grain size, and microstructure, all of which play a strong influence in magnetic and dielectric behaviour. Ionic substitution (e.g., Zn, Co, Ni, Sr, Mg) provides a versatile tool tune lattice parameter, increase saturation magnetization, vary coercivity, and shift ferromagnetic resonance frequencies into the 1-10 GHz. As a result, Y-type ferrites have been successfully applied in circulators, isolators, phase shifters, compact antennas, EMI shielding layers, and high-density magnetic recording media. Their high permeability, low dielectric loss, and resistance stability across the X-band also enable their application in advanced RF and microwave devices. Future work should focus on optimizing synthesis parameters to reduce secondary phases, using multivalent dopants for increasing tunability, and integrating these materials in planar chip-scale architectures for next generation communication and sensing technologies.

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