Synthesis, characterization, dielectric and magnetic properties of substituted Y-type hexaferrites

Syeda Rabia Batool\textsuperscript{1}, Muhammad Aslam Malana\textsuperscript{2}, Nada Al-Fryyan\textsuperscript{3}, Muhammad Naeeem Ashiq\textsuperscript{2,*}, Faryal Aftab\textsuperscript{2}, Salma Aman\textsuperscript{4,*}, Sajjad Ahmad Khan\textsuperscript{4}, Z. A. Alrowaili\textsuperscript{5}, M. S. Al-Buriahi\textsuperscript{6}, and Sultan Alomairy\textsuperscript{7}

\textsuperscript{1}Department of Chemistry and Applied Biosciences, Institute for Chemical and Bioengineering, ETH Zurich, 8093 Zurich, Switzerland
\textsuperscript{2}Institute of Chemical Sciences, Bahauddin Zakariya University, Multan 60800, Pakistan
\textsuperscript{3}Department of Physics, College of Science, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia
\textsuperscript{4}Department of Physics, Khwaja Fareed University of Engineering and Information Technology, Abu Dhabi Road, Rahim Yar Khan 64200, Pakistan
\textsuperscript{5}Department of Physics, Sakarya University, Sakarya, Turkey
\textsuperscript{6}Department of Physics, College of Science, Jouf University, P.O.Box: 2014, Sakaka, Saudi Arabia
\textsuperscript{7}Department of Physics, College of Science, Taif University, P.O.Box 11099, Taif 21944, Saudi Arabia

Received: 3 January 2022
Accepted: 24 May 2022
Published online: 15 June 2022

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

ABSTRACT

Fabrication of a series of zinc–strontium hexaferrites, \(\text{Sr}_2\text{Zn}_{2-x}\text{Mn}_x\text{Fe}_{12-y}\text{Ho}_y\text{O}_{22}\) \((x = 0.0–1.0, \ y = 0.0–0.1)\) was carried out by chemical co-precipitation route with the aim to enhance the saturation magnetization and coercivity and decrease the resistivity to make the materials applicable for recording media of high-density applications. The synthesized hexaferrites were interpreted by Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD). The results of XRD investigation certify the single magnetoplumbite phase formed in hexaferrites with regular crystallite particle size in the 31–38 nm range. Magnetic and dielectric properties of the hexaferrites were also observed. The dielectric parameters (dielectric loss also its tan loss and dielectric constant) were measured at ambient temperature and in 1.0 MHz to 3.0 GHz frequency range. These parameters of Mn–Ho-substituted Zn–Sr hexaferrites showed constant trend with frequency up to a certain value after that resonance sort of behavior was observed. In all the hexaferrites dielectric parameters initially decrease with frequency then become almost constant followed by resonance type behavior. The dielectric parameters of the synthesized samples decrease with dopant content initially but then increase up to maximum dopant level. The saturation magnetization \((M_s)\) and remanence \((M_r)\) increase as the dopant content increases due to magnetic substituents. The squareness ratios of all the nanomaterials...
1 Introduction

Over the past few years, the upsurge of pollution posed by electromagnetic radiations has caused a severe hazard to environment and human health. Therefore, researchers are driven to focus on synthesis of magnetic materials, which can serve as absorbers for electromagnetic radiations. In this respect, ferrites are most popular materials because of their excellent magnetic behavior [1–3]. These materials are very stable, electrically resistive and magnetically ferromagnetic due to which they are widely used for permanent magnets, magnetic recorders, memory chips and microwave devices [4]. Because of their structure, one can classify ferrites as garnets, ortho-ferrites, hexagonal ferrites and spinel ferrites [5]. Hexaferrites have gained extensive attention in technological fields during the last few decades because of their ease of manufacturing, low cost and remarkable electrical, dielectric and magnetic properties. Their properties are strongly influenced by manufacturing conditions, e.g. sintering temperature and time, composition, nature and extent of doping, etc. [6, 7]. They are now considered as the materials of demand for their applications in magnetic recording, microwave devices and multi-layer chip inductors [5]. Based upon their crystal structure and chemical composition, these ferrites are of six major types, i.e. M, W, Y, X, Z and U type hexaferrites. These hexaferrites differ from each other because of the different super-positioned arrangements of R, S and T building blocks [5]. Among these hexagonal ferrites, Y-type hexaferrites are an assembly of basic units of hexagonal barium M type ferrite and cubic spinel ferrites. They have otherwise complex structure but retain hexagonal structure parallel to the c-axis [8]. Thus Y-type ferrites are self-biased i.e. they possess uniaxial magnetic anisotropic field along with the easy axis of magnetization (normal to c-axis). Therefore they have a favored plane to align the saturation magnetization and this particular plane can be selected as a plane of microwave devices [9]. As the operational frequencies of electronic devices are escalating to GHz range, so there is a need to propose materials that are suitable candidates for gigahertz frequency range. Y-type hexagonal ferrites have a planar magnetic assembly and excellent magnetic behavior possessing cut off frequencies in GHz range to meet the requirements for the above mentioned applications [10].

Earlier investigations are mainly dedicated for the adjustment of the intrinsic magnetic and electrical properties of hexaferrites by doping them with either single trivalent metal ions or the suitable combinations of divalent and trivalent metal ions keeping in view the end applications. Iqbal et al. reported the nano-sized crystallites of Y-type strontium hexaferrites (Sr$_2$Ni$_2$Fe$_{12}$O$_{22}$) and its Mn- and Cr-doped derivatives [11]. The magnetic properties of Y-type hexaferrites with formula Ba$_2$Me$_2$Fe$_{12}$O$_{22}$ (Me = Zn, Co, Cu) have been investigated by Bai et al. [10]. Xu et al. reported effects of aluminum substitution on the crystal structure and magnetic properties in Zn$_2$Y-type hexaferrites [12]. Mirzaee et al. studied the effect of co-doping of Al and Cr on magnetic and structural properties of Y-type hexaferrites [13]. Nikzad et al. studied the role of Al supplant on structural and magnetic properties of Y-type strontium hexaferrites [14]. Farzin et al. reported the influence of Mg and Ni replacement on structural, microstructural and magnetic characteristics of Sr$_2$Co$_{2-x}$Mg$_x$Fe$_{12}$O$_{22}$ (Co$_2$Y) hexaferrite [15]. However, the Y-type hexaferrites co-doped with rare earths along with the combination of transition metals have been less explored in literature.

Rare-earth elements (RE) have typical relaxation properties, which can contribute to change the magnetic interactions and considerably affect the electromagnetic properties of ferrites. Ali et al. [16] used an interesting approach of co-doping the rare earth (RE) terbium Tb$^{3+}$ at the octahedral site (Fe$^{3+}$ site) and transition metal manganese Mn$^{2+}$ at tetrahedral site (Co$^{2+}$ site) in Sr$_2$Co$_2$Fe$_{12}$O$_{22}$ hexaferrite. They report that, Mn$^{2+}$ with greater number of unpaired electrons (5e$^-$) than Co$^{2+}$ (3e$^-$) and Tb$^{3+}$ with greater number of electrons (6e$^-$) than Fe$^{3+}$ (5e$^-$) gainfully enhanced the magnetic properties of hexaferrite. Thus, the combination of rare earth cation and transition metal cation shows excellent magnetic properties, i.e. increase in coercivity and decrease in...
saturation magnetization. Therefore, in search of novel materials with promising magnetic and dielectric properties, we have chosen rare earth holmium (Ho$^{3+}$) at iron (Fe$^{3+}$) site and transition metal manganese (Mn$^{2+}$) at zinc (Zn$^{2+}$) site for substitution in Y-type Sr–Zn hexaferrite to tune the dielectric and magnetic behavior of these materials for magnetic recording media applications. The aim of the present research work is to correlate systematically, the effect of occupation sites and transition metal and RE metal cations on the structure, magnetic and dielectric behavior of nano-sized Y-type hexagonal ferrites. This work leads towards a fine understanding and potential use of these materials as electromagnetic wave absorbers in GHz range. For the synthesis of hexaferrite materials, different low temperature synthetic procedures, e.g. hydrothermal method, sol–gel method, citrate precursor technique, micro-emulsion technique, aerosol pyrolysis method, co-precipitation method, sonochemical method and glass crystallization method, etc. are employed keeping in view the homogeneity of the product material [17, 18]. However, co-precipitation technique is very efficient for the stoichiometric preparation of the product with controlled particle size thus ensuring the uniform distribution of different ionic species, e.g. co-precipitated Sr-hexaferrites exhibited smaller particle size when compared with the samples synthesized from glass crystallization and sol–gel method [19–21]. Therefore, we adopt chemical co-precipitation method as a synthetic route, in the present work, to prepare Mn–Ho-substituted Y-type hexaferrites.

2 Experimental

2.1 Chemicals

The starting materials used for the synthesis of Mn–Ho substituted Y-type Sr–Zn hexaferrites are strontium nitrate Sr(NO$_3$)$_2$ (Fluka, 99%), zinc nitrate hexahydrate Zn(NO$_3$)$_2$·6H$_2$O (Fluka, ≥ 99%), ferric nitrate nonahydrate Fe(NO$_3$)$_3$·9H$_2$O (Riedel deHaen, 97%), manganese chloride tetrahydrate MnCl$_2$·4H$_2$O (Fluka, 97%) holmium nitrate pentahydrate Ho(NO$_3$)$_3$·5H$_2$O (Aldrich, 99%) and potassium hydroxide KOH (Sigma Aldrich, 99%). All the chemicals were of analytical grade and were used without further treatment.

2.2 Synthetic procedure

The Mn–Ho-substituted strontium (Sr) hexaferrites with a nominal composition of Sr$_2$Zn$_{2-x}$Mn$_x$Fe$_{12-y}$Ho$_y$O$_{22}$ (x = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0 and y = 0.0, 0.02, 0.04, 0.06, 0.08, 0.1) were prepared by co-precipitation technique. Metal salt solution’s stoichiometric amounts were mixed together in 2000 ml beaker stirred at ambient temperature for 30 min on a magnetic stirrer. The molar ratio of 11 was maintained for iron (Fe) and strontium (Sr) instead of 12 because of the solubility reasons. The solution mixture was allowed to stir again at 333 K for 30 min. The pH of the solution was maintained at 10–11 by the dropwise addition of precipitating agent (KOH). The resultant mixture was further allowed to stand for 3 h at 333 K with constant stirring. The precipitates obtained were thoroughly washed and dried overnight at 373 K followed by grinding of precipitates using Agar Pestle Mortar. The precipitates were annealed in a Muffle furnace at 1173 K for 9 h to obtain the hexagonal phase. The annealed brownish ferrite powders were preserved for further studies.

2.3 Characterizations

The crystalline phase of the nanoparticles was determined using PANalytical X-ray diffractometer having CuK$_{α}$ as radiation source (λ = 1.5418 Å) with 40 kV generator voltage and 40 mA current. Different structural parameters, i.e. lattice constants, unit cell volume and crystallite size were calculated using following equations [11, 22, 23]:

$$\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2}$$

$$V_{cell} = 0.8666a^2c$$

$$D = \frac{K\lambda}{\beta \cos \theta}$$

The morphology and microstructure of the nanoparticles was investigated using Jeol JSM 5910 scanning electron microscope. The magnetic properties of synthesized materials were investigated at room temperature using Lake Shore-74071 vibrating magnetometer sample with the applied field ranging from 10 to 40 kOe. Moreover, the dielectric behavior of the nanoparticles was studied using computer controlled Material Analyzer/RF Impedance, Agilent E4991A with the maximum applied electric field of...
3.0 GHz. The AC conductivity of the samples was also calculated using following equation [24]:

$$\sigma_{ac} = \omega \cdot \varepsilon_0 \cdot \varepsilon''$$  \hspace{1cm} (4)

3 Results and discussion

3.1 XRD analysis

Figure 1 shows the XRD patterns for all the prepared materials. All the diffraction peaks show perfect match with reference pattern having code ICDD 00-019-0100 and were indexed accordingly by their corresponding h k l values. These XRD patterns verify the development of single Y-type phase in all the synthesized ferrites. However, the substitution of iron and zinc with dopants of different ionic radii produces minor shifts in peak positions. There is a slight increase in intensity of some diffraction peaks by this substitution which explains the slight improvement in crystalline nature of the synthesized samples suggesting the thorough solubility of Mn$^{2+}$ & Ho$^{3+}$ species in crystal framework of the Y-type Sr–Zn hexaferrite system [25].

The crystallite size of the synthesized compounds is in the range 27–38 nm (Table 1) that is very small, when compared with already reported materials. As pointed out by Che et al., less than 50 nm mean crystallite size is required to acquire the suitable signal to noise ratio for large density recording applications [26]. In present work, the Mn–Ho doped Sr–Zn hexaferrites have small enough size (< 50 nm) to attain the proper signal to noise ratio for the mentioned application.

The replacement of zinc and iron ions with manganese and holmium ions, respectively, reveals a slight alteration in lattice parameters, i.e. ‘a’ & ‘c’. The parameter “a” shows a variation from 5.86 to 6.01 Å and the lattice constant ‘c’ increases from 42.96 to 43.42 Å as listed in Table 1. It can be explained in terms of the difference in radii of the doped and the parent ionic species. The doping of elements of the larger ionic radius Mn (0.80 Å) and Ho (0.90 Å) [27] at the place of elements with smaller ionic size Zn$^{2+}$ (0.74 Å) and Fe$^{3+}$ (0.64 Å) induces enhancement in the lattice parameters ‘a’ and ‘c’. These results is are in good agreement with those already observed by different researchers [28, 29]. Moreover, the variation in the lattice constants points out that Mn and Ho ions are fully dissolved into the Sr–Zn–Y crystal framework. There is a gradual increase in cell volume ($V_{cell}$) of the crystal structure with the increase in dopant contents and the values of $V_{cell}$ are given in Table 1. This increase in $V_{cell}$ with dopant content is attributed to the direct dependence of cell volume with lattice constants ‘a’ and ‘c’ and can also be ascribed by the incorporation of large sized dopant cations [28, 29].

3.2 SEM analysis

The representative scanning electron microscopy (SEM) images for the parent Sr$_2$Zn$_2$Fe$_{12}$O$_{22}$ compound and substituted Sr$_2$Zn$_{2-x}$Mn$_x$Fe$_{12-y}$Ho$_y$O$_{22}$ ($x = 0.4$, $y = 0.04$) are given in Fig. 2a, b. The SEM image of the parent compound (Fig. 2a) depicts rather smooth surface, possessing the clusters of a

![Fig. 1 Powder XRD patterns of Sr$_2$Zn$_{2-x}$Mn$_x$Fe$_{12-y}$Ho$_y$O$_{22}$ hexaferrites ($x = 0.0–1.0, y = 0.0–0.1$)](image-url)
number of nanoparticles (irregularly shaped) which are formed because of agglomeration. The formation of clusters of several nanoparticles is because of the chemical reactions, throughout the sintering process. It is the weak Vander Waal’s interactions and magnetic bonds that are responsible to grip these agglomerates together [30]. Due to the effect of continuing forces, the individual agglomerates can be preserved. The particles are not uniformly oriented with narrow grain size distribution i.e. 0.211–1.54 μm. This grain size distribution has also been stated for hexaferrites by Wang et al. [31].

Due to the doping of Mn and Ho (Fig. 2b), the surface of material becomes rough, with non-uniform and irregular shaped particles. It is clear that the surface porosity also increases due to dopant addition and agglomerations are increased as well. The particles that are agglomerated together are of different sizes and shapes. Due to enhanced porosities, the average grain size distribution increases i.e. 0.769–2.11 μm. Hence, we infer that due to the substitution of Mn and Ho, surface of the substituted compound, shape of particles and grain size distribution becomes heterogeneous. Moreover, we notice that the size of crystallites computed by SEM is larger when compared with the particle size calculated from XRD data. It may be attributed to the existence of agglomerations of particles appearing in SEM images as discussed by researchers for other hexaferrites [32].

3.3 Dielectric studies

3.3.1 Frequency-dependent behavior of dielectric parameters

Figure 3 demonstrates the frequency dependence of dielectric constant ($\varepsilon'$) for all samples. It is obvious in the figure that the dielectric constant shows fall initially with rise in frequency, then becomes almost constant to a certain frequency, i.e. 1.6 GHz after which resonance type behavior can be observed. The decline of dielectric constant due to rise of frequency is a frequent dielectric behavior of ferrites which has been observed by various other researchers [33, 34]. The higher magnitude of dielectric constant in the region of lower frequency may be attributed to large number of species like ferrous metal ions, interfacial dislocations stacks, oxygen gaps, grain boundary defects, etc. [35]. While the fall of dielectric constant with frequency may be related to the dispersion caused by interfacial polarization of Maxwell–Wanger type, that agrees well with Koop’s phenomenological theory [36].

This model proposes that the dielectric materials having dissimilar structure may be expected to hold conducting grains, separated by grain boundaries that are poor conductors. Literature has established that the major basis of polarization phenomenon in ferrites is the electron hopping between ions of iron. The escalation of frequency decreases the polarization after which, it gets stable. The constant behavior of dielectric constant observed at higher frequencies, in the current results, relates to the deficiency of harmonization between induced electric moment and the frequency of external field which results in frequency invariant behavior of dielectric constant. After crossing a definite frequency of applied field, the exchange electronic interactions, between ferrous and ferric ionic species, become equivalent to the frequency of the applied field which leads to resonance nature character in the produced hexaferrites [37, 38]. A resonance peak observed at 1.67–2.17 GHz for all the compounds relates to the ionic relaxation taking place in different environment. The ionic relaxation in such ferrites may be related to the different valencies of ions [39]. This resonance type behavior holds good with the work, reported earlier.

Fig. 2 SEM images of a Sr$_2$Zn$_2$Fe$_{12}$O$_{22}$, b Sr$_2$Zn$_{2-0.4}$Mn$_{0.4}$Fe$_{12-0.04}$Ho$_{0.04}$O$_{22}$
Dielectric loss (Fig. 4) and dielectric tan loss (Fig. 5) also show the same trend with frequency as does the dielectric constant.

3.3.2 Composition-dependent behavior of dielectric parameters

The influence of Mn–Ho contents on the dielectric parameters, i.e. dielectric constant as well as dielectric loss for parent and doped Sr–Zn hexaferrites is presented in Fig. 6. The dielectric constant \( \varepsilon' \) and dielectric loss \( \varepsilon'' \) can be observed to decrease by the replacement of Mn and Ho with two \( \text{Fe}^{3+} \) ions. The reduction in dielectric constant with the addition of Ho and Mn contents is due to the enhancement of resistivity of the compounds. The microstructure including grain boundary and porosity, etc. plays an important role for the elucidation of resistivity and dielectric behavior [7]. The dielectric polarization is actually due to the formation of dipoles of cations and neighboring oxygen ions. However, in ferrites, primary source of dielectric dispersion is the electronic jumping between \( \text{Fe}^{3+} \) and \( \text{Fe}^{2+} \) ions at octahedral symmetry sites. Due to electronic hopping, intrinsic displacement of charge carriers occurs, which is responsible for the dielectric dispersion and relaxation [43–45]. In case of hexaferrites, the extent

![Fig. 3 Frequency-dependent behavior of dielectric constant for Ho–Mn-substituted Sr–Zn Y-type hexaferrites \((x = 0.0–1.0, y = 0.0–0.1)\)](image1)

![Fig. 4 Frequency-dependent behavior of dielectric loss for Ho–Mn-substituted Sr–Zn Y-type hexaferrites \((x = 0.0–1.0, y = 0.0–0.1)\)](image2)

![Fig. 5 Frequency-dependent behavior of dielectric tan loss for Ho–Mn-substituted Sr–Zn Y-type hexaferrites \((x = 0.0–1.0, y = 0.0–0.1)\)](image3)
maximum value of dielectric constant of sample with maximum substitution is still less than that of undoped compound. The decrease in the permittivity with the dopant content is largely due to reduction in electron exchange between $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^{-}$, which subsequently decreases the electric dispersion and dielectric constant.

When the $\text{Ho}^{3+}$ ions reach at the octahedral sites, they will cause decrease in $\text{Fe}^{3+} - \text{Fe}^{2+}$ ion pairs numbers at this site. As a result of reduced ion pairing, interfacial dispersion will also decrease leading to the decline of $\varepsilon'$ and $\varepsilon''$ in the synthesized samples [7]. The literature reports that $\text{Mn}^{2+}$ ions have strong preference for the tetrahedral $6c_{1v}$ symmetry sites and almost 80% of the $\text{Mn}^{2+}$ cations tend to reside in the tetrahedral sites but rest of $\text{Mn}^{2+}$ ions also occupy the octahedral sites [46]. These $\text{Mn}^{2+}$ ions going to octahedral sites inside the T block are also responsible for lessening the $\text{Fe}^{3+} - \text{Fe}^{2+}$ ion pairs at octahedral sites. Because of these factors, dielectric polarization decreases in all the doped materials as depicted in Fig. 6.

It is an established fact in the literature that nanomaterials with less dielectric constant are usefully employed for high frequency applications [47]. In the present work, the Mn–Ho-substituted materials possessing lower dielectric constant than that of unsubstituted hexaferrite can therefore be employed as suitable candidates in high frequency applications [18]. The sample with dopant level $x = 0.2, y = 0.02$ may be regarded most appropriate for this concern.

Figure 7 shows that, with an increase in dopant concentration, the dielectric tan loss reveals the same behavior as do the dielectric constant and dielectric loss.

### 3.3.3 Room temperature AC conductivity

The room temperature AC conductivity values, calculated using dielectric data are plotted with respect to frequency in Fig. 8. The room temperature AC conductivity also demonstrates similar behavior with frequency, as do the dielectric parameters. According to Murthy and Sobhanadri [48], a firm correlation exists regarding dielectric phenomenon and conductivity mechanism in ferrites. By considering the polarization phenomenon similar as the conduction phenomenon, they concluded that exchange of electrons between $\text{Fe}^{2+}$ and $\text{Fe}^{3+}$ causes local shifts thus giving birth to the polarization in the ferrite systems. In the current studies, dielectric results are in accordance with above-mentioned argument.

### 3.3.4 Cole–Cole plots

The representative Cole–Cole plots of the Mn–Ho-substituted $\text{Sr}_2\text{Zn}_2\text{Fe}_{12-y}\text{Ho}_y\text{O}_{22}$ hexaferrites ($x = 0.0, y = 0.0, x = 0.2, y = 0.02$ and $x = 1.0, y = 0.1$) are presented in Fig. 9. The left low frequency portion of the semicircle explains the grain resistance; the intermediate frequency regions depicts grain boundary resistance and the high frequency region in
the right side of semicircle explains the collective resistance of both the grains as well as grain boundaries [10, 49].

The substituents usually make less effect to grain resistance while showing an enormous increase in resistance of the grain boundaries, i.e. greater the Ho addition, greater would be the resistance of grain boundaries. The principal mechanism of conduction in ferrites is regarded as the hopping of electron between iron ions of different valency. Therefore, limitation of exchange of electrons between Fe$^{2+}$ and Fe$^{3+}$ will occur due to an increase in Ho concentration at the area of iron. Hence, the grain boundary content and composition are responsible for the difference in resistivity of ferrites. At the grain boundaries, regions of high resistance form to restrain the conductivity. The high resistance of the grain boundaries has decisive importance for the determination of resistivity and dielectric parameters.

3.4 Magnetic properties

3.4.1 Hysteresis

The hysteresis curves for the unsubstituted Sr–Zn hexaferrite and its Mn–Ho-doped samples are depicted in Fig. 10. The parents as well as the doped samples show complete saturation in the studied of magnetic field range. Various magnetic parameters like remanence $M_r$, saturation magnetization $M_s$, and coercivity $H_c$, have been calculated from hysteresis curves.

The change in these magnetic properties by the doping of various cations is due to the effect of stoichiometry of cations as well as their site preferences in the crystallographic sites [50]. The knowledge of allocation of dopants in a variety of interstitial sites is very crucial to enlighten the magnetic character of Y-type hexaferrites. Therefore, we investigated our materials keeping in consideration the site occupancy of the substituent cations in S & T units of Y-type structure. T unit can accommodate three ions in each formula unit. It comprises of two symmetry sites that are octahedral (6cv$^I$ & 3 bv$^I$), present end to end with vertical threefold axis. The octahedral site 3bv$^I$ interestingly shares its two surfaces of coordination with 6cv$^I$ sites present adjacent to it [46]. Thus, this 3bv$^I$ site present in the center of T block has very strong connection with ions present in 6cv$^I$ symmetry site. Hence, 3bv$^I$ site beautifully interlinks lower and
upper portion of unit cell of Y-type systems. Such an organization of two octahedral symmetry sites residing at distances in the T unit is accountable for assembling structural configuration of very high potential energy (Table 2).

3.4.2 Saturation magnetization (M_s) & remanence (M_r)

The values of saturation magnetization (M_s) and remanence (M_r) for the parent Sr–Zn hexaferrite and its Mn–Ho-doped samples are given in Table 3. Generally, M_s and M_r are expected to exhibit same trend and this is true in the present case. The careful examination of spinel block present in Y-type structure establishes that super exchange contact is responsible of magnetic ordering occurring between the octahedral and the tetrahedral sites (3a_v1 and 6c_1v respectively) of this block. In the present series, doping of rare earth Holmium ion in place of iron site is chiefly responsible for concentrating the magnetic interactions because Ho has greater magnetic moment (10 μB) than that of Fe (5 μB) [51]. Holmium has strong preference for 3a_v1 octahedral site, thus at this site, the number of unpaired electrons is enhanced and the magnetic moment will increase. As a result, enhancement in super exchange interaction of 3a_v1 and 6c_1v sites occurs. Thus raising the content of Ho increases the net magnetization level at 3a_v1 symmetry site resulting in enhanced saturation magnetization and remanence. Moreover, it is an established fact that Mn^{2+} ions have strong preference at the tetrahedral sites. Almost 80% of the Mn^{2+} ions occupy the tetrahedral sites and remaining will reside at octahedral sites. Although, only a small amount of Mn^{2+} occupy the octahedral sites inside the T block, still it is able to favor the occurrence of drastic variations in the magnetic configuration with respect to the usual Gorter’s scheme.

3.4.3 Coercivity (H_c)

The values of coercivity for all the synthesized Sr_{2−x}Zn_{x}Mn_{x}Fe_{12−y}Ho_{y}O_{22} hexaferrites for x = 0.0–1.0, y = 0.0–0.1 are listed in Table 3. With an increase in the substitution of Ho–Mn, coercivity declines. Literature claims that coercivity and saturation magnetization are inversely proportional to one another through Browns equation i.e. $H_c = K_1/\mu_o M_s$ [52, 53]. In the equation $H_c$ is coercivity, $K_1$ is magnetocrystalline anisotropy, $M_s$ is saturation magnetization and $\mu_o$ is vacuum susceptibility. Our results of present studies are in good agreement with this relation i.e. with increase in dopant content $M_s$ increases and $H_c$ declines. If the value of $H_c$ is lower than $M_r/2$, the material will be a semi hard magnet and can be employed for information storage applications [22]. On the other hand, the materials with $H_c > M_r/2$ are regarded as hard magnets, employed in best frequency applications [54]. In the present studies, coercivity of all the compounds is greater than $M_r/2$. Therefore, these materials are considered hard magnets and can be used in high frequency media applications.

Furthermore, it is also an established criterion that the nanomaterials exhibiting the values of coercivity greater than 600 Oe are useful contenders for longitudinal magnetic recording media industries. The materials with coercivity values higher than 1200 Oe are favorable candidates for perpendicular recording media [55]. Keeping in consideration this fact, all the synthesized hexaferrite materials having coercivity

| Samples | Quality factor | Relaxation time (s) |
|---------|---------------|---------------------|
| H1      | 291           | $6.93 \times 10^{-11}$ |
| H2      | 2144          | $7.97 \times 10^{-11}$ |
| H3      | 426.7         | $1.12 \times 10^{-10}$ |
| H4      | 230.5         | $5.76 \times 10^{-11}$ |
| H5      | 367           | $7.32 \times 10^{-11}$ |
| H6      | 3786.6        | $7.74 \times 10^{-11}$ |
values above 1200 Oe can be employed as the suitable candidates for perpendicular magnetic recording media applications.

3.4.4 Squareness ratio ($M_{rs}$)

Squareness ratio ($M_{rs}/M_s$) of Ho–Mn-substituted Sr–Zn Y-type hexaferrites is calculated from VSM data using the equation $M_{rs} = M_r/M_s$ and are given in Table 3. The values of squareness ratio ($M_r/M_s$) for all the samples range from 0.47 to 0.50. It is reported in literature that the materials possessing squareness ratio greater than or equal to 0.5 are regarded in magnetic single domain and those with $M_{rs} \leq 0.5$ are considered to possess magnetic multi domain in their crystal structure [56]. In the present studies, $M_{rs}$ of all the hexaferrite materials is $\leq 0.5$, considering these compounds as randomly oriented multi-domain ferrites. Furthermore, the anisotropic constant $K$ was also determined by using an equation $K = H_c M_s/2$ to verify the multi-domain assemblies of the said materials [57]. The values of $K$ obtained for all the samples is lower than other reported ferrites which ascribes that the synthesized hexaferrite samples don’t possess single domain structure [58].

3.4.5 Effect of holmium and manganese on magnetic parameters

It is well known that Sr$_2$Zn$_3$Fe$_{12}$O$_{22}$ hexaferrite has a rhombohedral crystal system. In the hexagonal unit cell, every spinel layer and Sr–O block is repeated three times. The anion framework comprises of $c$-axis which is overlaid by two distinct layers; the first having only oxygen, the second with an ordered replacement of strontium for every fourth oxygen. All the smaller cations, i.e. Zn$^{2+}$ or Fe$^{3+}$ are present at positions inside the anion framework [55]. Since Zn is divalent, the average valency of Fe ions is three with oxygen anions present at vertices of a tetrahedron or an octahedron. Zn$^{2+}$ ions are diamagnetic because all the 3d electrons are paired but the antiferromagnetic exchange interactions can occur between neighboring Fe$^{3+}$ ions (five unpaired electrons). The O and Sr–O layer can interlink to form O, Sr–O, Sr–O, O structural blocks called S and T blocks, respectively, whereas, further stacking of S and T blocks gives the ST unit. The metallic cations are distributed among six sub-lattices as shown in Table 4. Three octahedral ions of $6_{cv1}$ and $3_{bv1}$ sub-lattices lie on a vertical threefold axis while the central $3_{bv1}$ ion sharing two faces of its coordination with the adjacent $6_{cv1}$ ions inside T block [51]. The choice of the dopant ions have a strong influence on the magnetic interactions in Y-type hexaferrites and play a decisive role for the end applications of these materials.

In the present case, the doping of the Y-type hexaferrite material with manganese and holmium resulted in considerable difference in magnetic properties i.e. saturation magnetization, remanence and coercivity. Figure 11 depicts the composition-dependent behavior of these parameters. We can see that the saturation magnetization and remanence of the materials increases due an increase in holmium and manganese content with slight exceptions. Whereas the coercivity of the materials drops considerably after first dopant concentration ($x = 0.2$, $y = 0.0–0.1$).

### Table 3  Magnetic parameters of Sr$_2$Zn$_{2-x}$Mn$_x$Fe$_{12-y}$Ho$_y$O$_{22}$ hexaferrites ($x = 0.0–1.0$, $y = 0.0–0.1$)

| Samples | $M_s$ (emu/g) | $M_r$ (emu/g) | $H_c$ (Oe) | Sq. ratio $M_r/M_s$ | Anisotropic constant (erg/cm$^3$) | $M_r/2$ |
|---------|---------------|---------------|-----------|-------------------|-------------------------------|---------|
| H1      | 53.15         | 25.20         | 4103.09   | 0.47              | $1.1 \times 10^4$            | 12.60   |
| H2      | 56.86         | 28.72         | 4045.40   | 0.50              | $1.2 \times 10^4$            | 14.36   |
| H3      | 67.26         | 32.14         | 5132.81   | 0.47              | $1.7 \times 10^4$            | 16.06   |
| H4      | 61.10         | 29.66         | 4590.96   | 0.48              | $1.4 \times 10^4$            | 14.83   |
| H5      | 74.58         | 34.98         | 4484.44   | 0.47              | $1.6 \times 10^4$            | 17.49   |
| H6      | 66.37         | 32.67         | 5203.67   | 0.49              | $1.7 \times 10^4$            | 16.34   |

### Table 4  Number of ions per unit formula, coordination and spin orientation for the various metallic sublattices of Y-type structure

| Sublattices | Coordination | Block | Number of ions | Spin |
|-------------|--------------|-------|----------------|------|
| 6$_{cv1}$   | Tetrahedral  | S     | 2              | Down |
| 3$_{bv1}$   | Octahedral   | S     | 1              | Up   |
| 1$_{bw1}$   | Octahedral   | S–T   | 6              | Up   |
| 6$_{cv1}$   | Octahedral   | T     | 2              | Down |
| 6$_{cv1}$   | Tetrahedral  | T     | 2              | Down |
| 3$_{bv1}$   | Octahedral   | T     | 1              | Up   |
After which there is a sharp increase in the coercivity at $x = 0.4$, $y = 0.06$, after which it almost remains constant. Ho$^{3+}$ ions with greater number of unpaired electrons ($7e^-$) than Fe$^{3+}$ ions ($5e^-$) have strong preference for octahedral $3a_{v1}$ site, whereas, Mn$^{2+}$ ions which have greater number of unpaired electrons ($5e^-$) than Zn$^{2+}$ (0e) have strong preference for the tetrahedral $6c_{1v}$ sites. Firstly, as the number of unpaired electrons increases due to the doping of Ho$^{3+}$ at Fe$^{3+}$ at $3a_{v1}$ site, the net magnetic moment at this site increases. Consequently, there should be an upsurge in super exchange interactions between octahedral $3a_{v1}$ and tetrahedral $6c_{1v}$ sites, leading to an increase in saturation magnetization and remanence. Secondly, almost 20% of the Mn$^{2+}$ ions occupy the octahedral sites in the T block, which can also add to increase the magnetic moment at octahedral sites. This is the reason we see an average increase in $M_r$ and $M_s$ after doping. Furthermore, literature reports that the RE cations usually increase the coercivity of the hexaferrite material [46]. Therefore, after an initial huge drop of coercivity at first dopant concentration (following Brown’s equation), coercivity increases due to greater concentration of holmium in the materials.

4 Conclusions

Mn–Ho-substituted Sr–Zn hexaferrites were synthesis by following an economical chemical co-precipitation route. XRD results confirm the formation of pure hexagonal phase in the substituted samples. The mean crystallite size of 31–38 nm suggests these materials as useful contenders for high frequency magnetic recording applications. The mean crystallite size of 31–38 nm suggests these materials as useful contenders for high frequency magnetic recording applications. SEM analysis suggests the enhancement of roughness of the surface, extent of agglomerations, particle size, etc. The dielectric constant, loss and dielectric tan loss of all the samples decreases with frequency, remained invariant up to particular frequencies and then resonance appeared. Moreover, Mn–Ho substitution results in the enhancement of saturation magnetization and remanence of the doped samples. Squareness ratios of all the compounds is less than 0.5 proposing that these materials are in multi-magnetic domains. The coercivity values of all the samples are greater than $M_r/2$ illustrating these materials as hard magnets, so these synthesized materials can be used in high frequency devices. The values of coercivity i.e. in the range 4000–5000 Oe propose the use of these materials in perpendicular magnetic recording applications.

Acknowledgements

The authors express their gratitude to Princess Nourah bint Abdulrahman University Researchers Supporting Project (Grant No. PNURSP2022R26), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia. Moreover, we would like to thank Taif University Research Supporting Project Number (TURSP-2020/63), Taif University, Taif, Saudi Arabia.

Author contributions

SRB, MAM: worked in the laboratory, i.e. experimental work done and also wrote the manuscript. SA: development or design of methodology; creation of models. NA, SAK, ZAA, MSA-B, SA: review writing and editing. FA: visualization. MNA: supervision.

Fig. 11 Composition-dependent saturation magnetization ($M_s$), remanence ($M_r$) and coercivity ($H_c$) of Sr–Zn Y type hexaferrites as a function of Mn and Ho content
Funding

This study was supported by Princess Nourah Bint Abdulrahman University [Grant No. PNURSP2022R26].

Data availability

Data sharing are not applicable to this article as no data sets were generated during the present study.

Declarations

Conflict of interest  The authors report no potential conflict of interest.

References

1. X. Chen, Y. Wang, H. Liu, S. Jin, G. Wu, Interconnected magnetic carbon@Ni_{x}Co_{1-x}Fe_{2}O_{4} nanospheres with core–shell structure: an efficient and thin electromagnetic wave absorber. J. Colloid Interface Sci. 606, 526–536 (2022)
2. C.-H. Wang, Y. Liu, J.-R. Luo, S.-K. Zheng, J. Tu, H.-Y. Xu, H. Huang, J.-M. Chen, P.-H. Wang, Deformation substructure development in Al_{x}CoCrFeNi (X = 0, 0.3) high entropy alloy under different influencing factors. J. Alloys Compd. 893, 162196 (2022)
3. D. Lan, Z. Zhao, Z. Gao, K. Kou, H. Wu, Novel magnetic silicate composite for lightweight and efficient electromagnetic wave absorption. J. Mater. Sci. Technol. 92, 51–59 (2021)
4. S.B. Narang, K. Pubby, Nickel spinel ferrites: a review. J. Magn. Magn. Mater. 519, 167163 (2021)
5. A. Houbi, Z.A. Aldashevich, Y. Atassi, Z. Bagasharova Telmanovna, M. Saule, K. Kubanych, Microwave absorbing properties of ferrites and their composites: a review. J. Magn. Magn. Mater. 529, 167839 (2021)
6. I. Ali, M.U. Islam, I. Sadiq, N. Karamat, A. Iftikhar, M.A. Khan, A. Shah, M. Athar, I. Shakir, M.N. Ashiq, Synthesis and magnetic properties of (Eu–Ni) substituted Y-type hexaferrite by surfactant assisted co-precipitation method. J. Magn. Magn. Mater. 529, 167839 (2021)
7. I. Ali, M. Islam, M.N. Ashiq, M.A. Iqbal, H.M. Khan, G. Murtaza, Role of grain boundaries in the conduction of Eu–Ni substituted Y-type hexaferrites. J. Magn. Magn. Mater. 362, 115–121 (2014)
8. M. Ahmad, M. Ahmad, I. Ali, W. Ahmad, G. Mustafa, M.N. Akhtar, A. Ali, G. Abbas, Temperature dependent structural and magnetic behavior of Y-type hexagonal ferrites synthesized by sol–gel auto-combustion. J. Alloys Compd. 651, 749–755 (2015)
9. M. Obol, X. Zuo, C. Vittoria, Oriented Y-type hexaferrites for ferrite device. J. Appl. Phys. 91, 7616–7618 (2002)
10. Y. Bai, J. Zhou, Z. Gui, L. Li, Electrical properties of non-stoichiometric Y-type hexagonal ferrite. J. Magn. Magn. Mater. 278, 208–213 (2004)
11. S.Z. Iqbal, R. Paterson, I.A. Bhatti, M.R. Asi, Survey of aflatoxins in chillies from Pakistan produced in rural, semi-rural and urban environments. Food Addit. Contam. 3, 268–274 (2010)
12. W. Xu, J. Yang, W. Bai, Y. Zhang, K. Tang, C.-G. Duan, X. Tang, J. Chu, Effects of aluminum substitution on the crystal structure and magnetic properties in Zn2Y-type hexaferrites. J. Appl. Phys. 117, 17D909 (2015)
13. O. Mirzaee, M. Mohamady, A. Ghasemi, Y.A. Farzin, Study of the magnetic and structural properties of Al–Cr codoped Y-type hexaferrite prepared via sol–gel auto-combustion method. Int. J. Mod. Phys. B 29, 1550090 (2015)
14. A. Nikzad, A. Ghasemi, M.K. Tehrani, G.R. Gordani, Y-type strontium hexaferrite: the role of Al substitution, structural, and magnetic consequence. J. Supercond. Nov. Magn. 28, 3579–3586 (2015)
15. M.R. Farzin, M.S. Kahreh, M. Hesan, A. Khalouei, A survey of critical success factors for strategic knowledge management implementation: applications for service sector. Procedia Soc. Behav. Sci. 109, 595–599 (2014)
16. I. Ali, M.U. Islam, M.N. Ashiq, M. AsifIqbal, N. Karamat, M.S. Awan, S. Naseem, Role of Tb–Mn substitution on the magnetic properties of Y-type hexaferrites. J. Alloys Compd. 599, 131–138 (2014)
17. K. Samikannu, J. Sinnappan, S. Mannarswamy, T. Cinnasamy, K. Thirunavukarasu, Synthesis and magnetic properties of conventional and microwave calcined strontium hexaferrite powder. Mater. Sci. Appl. 2, 638–642 (2011)
18. M.J. Iqbal, M.N. Ashiq, Physical and electrical properties of Zr–Cu substituted strontium hexaferrite nanoparticles synthesized by co-precipitation method. Chem. Eng. J. 136, 383–389 (2008)
19. L. Rezlescu, E. Rezlescu, P.D. Popa, N. Rezlescu, Fine barium hexaferrite powder prepared by the crystallisation of glass. J. Magn. Magn. Mater. 193, 288 (1999)
20. W. Zhong, W. Ding, N. Zhang, J. Hong, Q. Yan, Y. Du, Key step in synthesis of ultrafine BaFe_{12}O_{19} by sol–gel technique. J. Magn. Magn. Mater. 168, 196–202 (1997)
21. F. Leccabue, O.A. Muzio, M.S.E. Kany, G. Calestani, G. Albanese, Magnetic properties and phase formation of SrMn_{2}Fe_{16}O_{27} (SrMn_{2}–W) hexaferrite prepared by the coprecipitation method. J. Magn. Magn. Mater. 68, 201–212 (1987)
22. I. Ali, M. Islam, M. Aswan, M. Ahmad, Effects of Ga–Cr substitution on structural and magnetic properties of hexaferrite (BaFe12O19) synthesized by sol–gel auto-combustion route. J. Alloys Compd. 547, 118–125 (2013)

23. S.G. West, W.G. Graziano, Long-term stability and change in personality: an introduction. J. Pers. 57, 175–193 (1989)

24. L.-X. Dai, X.-L. Hou, Chiral Ferrocenes in Asymmetric Catalysis: Synthesis and Applications (Wiley, Hoboken, 2010)

25. I. Ali, M. Islam, M.N. Ashiq, H.M. Khan, M.A. Iqbal, M. Najam-Ul-Haq, Effect of Eu–Ni substitution on electrical and dielectric properties of Co–Sr–Y-type hexagonal ferrite. Mater. Res. Bull. 49, 338–344 (2014)

26. S. Che, J. Wang, Q. Chen, Soft magnetic nanoparticles of BaFe12O19 fabricated under mild conditions. J. Phys.: Condens. Matter 15, L335 (2003)

27. E. Pervaiz, I. Gul, High frequency AC response, DC resistivity and magnetic studies of holmium substituted Ni-ferrite: a novel electromagnetic material. J. Magn. Magn. Mater. 349, 27–34 (2014)

28. S. Ounnunkad, Improving magnetic properties of barium hexaferrites by La or Pr substitution. Solid State Commun. 138, 472–476 (2006)

29. M.J. Iqbal, S. Farooq, Extraordinary role of Ce–Ni elements on the electrical and magnetic properties of Sr–Ba M-type hexaferrites. Mater. Res. Bull. 44, 2050–2055 (2009)

30. W.E. Lee, M. Rainforth, Ceramic Microstructures: Property Control by Processing (Springer Science & Business Media, Berlin, 1994)

31. Y. Wang, L. Li, H. Liu, H. Qiu, F. Xu, Magnetic properties and microstructure of La-substituted BaCr-ferrite powders. Mater. Lett. 62, 2060–2062 (2008)

32. G. Asghar, M. Anis-ur-Rehman, Structural, dielectric and magnetic properties of Cr–Zn doped strontium hexa-ferrites for high frequency applications. J. Alloys Compd. 526, 85–90 (2012)

33. A.A. El Ata, S. Attaia, Dielectric dispersion of Y-type hexaferrites at low frequencies. J. Magn. Magn. Mater. 257, 165–174 (2003)

34. M.A. Iqbal, Mishbah-ul-Islam, I. Ali, H.M. Khan, G.M. Mustafa, I. Ali, Study of electrical transport properties of Eu³⁺ substituted MnZn-ferrites synthesized by co-precipitation technique. Ceram. Int. 39, 1539–1545 (2013)

35. J. Maxwell, Electric and Magnetism, vol. 2 (Oxford University Press, New York, 1973)

36. C.G. Koops, On the dispersion of resistivity and dielectric constant of some semiconductors at audiofrequencies. Phys. Rev. 83, 121–124 (1951)

37. S. Watawe, B. Sarwade, S. Bellad, B.D. Sutar, B.K. Chougule, Microstructure, frequency and temperature-dependent dielectric properties of cobalt-substituted lithium ferrites. J. Magn. Magn. Mater. 214, 55–60 (2000)

38. M.B. Reddy, P.V. Reddy, Low-frequency dielectric behaviour of mixed Li–Ti ferrites. J. Phys. D 24, 975 (1991)

39. Y. Wang, L. Zhou, M. Zhang, X. Chen, J.-M. Liu, Z. Liu, Room-temperature saturated ferroelectric polarization in BiFeO₃ ceramics synthesized by rapid liquid phase sintering. Appl. Phys. Lett. 84, 1731–1733 (2004)

40. D. Ravinder, P.V.B. Reddy, P. Shalini, Frequency and composition dependence of dielectric behavior of copper substituted lithium ferrites. J. Mater. Sci. Lett. 22, 1599–1610 (2003)

41. D. Ravinder, K.V. Kumar, Dielectric behaviour of erbium substituted Mn–Zn ferrites. Bull. Mater. Sci. 24, 505–509 (2001)

42. M.M. Haque, M. Huq, M. Hakim, Densification, magnetic and dielectric behaviour of Cu-substituted Mg–Zn ferrites. Mater. Chem. Phys. 112, 580–586 (2008)

43. P. Singh, V. Babbar, A. Razdan, S. Srivastava, V. Agrawal, T. Goel, Dielectric constant, magnetic permeability and microwave absorption studies of hot-pressed Ba–CoTi hexaferrite composites in X-band. J. Mater. Sci. 41, 7190–7196 (2006)

44. S.B. Narang, I. Hudiara, Microwave dielectric properties of M-type barium, calcium and strontium hexaferrite substituted with Co and Ti. J. Ceram. Process. Res. 7, 113–116 (2006)

45. S. Camci Cetin, A. Namli, R. Kizilkaya, O. Turgay, Role of plant growth promoting bacteria and fungi in heavy metal detoxification, in Detoxification of Heavy Metals. ed. by I. Sherameti, A. Varma (Springer, Berlin, 2011), pp. 369–388

46. G. Albanese, Recent advances in hexagonal ferrites by the use of nuclear spectroscopic methods. J. Phys. Colloq. (1977). h https://doi.org/10.1051/jphyscol:1977117

47. N. Karamat, M.N. Ashiq, M. Najam-ul-Haq, I. Ali, M.A. Iqbal, M. Irfan, Y. Abbas, M. Athar, Investigation of structural and electrical properties of vanadium substituted disordered pyrochlore-type Ho2–xVxZr2O7 nanostructure. J. Alloys Compd. 593, 117–122 (2014)

48. V. Murthy, J. Sobhanadri, Dielectric properties of some nickel–zinc ferrites at radio frequency. Phys. Status Solidi (a) 36, K133–K135 (1976)

49. M. Chourashiya, J. Patil, S. Pawar, L. Jadhav, Studies on structural, morphological and electrical properties of Ce1–xGd2O3–x/2 ferrites. Mater. Chem. Phys. 109, 39–44 (2008)

50. M.A. Gabal, W. Bayoumy, Effect of composition on structural and magnetic properties of nanocrystalline Ni0.8–xZn0.2MgFe2O4 ferrite. Polyhedron 29, 2569–2573 (2010)

51. F. Aen, S.B. Niazi, M. Islam, M. Ahmad, M. Rana, Effect of holmium on the magnetic and electrical properties of barium based W-type hexagonal ferrites. Ceram. Int. 37, 1725–1729 (2011)
52. I. Ali, M.U. Islam, M. Ishaque, H.M. Khan, M. Naeem Ashiq, M.U. Rana, Structural and magnetic properties of holmium substituted cobalt ferrites synthesized by chemical co-precipitation method. J. Magn. Magn. Mater. 324, 3773–3777 (2012)

53. S.E. Shirsath, B. Toksha, K. Jadhav, Structural and magnetic properties of In$^{3+}$ substituted NiFe$_2$O$_4$. Mater. Chem. Phys. 117, 163–168 (2009)

54. R. Skomski, J.M.D. Coey, Permanent Magnetism (Institute of Physics Pub., Bristol, Philadelphia, 1999)

55. Y. Li, R. Liu, Z. Zhang, C. Xiong, Synthesis and characterization of nanocrystalline BaFe$_{0.6}$Co$_{0.8}$Ti$_{0.8}$M$_{0.2}$O$_{19}$ particles. Mater. Chem. Phys. 64, 256–259 (2000)

56. C. Sudakar, G. Subbanna, T. Kutty, Wet chemical synthesis of multicomponent hexaferrites by gel-to-crystallite conversion and their magnetic properties. J. Magn. Magn. Mater. 263, 253–268 (2003)

57. I.P. Muthuselvam, R. Bhowmik, Mechanical alloyed Ho$^{3+}$ doping in CoFe$_2$O$_4$ spinel ferrite and understanding of magnetic nanodomains. J. Magn. Magn. Mater. 322, 767–776 (2010)

58. R. Zhou, Y. Huang, J. Zhou, H. Niu, L. Wan, Y. Li, J. Xu, J. Xu, Copper selenide (Cu$_3$Se$_2$ and Cu$_{2-x}$Se) thin films: electrochemical deposition and electrocatalytic application in quantum dot-sensitized solar cells. Dalton Trans. 47, 16587–16595 (2018)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.