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Tri-valent (Nd^{3+} & Cr^{3+}) Substituted Pb-M Hexaferrite for Structural, Magnetic, Electric & Photoluminescence Investigations

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Abstract: Tri-valent (Nd^{3+} & Cr^{3+}) Substituted Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Solid Solution has been synthesized using Auto-Combustion synthesis approach and reported for tailored Crystalline Signature, Magnetic Investigations, enhanced Photoluminescence and Electric (ϵ' , ϵ'' & σ_{ac} vs. Frequency at Room Temperature) properties. Hexagonal structural phase with space group $\text{P6}_3/\text{mmc}$ No. 194 has been identified from Bragg reflection positioned at $2\theta \sim 34.12$ & 34.36 in $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$. Decreased Porosity with enlarged grain size and grain growth demonstrate densification and compactness of grain due to high temperature sintering identified from Micrographs recorded using Scanning Electron Microscope. Other crystalline signatures such as calculated crystallite size calculated using Debye Scherrer formula, Macro strain, Dislocation density have been stamped for successful synthesis of Nano sized hexagonal ceramic oxide. Least value of Macrostrain, Dislocation density signature for well-ordered crystalline lattice arrangement after substitution of with different ionic radii of substituent (Nd^{3+} & Cr^{3+}) compared with Parent Metal ion (Pb^{2+}) in $\text{PbFe}_{12}\text{O}_{19}$ M type hexaferrite. S- shaped M (Magnetization) vs. H (Applied External Magnetic Field) identified enhanced magnetic signature after substitution of (Nd^{3+} & Cr^{3+}) with Parent Metal ion (Pb^{2+}) in $\text{PbFe}_{12}\text{O}_{19}$ M type hexaferrite where at least coercive behavior confined soft ferrite nature (suitable for Temporary Magnet) suggests that prepared solid solutions crucial for storage devices based on (0 & 1) memory as well as for in transformers used in electrical devices whereas multi domain structural arrangement along with ferromagnetic behavior evident for < 1 square-ness ratio. Spin up and down coupling of Fe^{3+} at octahedral and tetrahedral sites has been confirmed from variation in value of magnetic moment (η_B) as substituent varied from Nd^{3+} to Cr^{3+} . Shift in emission peak in luminescence spectra shows change in rate of recombination after emission whereas capacitive response studied using dielectric and conductivity spectroscopy shows that prepared Nano-Ceramic hexaferrite can be useful in Capacitive Applications

Keyword: Multifunctional Ceramic Oxides, Magneto-Crystalline Anisotropy, Anisotropy field (H_a), Magneto & Dielectric response.

I. INTRODUCTION

Demand of Materials exhibiting properties in various domains drive the intension of Researcher for development of devices with multiple functionality such as used in data storage applications, light emission devices such as Solid State Emission, Photocatalytic activity (PCA) etc. M-type hexaferrite ceramic solid solutions can be considered as suitable candidate by tailoring both Pb^{2+} as well as M-site or Fe-site results in tuning of magnetic and dielectric behavior corresponds specific applications. Modification in Magneto-crystalline anisotropy through 4f-3d exchange interactions is powerful way to enhance magnetic and dielectric behavior by aliovalent substitution of Rare-earth (Nd^{3+}) & Cr^{3+} by formation of free charge carriers & oxygen vacancy dynamics.

Ceramic oxides due to their chemical & thermal stability become important and attract considerable intension of scientific community for their scientific and technological interest. Due to unique characteristic appears from their modified crystalline lattice arrangement, formation of structural defects by creation of charge imbalance, substituents with ionic radii etc demonstrate versatile spectrum of functionality. Ceramics also falls in category of mechanically important materials due to their hardness & wear resistance. Due to structural defects & oxygen vacancies, ceramics oxides are important for Solid State Luminescence applications. Ceramics Specially composed of metallic or non-metallic ions bonded each other via O^{2-} exhibits excellent reductive oxidative response for Photo-Catalytic Activity (PCA) for degradation of organic dye as well as removal heavy metal ions from water treatment.

Stoichiometric variation in these ceramics oxides results for engineered tailored functionality evidence for suitable for a broad range of modern day technological applications for society usefulness. Ex. BaTiO_3 ceramic oxide very useful in ferroelectric and dielectric (Charge Storage Applications), Ferrites (Spinel, Hexaferrite as well as Perovskite ferrites) used in PCA as well as data storage and radiation shielding applications.

In modern day electronic device usage, ceramic oxides especially perovskite & hexaferrite having dielectric, ferroelectric & piezoelectric characteristics are important for energy storage devices as well as used as magnetic components in data storage applications. Due to dielectric behavior of ceramics oxides, these can be used for MLCC applications, multilayer ceramic devices, frequency resonators & filters, high-frequency electronic devices, extensively used in transformers coils, inductors, electromagnetic interference (EMI) & Absorption as well as reflection (Antenna), microwave devices for house hold appliances, antennas, & high-frequency communication systems. High electrical resistivity of ceramic oxides as compared to metallic materials also helps reduce eddy-current losses at high frequencies. Due to low electrical loss, ceramic oxides become promising candidates for Energy Generation & Energy Storage technologies. Due to low electrical loss, ceramic oxides specially composed from rare earth ions used in modern battery transport as crucial component for SOFC (Solid Oxide Fuel Cells), Lithium Ion as well as Sodium Ion Batteries. The impedance response of hexaferrites reveals that hexaferrites are suitable for candidates for super capacitors & solar-energy conversion. Ionic transport (movement of free charge carriers in form of oxygen vacancies) facilitate transportation of charge efficiently made ceramics important for Electrode and electrolyte materials.

The rapid development in nanotechnology has further tailored some specific properties such as dimensional modification, particle size, crystallite size, grain size led by grain growth, Surface to Volume ratio and all these termed as scaling effect made number of modification called size dependent characteristics made ceramics important in Energy-related technologies such as, Batteries, Super capacitors, solar-energy conversion (Band Gap Engineering in Nano sized Ceramic), hydrogen-generation technologies. In addition, Biocompatibility of ceramics oxide in Zirconia, Alumina & Titania have explored their significant potential in dental and orthopedic implantation, and biomedical applications.

Among the various classes of reported oxide ceramics such as ABO_3 , AB_2O_4 , $\text{AB}_{12}\text{O}_{19}$ etc. M-type hexaferrite having general formula $\text{AB}_{12}\text{O}_{19}$, due to their high electrical resistivity, Magnetic anisotropy, moderate saturation magnetization, chemical stability, and low eddy-current losses. These characteristics make them suitable for microwave and radio-frequency applications, permanent magnets, electromagnetic interference suppression, magnetic recording, and communication technologies. Their magnetic behavior can be systematically modified by substituting appropriate ions at specific crystallographic sites, thereby controlling parameters such as saturation magnetization, remanent magnetization, coercivity, magnetic anisotropy, and squareness ratio. Such compositional engineering provides an effective route for developing advanced magnetic ceramics with application-oriented properties.

Ferrites with Hexagonal Structural phase are important and attracts extensive research interest because of their excellent magnetic, dielectric, microwave reflection as well as absorption as well as electromagnetic properties. M type hexaferrites with general formula $\text{MFe}_{12}\text{O}_{19}$ where M = Divalent ion particularly exhibiting high value of Magneto-Crystalline anisotropy, Thermal, Mechanical and chemical stability. Due to free charge carriers availability due to formation of oxygen vacancies results from charge imbalance created by aliovalent substitution, M type due to hopping of free charge carriers, shows good conducting response made hexaferrites usefulness for microwave shielding, High Frequency Electronic Devices, magnetic recording and data storage applications etc.

Lead M-Hexaferrite having general formula $\text{PbFe}_{12}\text{O}_{19}$ with structural phase of Hexagonal is an M-type hexagonal ferrite possessing a magneto-plumbite-type crystal structure. Its structural and functional properties are closely associated with the distribution of Pb^{2+} & Fe^{3+} ions over different crystallographic sites and with the strength of the Fe–O–Fe super exchange interactions resulted ferromagnetic behavior of $\text{PbFe}_{12}\text{O}_{19}$ originates from the antiparallel alignment of magnetic moments associated with the nonequivalent iron sub lattices. Consequently, parameters such as saturation magnetization (M_s), Remanent magnetization (M_r), coercivity (H_c), and Magneto-crystalline anisotropy are strongly influenced by crystal structure, cation distribution, crystallite size, and microstructural features.

Pb (PbO) -based M type hexaferrites with high Magneto-crystalline anisotropy and excellent chemical stability can be a crucial candidate to be served as foundational materials magnetic utility as well as electronic devices operates at high-frequency. Stoichiometric modification in Pb (PbO) -based M type hexaferrites with Trivalent substituent (Re^{3+} & B^{3+} where Re = Rare Earth Ion & B = Transition Metal Ion) made M type ferrite important in next-generation applications. Trivalent especially Rare Earth ion (Nd^{3+}) or Transition metal ion (Cr^{3+}) considered as important candidates capable in tailoring magnetic and electrical order intrinsically.

The substitution on Nd^{3+} as well as Cr^{3+} results in tailoring magnetic and dielectric properties within Solid Solubility whereas as Nd^{3+} & Cr^{3+} at Pb^{2+} (Octahedral Position in Hexagonal Structural Arrangement commonly known as 2a, 12k, and 4f lattice sites) responsible for effective tailoring in Magneto Crystalline anisotropy.

Interplay in-between Structural arrangement distortion as well as exchange interaction mechanism & hopping mechanism due to substitution with ion with different valence state as well as different atomic radii made M-type hexaferrite important for various industrial application. For such Interplay, some various synthesis conditions and are key challenges include correlation between lattice arrangement and site occupancy, elucidation in role of oxygen vacancies as well as cation redistribution in dielectric dispersion and loss mechanisms and optimization of processing parameters for magnetic improvement with dielectric tunability for microwave and spintronic device applications.

While individual dopant effects are well-documented, the synergistic influence of Nd^{3+} and Cr^{3+} co-substitution on the electronic exchange interactions within the $\text{PbFe}_{12}\text{O}_{19}$ lattice remains inadequately characterized. Specifically, the interplay between the larger ionic radius of Nd^{3+} and the smaller radius of Cr^{3+} necessitates a systematic evaluation of lattice strain and internal magnetic exchange mechanisms, as prior studies on similar M-type hexaferrites suggest that doping significantly alters Super-exchange pathways and dielectric loss characteristics. These structural perturbations alter the occupancy of the five distinct crystallographic sites, thereby modulating the Super-exchange interactions essential for determining the net magnetic moment. Despite this fundamental understanding, the competing influence of rare-earth-induced structural relaxation and transition-metal-driven sub lattice exchange remains a critical gap, particularly regarding how these co-dopants modify the frequency-dependent dielectric response. Elucidating these mechanisms is essential for controlling electromagnetic dissipation, as the modification of polarizability and hopping conduction mechanisms under high-frequency electromagnetic fields remains largely unexplored in co-substituted $\text{PbFe}_{12}\text{O}_{19}$ systems.

M-type hexaferrites have attracted considerable interest as multifunctional magnetic and electronic materials because of their high magnetic anisotropy, chemical stability, relatively high Curie temperature, good resistance to demagnetization and useful dielectric characteristics. These properties make them attractive for applications in permanent magnets, high-frequency magnetic components, microwave devices, electromagnetic interference shielding, magnetic recording and magneto-dielectric systems. Among the different hexaferrite families, $\text{PbFe}_{12}\text{O}_{19}$ possesses a hexagonal magneto-plumbite-type structure in which the magnetic response is governed by the distribution and magnetic interactions of Fe ions occupying crystallographic ally inequivalent sites. Consequently, controlled modification of the cationic composition provides an effective approach for tailoring the magnetic and electrical properties of the parent ferrite.

Cation substitution is widely employed to modify the structural, magnetic and electrical characteristics of hexaferrites. The incorporation of foreign cations can alter the lattice environment, cation distribution, exchange interactions, Magneto-crystalline anisotropy, grain-growth behavior and charge-carrier transport. In particular, rare-earth ions can introduce substantial changes in magnetic anisotropy because of their relatively large ionic dimensions and spin-orbit interactions, whereas transition-metal ions can modify the Fe-O-Fe exchange pathways and local electronic environment. Therefore, comparative substitution using rare-earth and transition-metal cations is useful for establishing correlations between chemical composition and functional properties [1-15].

In the present investigation reports, trivalent (Nd^{3+} & Cr^{3+}) substitution at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Nano ceramic have been synthesized using Auto Combustion method and reported for magnetic, luminescent and dielectric response. Structural investigation of hexagonal phase has been analyzed from X-ray diffraction data whereas Scanning Electron Microscope used to study morphology of prepared ceramic. Vibrating Sample Magnetometer has been used to investigate influence of oxygen vacancies forms due to charge imbalance created by Nd^{3+} & Cr^{3+} substitution at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ and also study effect of magnetic response. Furthermore, room temperature frequency-dependent dielectric response was analyzed to understand the underlying polarization and charge-transport mechanisms. The dielectric response of ferrites is commonly explained using the Maxwell-Wagner interfacial polarization mechanism in conjunction with Koop's phenomenological theory. The aim of present investigation is to explore relationship between the structural characteristics and functional properties of $\text{PbFe}_{12}\text{O}_{19}$ results for thereby providing useful insight into its potential application in advanced magnetic, dielectric, and high-frequency electronic devices.

II. EXPERIMENTAL

Magnetic & Dielectric Hexagonal Ceramic Oxides of Nd^{3+} & Cr^{3+} substituted $\text{PbFe}_{12}\text{O}_{19}$ ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano-Ceramic Oxide have been synthesized using Auto-Combustion reported for influence of Oxygen vacancies created due to charge imbalance created by Nd^{3+} & Cr^{3+} substituted Pb^{2+} on structural, magnetic, optical, luminescence and dielectric response. For Auto

Combustion methods, nitrates of required metal weighed in above mentioned stoichiometric proportions and dissolved in de-ionized water and stirred continuously until clear solution obtained individually. All the solution of dissolved metal nitrates has been mixed step by step and stirred along with continuously heating until solution get converted into powder through combustion process. Citric Acid has been used as internal fuel agent. The collected powder after combustion process calcined at 900°C for 8 hours continuously for phase formation. The calcined of $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ Nano-Ceramic Oxide mixed with 2 wt% PVA as binder for pellets making. The pellets have been sintered at 1100°C for 2 hours. The structural analysis was carried out over powder of sintered pellets whereas other characterization such as magnetic, dielectric, magnetodielectric properties were carried over sintered pellets. The structural analysis was carried out using X-ray diffractometer by using diffractometer from Shimadzu (Maxima) whereas magnetic properties were done using vibrating sample magnetometer from Microsense (EZ9). The dielectric properties were done using impedance analyzer from Keysight. Microstructure has been analyzed from micrographs recorded using scanning electron microscope. The influence of Di & TetraValant Substitution on optical characteristic of $\text{BaFe}_{12}\text{O}_{19}$ has been estimated from Band Gap (E_g) whereas luminescence response from Photo-luminescence Spectrophotometer.

III. RESULTS AND DISCUSSION

The structural phase and extent of Crystallinity of synthesized Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics were investigated using room-temperature X-ray diffraction (XRD) Data. Figure 1 shows 2θ vs. Intensity of X-ray diffraction data. Highly sharpened narrow peaks corresponding to particular 2θ reveals crystalline nature of prepared hexagonal ceramic oxides whereas sharpness of diffraction peaks shows micro sized crystallite due to high temperature sintering results in high densification and crystalline growth. Identification of crystallization of prepared hexaferrite Nano ceramics has been confirmed by comparing diffraction peak position with reported diffraction data of M type hexaferrite in JCPDS card no. 79-1411, evident for hexagonal crystal phase of prepared M-type hexaferrite with space group $\text{P6}_3/\text{mmc}$ No. 194. The diffraction peak $2\theta \sim 34.12$ in $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $2\theta \sim 34.36$ in $\text{Pb}_{0.8}\text{Pb}_{0.2}\text{Fe}_{12}\text{O}_{19}$ signature for crystallization of prepared Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics. The high intensity diffraction peak corresponds to hexagonal structural phase (M Type Hexaferrite) in JCPDS card no. 79-1411 corresponds to $2\theta \sim 34.26$ and deviation in position of diffraction peak of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ results for change in Lattice parameters (a , b & c [$\text{\AA}$]), crystallite size (nm) and deviation in crystalline arrangement (Macro strain, Dislocation Density). The diffraction peaks of $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ Nano Ceramics have been indexed according to JCPDS card no. 79-1411, evident for hexagonal crystal phase of prepared M-type hexaferrite with space group $\text{P6}_3/\text{mmc}$ No. 194 and Tabulated in Table 1. Shift in peak position of diffraction peaks clearly visualized from Table 1 clearly stamped for change in crystallographic arrangement (a , b & c [$\text{\AA}$]), crystallite size (d), Macrostrain (ϵ) and Dislocation density either due to different ionic radii of substituents (Nd^{3+} & Cr^{3+}) as compare with Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$, structural defects and densification due to high temperature sintering.

To further retrieve these signatures such as change in Lattice parameters (a , b & c [$\text{\AA}$]), crystallite size (nm) and deviation in crystalline arrangement (Macro strain, Dislocation Density). The observed reflections were indexed in terms of their corresponding (hkl) planes, while the interplanar spacing (d) and lattice parameters have been evaluated to intensified M type hexagonal crystal structure of the synthesized $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ Nano Ceramics using Equations of hexagonal M-type structure with space group $\text{P6}_3/\text{mmc}$ (No. 194).

For a hexagonal crystal system, the lattice parameters satisfy $a = b \neq c$, with $\alpha = \beta = 90^{\circ}$ and $\gamma = 120^{\circ}$. The interplanar spacing, d_{hkl} , corresponding to the different crystallographic planes was calculated using the standard relation for a hexagonal crystal system and Tableted in Table 2 given below

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

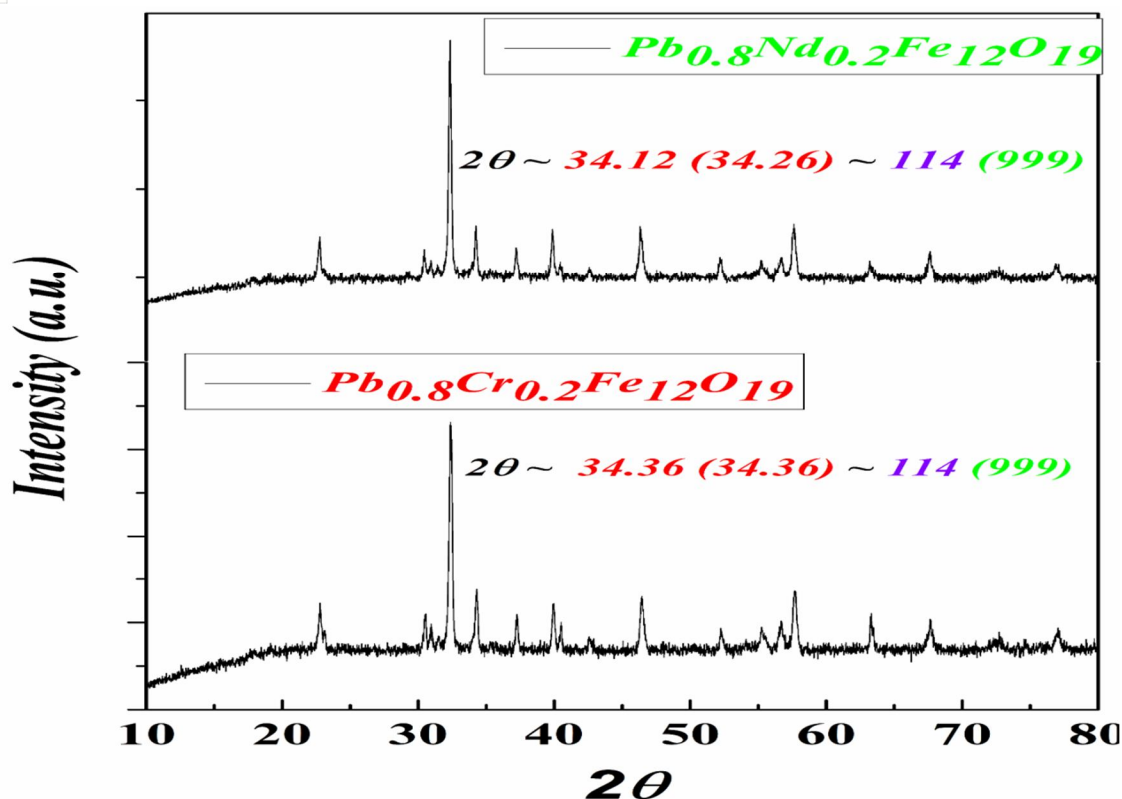


Figure 1: X-ray Diffraction Profile of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}\text{Pb-M}$ Hexaferrite($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

Where d_{hkl} is the interplanar spacing and ‘ a ’ and ‘ c ’ represent the lattice parameters of the hexagonal unit cell. The calculated d_{hkl} values, together with the lattice parameters and unit-cell volume, provide further confirmation of the structural evolution produced by Nd^{3+} and Cr^{3+} substitution in Pb-M hexaferrite.

2θ for $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$	2θ for $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$	hkl
22.71(20.947)	22.70(20.947)	103
30.586(30.400)	30.341 (30.400)	110
32.486(32.451)	32.241 (32.451)	107
34.142 (34.260)	34.142 (34.260)	114
36.983(37.210)	37.228(37.210)	203
39.825(39.485)	39.825(39.485)	109
42.422(42.639)	42.666(42.639)	206
46.453(47.020)	46.325(47.020)	10 11
52.158(51.470)	52.131(51.470)	215
55.217(55.327)	55.217(55.327)	217
56.629(56.528)	56.647(56.528)	304
57.833(57.648)	57.607(57.648)	218
63.290(63.252)	63.271(63.252)	220
67.787(67.950)	67.543(67.950)	20 14
72.755(72.907)	72.510(72.907)	317
77.026(77.015)	76.782(77.015)	22 10

Table 1: 2θ and their corresponding ‘ hkl ’ of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}\text{Pb-M}$ Hexaferrite($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

The lattice constants ('a' & 'c') evaluated by using above equations and Bragg's diffraction law for the studied hexagonal crystal system range Table 2. It has been clear seen in Table 2 that slight variation in lattice parameter (Increase in 'a' whereas Decrease in 'c') with Nd^{3+} & Cr^{3+} may results due to larger ionic radii of Nd^{3+} as compare to Cr^{3+} with similar coordination number. The volume of unit cell of studied hexagonal crystal system and tetragonal crystal system has been calculated using equation – (2) [17] and also tabulated in Table 1:

$$V=(a^2c).\sin 120^\circ \quad (2)$$

The cell volume shows also slight increase along with increase of crystallite also stamped that substituent with larger ionic radii also responsible for enhance in crystallographic signature as compare with substituent smaller ionic radii. The average value of the crystallite size (D) of each phase of the MF ceramic composite has been determined by using the Debye-Scherrer's formula in equation – (3),

$$D = \frac{0.9 \cdot \lambda}{\beta \cdot \cos \theta} ; \quad (3)$$

where $\lambda = 1.54 \text{ \AA}$ is wavelength of X-ray beam used in X-ray diffractometer, β is FWHM of XRD data peak and θ is Bragg's angle of diffraction and tabled in Table 1. The average crystallite size decreases.

Composition↓ Crystal Phase→	Hexagonal Space Group $P6_3/mmc$ No. 194			
Crystal Parameter	a(Å)	c(Å)	D (nm)	V(Å ³)
$\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$	5.434	21.015	72.414	537.40
$\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$	5.443	20.978	73.539	538.23

Table 2: Crystallographic Investigations such as Lattice Parameters (a & c) of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

This decrease in crystallite size with substituents also responsible for decrease in cell volume as well as strain produced due to large difference in c-axis of both Hexagonal. To calculate effect of large difference in c-axis of both Hexagonal, further micro strain (ϵ) and dislocation density (δ) have also been calculated using formula given in equation – (4) & equation – (5) and tabled in Table 2 given below

$$\epsilon = \frac{\beta \cos \theta}{4} \quad (4)$$

$$\delta = \frac{1}{\text{Average Crystallite Size (D)}^2} \quad (5)$$

Composition↓ Crystal Phase→	Hexagonal Space Group $P6_3/mmc$ No. 194	
Crystal Parameter	ϵ	δ
$\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$	0.00170	1.90E-4
$\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$	0.00167	1.84E-4

Table 3: Macro-strain, Dislocation of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

The Table 3 clearly reveals that both strain as well as dislocation density decreases continuously with substituents with larger ionic radii. The micro-strain has been decreased to 0.00167 for $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ to 0.00170 for $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ whereas dislocation density also decreases from 1.90E-4 to 1.84E-5. This decrease in micro-strain and dislocation density may results large difference in c-axis of both Hexagonal. This change in micro-strain and dislocation density may further explained on basis of porosity as well as densification.

Analysis of the XRD patterns of $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ that observed peak shifts therefore provide evidence for the successful incorporation of Nd^{3+} and Cr^{3+} ions into the M-type hexaferrite lattice with in solid solubility limit with absence of any secondary phases means that prepared hexagonal ferrite retain the characteristic of unmodified pure $\text{PbFe}_{12}\text{O}_{19}$ with mere enhancement in crystallographic signatures.

Microstructural analysis of Surface morphology of synthesized Tri-valent (Nd^{3+} & Cr^{3+}) Substituted Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) of Nano Ceramic hexaferrite has been examined using scanning electron microscopy (SEM). Microstructural analysis of prepared ceramics helps in investigating grain size and grain growth results in grain development and degree of agglomeration. It also clearly visualizes from SEM that reported micrographs comprises compacted polycrystalline morphology constitute of irregular to quasi-hexagonal/Square like grains with considerable inter-particle contact. Micrographs also reveals agglomeration results due to strong interaction between magnetic and electrostatic interactions between ferrite particles during sintering. A comparative examination of for both two $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ produces noticeable changes in particle morphology and microstructural homogeneity associated due to differences in ionic size, distribution, diffusion behaviour and grain-growth kinetics of substituents. The Nd^{3+} -containing composition $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ results for expected comparative well-developed grains, whereas Cr substitution $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ can modify grain growth and produce differences in particle size and agglomeration. Such microstructural improvements are important because grain size and grain-boundary characteristics strongly influence magnetic and dielectric properties of hexaferrites via surface defects and grain boundaries. In particular, grain boundaries are considered as low permittivity region act as barriers for charge-carrier motion and therefore influenced dielectric dispersion as well as frequency-dependent AC conductivity, while grain morphology and domain structure influence coercivity and magnetization.

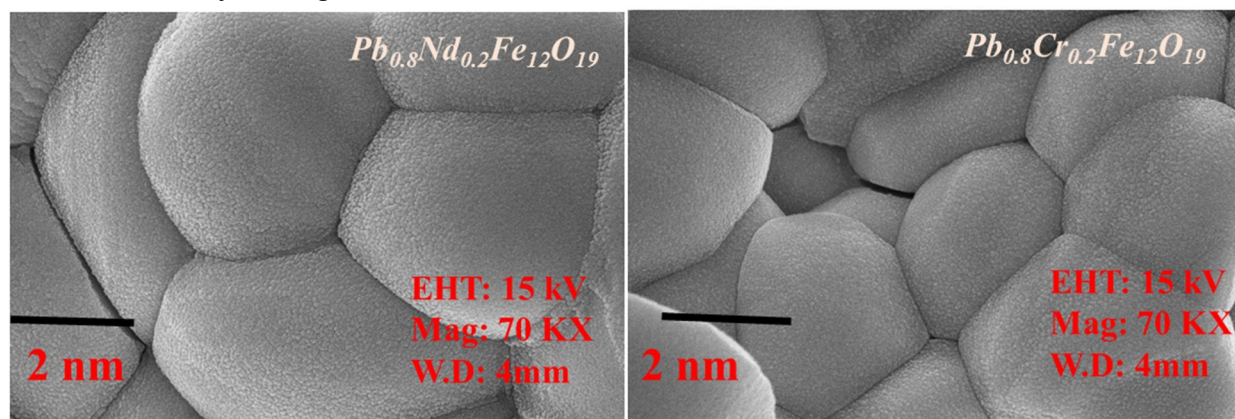


Figure 2: SEM Micrograph of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}\text{Pb-M}$ Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

Room Temperature Magnetic properties of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}\text{Pb-M}$ Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics has been investigated from Magnetization vs. Magnetic Field intensity. Figure 3 shows Magnetization vs. Magnetic Field intensity profile of $\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$ Nano Ceramics. Variation of Remnant magnetization (M_r), Saturation Magnetization (M_s), Coercivity (H_c), Bohr magneton (η_B), Anisotropy Constant (K_c), and Squareness ratio (M_r/M_s) used to investigate Magnetic characteristics. Non Linear Well-defined S- shaped hysteresis reveals magnetically ordered state. With ferrimagnetic nature of magnetic ordering arising mainly due to alignment of magnetic moment of Fe^{3+} antiparallely distributed entirely over different sub lattice in crystallographic axis of hexaferrite structure. Partial substitution of Nd^{3+} and Cr^{3+} at the Pb^{2+} site in $\text{PbFe}_{12}\text{O}_{19}\text{Pb-M}$ hexaferrite modifies Super-Exchange interactions {(Strong Negative Super Exchange Interaction between Fe^{3+} and Fe^{3+} through oxygen (O^{2-}) anion results in Antiferromagnetic ordering whereas Direct Exchange Interaction between $\text{Fe}^{3+}/\text{Fe}^{3+}$ and $\text{Fe}^{3+}/\text{Fe}^{2+}$ through vacancies ($V_{\bullet}$) may responsible in Ferromagnetic ordering)} & Magnetic Anisotropy responsible for resulting a noticeable modification in the magnetic parameters. The distribution of substituted cation (Nd^{3+} & Cr^{3+}) also responsible for change in Remnant magnetization (M_r), Saturation Magnetization (M_s), Coactivity (H_c). The differ ionic radii of substituted cation of cation (Nd^{3+} & Cr^{3+}) significantly results in spin-orbit coupling enhancement which also responsible for improvement in Local Crystal Field which impacts Magneto-crystalline anisotropy. The valence charge difference of substituent results in alteration of $\text{Fe}^{3+}-\text{O}^{2-}-\text{Fe}^{3+}$ super-exchange interactions responsible for ferromagnetic ordering. The value of Remnant magnetization (M_r), Saturation Magnetization (M_s), Coercivity (H_c), Bohr magneton (n^B), Anisotropy Constant (K_c), and Squareness ratio (M_r/M_s) shown in Table

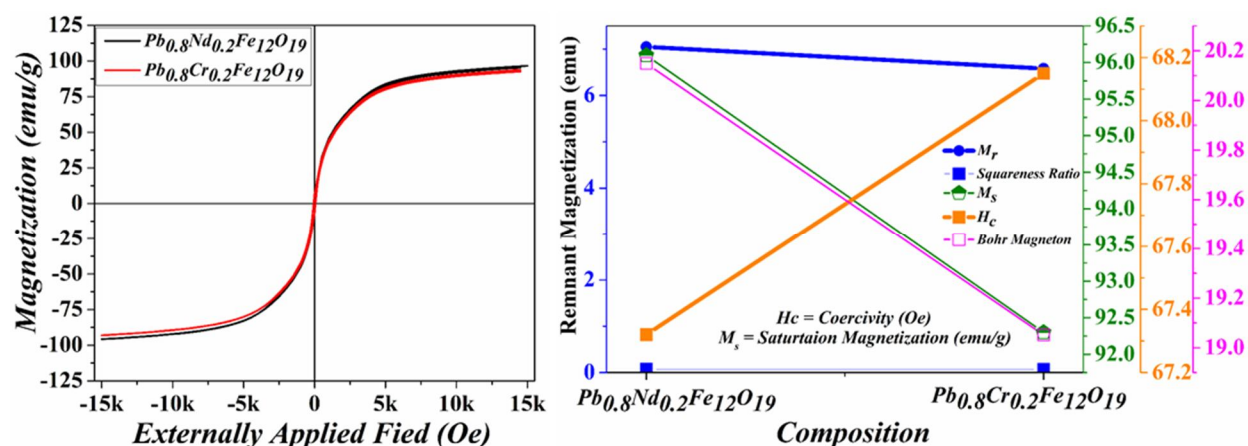


Figure 3: (a) Magnetization Vs. Magnetic Field Profile & (b) Remnant magnetization (M_r), Saturation Magnetization (M_s), Coercivity (H_c), Bohr magneton (η_B), Anisotropy Constant (K_c), and Squareness ratio (M_r/M_s) Vs. Composition of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}Pb$ -M Hexaferrite($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics

Composition (x)	M_r (emu/g)	M_s (emu/g)	H_c (Oe)	$\eta_B = \frac{M_r \times M_s}{5585}$ M_r = Remnant Magnetization M_s = Saturation Magnetization	Anisotropy Constant = $\frac{H_c \times M_s}{0.96}$ M_s = Saturation Magnetization H_c = Coercivity	M_r/M_s
$Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$	7.049	96.1	67.32	20.149	6939.01	0.073
$Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$	6.582	92.3	68.15	19.052	6552.33	0.071

Table 4: Remnant magnetization (M_r), Saturation Magnetization (M_s), Coercivity (H_c), Bohr magneton (η_B), Anisotropy Constant (K_c), and Squareness ratio (M_r/M_s) of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}Pb$ -M Hexaferrite($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics

It has been clear from Table that value of Remnant magnetization (M_r) & Saturation Magnetization (M_s) both increases with substitution of Nd^{3+} as compare with Cr^{3+} whereas Coercivity (H_c) decreases governs by Magneto crystalline anisotropy, crystallite/grain size, domain-wall motion, and defect concentration. Decrease in Coercivity (H_c) reveals indication of enhancement in magnetic-domain structure. The Bohr magneton (η_B) calculated from saturation magnetization, gives information of estimation of effective magnetic moment per formula unit varies according to Saturation Magnetization (M_s). Magneto crystalline anisotropy constant (K_c) reflects the resistance of the magnetic moments to rotation away from the preferred easy-magnetization direction and is strongly influenced by the substituted rare-earth/transition-metal ions. The squareness ratio, M_r/M_s , provides information about the domain configuration and magnetic reversal mechanism; its variation between the two samples indicates differences in domain-wall pinning and magnetic-domain interactions [17-29].

Luminescence behavior Influence of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}Pb$ -M Hexaferrite($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics has been from Emission spectra vs. Wavelength (nm) profile at room temperature. Figure 4 shows Emission Intensity (a.u.) vs. Wavelength (nm) profile of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}Pb$ -M Hexaferrite($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics. The defects, substitution enhanced energy level and electronic transition in M type hexagonal with magneto-plumbite structure mainly responsible for luminescence behavior. Emission peak at around ~ 661 nm in M type hexagonal ferrite must signature of Red Colored emission mainly due to d-d transition of Fe^{3+} d-sub shell in Photoluminescence (PL) spectra mainly either due to oxygen vacancy-related traps by oxygen vacancies formed during high temperature sintering or distortion of unit cell arrangement already discussed in X-ray diffraction section, shifting of Raman modes and PL peaks due to alteration in Fe-O bond lengths as well as due to micro strain, Dislocation density. It has clear from Figure 4 that peak positioned at wavelength ~ 350 nm mainly results from association of defect-mediated electronic transitions as well as lattice imperfections, oxygen vacancies, and localized energy states generated within the hexaferrite matrix.

It has also clear from Figure 4 that emission intensity decreases as substitution varies from Nd^{3+} to Cr^{3+} . This decrease in emission intensity directly evident for changes in local electronic structure due to substitution from Nd^{3+} to Cr^{3+} introduce additional defect centers which may act as non-radiative recombination sites, formation of oxygen vacancies due to charge imbalance created by substitution of Nd^{3+} to Cr^{3+} at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ which provide passage for non-radiative relaxation to quench consequently the luminescence response and increased lattice disorder and electron–phonon interactions. This broad peak composed more than one peak and each peak represent particular emission of peak. The undoped $\text{PbFe}_{12}\text{O}_{19}$ exhibits a weak and broad emission band in the blue–green region $\sim 410\text{--}500\text{ nm}$ due to Magneto-plumbite nature of ferrimagnetic oxides. The enhancement can be primarily ascribed to the optically inactive but defect-inducing nature of Fe^{3+} ions ($3d^1$ configurations). The observed emission in Nd^{3+} & Cr^{3+} doped $\text{PbFe}_{12}\text{O}_{19}$ therefore dominated by charge-transfer transitions, particularly $\text{O}^{2-} \rightarrow \text{Fe}^{3+}$ and $\text{O}^{2-} \rightarrow (\text{Nd}^{3+} \& \text{Cr}^{3+})$ transitions, rather than defect-induced recombination. This stabilization results in improved emission uniformity and a slight red-shift, indicative of band structure modification and enhanced metal–oxygen covalency [23].

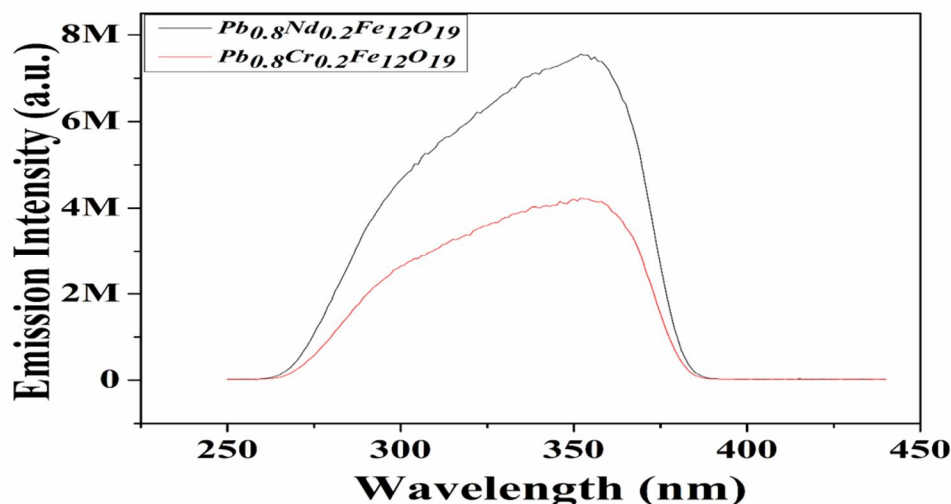


Figure 4: Emission Intensity (a.u.) Vs. Wavelength (nm) of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

Room temperature Frequency dependent dielectric response of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics has been investigated from Frequency dependent real (ϵ') and imaginary (ϵ'') components of dielectric constant with continuously increasing frequency and approaching frequency-independent region at higher frequencies. Figure 5 shows real (ϵ') and imaginary (ϵ'') components of dielectric constant Vs. Frequency of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics.

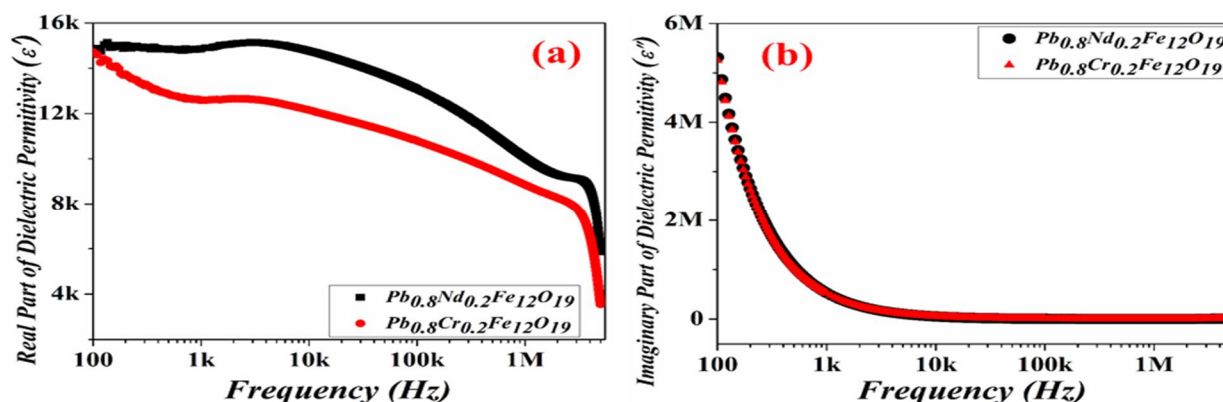


Figure 5: Real (ϵ') and Imaginary (ϵ'') components of dielectric constant Vs. Frequency of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $\text{PbFe}_{12}\text{O}_{19}$ Pb-M Hexaferrite ($\text{Pb}_{0.8}\text{Nd}_{0.2}\text{Fe}_{12}\text{O}_{19}$ & $\text{Pb}_{0.8}\text{Cr}_{0.2}\text{Fe}_{12}\text{O}_{19}$) Nano Ceramics

Figure 5 display maximum value of real (ϵ') and imaginary (ϵ'') components of dielectric constant at lower frequency and starts decreases with increasing frequency continuously and become independent at certain frequency. This maximum value of real (ϵ') and imaginary (ϵ'') components of dielectric constant at lower frequency range must be evidence of contribution of electronic, ionic, orientation & interfacial polarization in value of dielectric contribution and at higher frequency, ionic & orientation polarization gets eliminated from value of (ϵ') and imaginary (ϵ'') components of dielectric constant results in lowering value and dielectric permittivity of real (ϵ') and imaginary (ϵ'') only due to interfacial and space charge polarization. It has been clearly visualized that relatively high dielectric response in low-frequency region can be attributed to interfacial or space-charge polarization associated with the accumulation of charge carriers at grain boundaries, whereas get reduced dielectric response at higher frequencies results from the inability of comparatively sluggish of charge carriers to follow rapidly alternating electric field. This response can be interpreted using the Maxwell–Wagner interfacial polarization mechanism or Koop's phenomenological theory which assumes considering that in hexaferrite as a heterogeneous system consisting of comparatively conducting grains separated by resistive grain boundaries. The of real (ϵ') and imaginary (ϵ'') component also decreases with increasing frequency indicating higher dielectric loss arising from migration of charge-carrier, interfacial polarization and leakage-related processes; at higher frequencies. The differences in of real (ϵ') and imaginary (ϵ'') between in $Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$ compositions can be associated with enhancement in cation distribution, defect concentration formation, grain/grain-boundary characteristics and localized charge compensation produced by the respective substitutions. The increased grain size also results in enhancement in real (ϵ') and imaginary (ϵ'') in ferrite systems because larger grain size means least grain boundaries and grain boundaries considered as low permittivity regime. In ferrite, localized electron hopping between Fe^{2+} and Fe^{3+} ions due to aliovalent substitution (Nd^{3+} & Cr^{3+}) at Pb^{2+} in $PbFe_{12}O_{19}$ results in formation of oxygen for charge balance also additionally contribute to dielectric polarization. The AC conductivity increases also with increasing frequency for both compositions, demonstrating that charge transport is frequency dependent. At lower frequencies, the motion of charge carriers is strongly restricted by grain boundaries and localized trapping sites, whereas at higher frequencies, localized carriers acquire a greater probability of hopping between neighboring and energetically favorable sites responsible for enhanced charge transport. The simultaneous decrease in dielectric dispersion and increase in σ_{ac} with frequency therefore also suggest for transition for long-range interfacial as well as space-charge polarization at low frequencies to localized charge-carrier hopping at higher frequencies. The substitution of Nd^{3+} and Cr^{3+} at Pb^{2+} also responsible for improvement in polarization as well as charge-transport processes through their influence on the local structural and electronic environment thereby suggesting Nd^{3+} and Cr^{3+} at Pb^{2+} in $PbFe_{12}O_{19}$ potential use in high-frequency electronic, dielectric and electromagnetic-device applications [30-33].

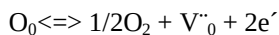
To effect of substitution of Nd^{3+} & Cr^{3+} on at Pb^{2+} site in $PbFe_{12}O_{19}$ on concentration of oxygen vacancies created has been studied from ac conductivity vs. Frequency at RT. Figure 6 shows the Frequency dependence of ac electrical conductivity of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}$ Pb-M Hexaferrite ($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics at room temperature. The ac conductivity is calculated from the recorded dielectric data using relation:

$$\sigma_{ac} = 2\pi f \epsilon' \epsilon'' \tan \delta \quad [30]$$

Parameters used to calculate ac conductivity from recorded dielectric parameters have their usual standard meaning. Figure 6 reveals two distinct segments of ac conductivity profile. One segment represents constant frequency independent region termed as dc conductivity and other frequency dependent segment corresponds to i conductivity. The frequency dependence of ac conductivity in ceramics is generally analyzed by Jonscher's power law [36];

$$\sigma_{dc} + A\omega^n = \sigma_{ac}$$

Where “A” represent dispersion parameter representing strength of polarizability and “n” is dimensionless frequency exponent representing the interaction between mobile ions with the lattice around them. According to Jonscher, the origin of frequency dependence of conductivity lies in the relaxation phenomenon arising due to hopping of mobile charge carriers. Thus with increasing concentration of oxygen vacancies, the concentration of structural defects increases and hence increase in the value of conductivity. As it clearly analyzed from dielectric variation with frequency that two important feature which play important role in modification of dielectric constant that first is grain boundaries followed interfacial polarization and secondly oxygen vacancies formation for charge balancing due to charge imbalance created by substitution of Nd^{3+} & Cr^{3+} on at Pb^{2+} site in $PbFe_{12}O_{19}$ by KronigVink Notation



results in electron exchange between $Fe^{2+} \leftrightarrow Fe^{3+}$ with alternating applied field and orientation polarization arises due to hopping of Fe^{3+} to Fe^{2+} known as relaxation phenomenon arising due to hopping of mobile charge carriers. Thus as concentration of oxygen vacancies increases, concentration of structural defects also increases and hence increase in the value of conductivity [32-36].

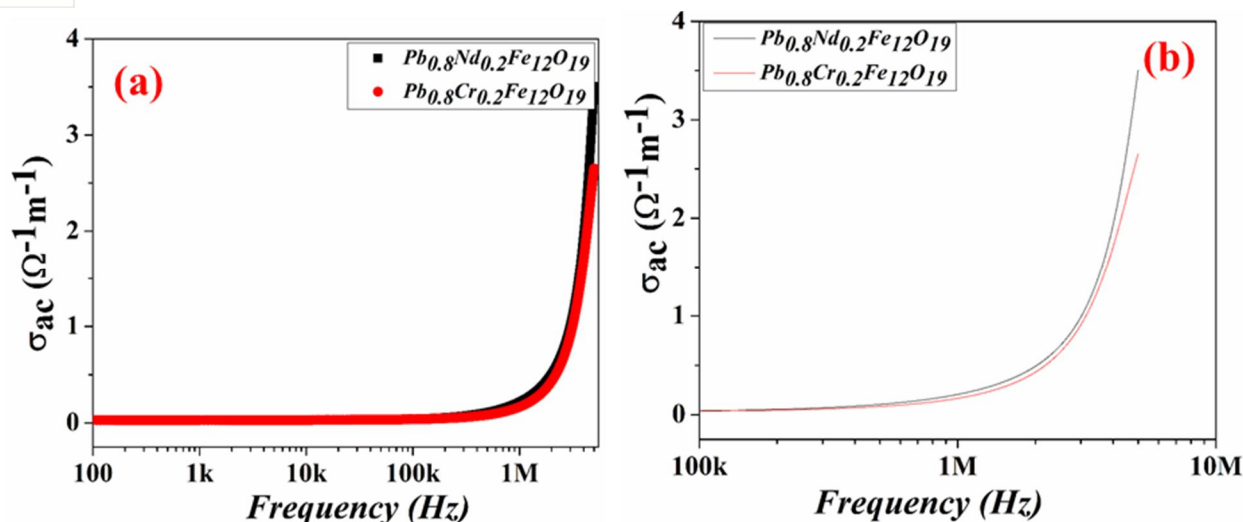


Figure 6: σ_{ac} Vs. Frequency of Tri-valent (Nd^{3+} & Cr^{3+}) Substituted at Pb^{2+} in $PbFe_{12}O_{19}$ Pb-M Hexaferrite ($Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ & $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$) Nano Ceramics

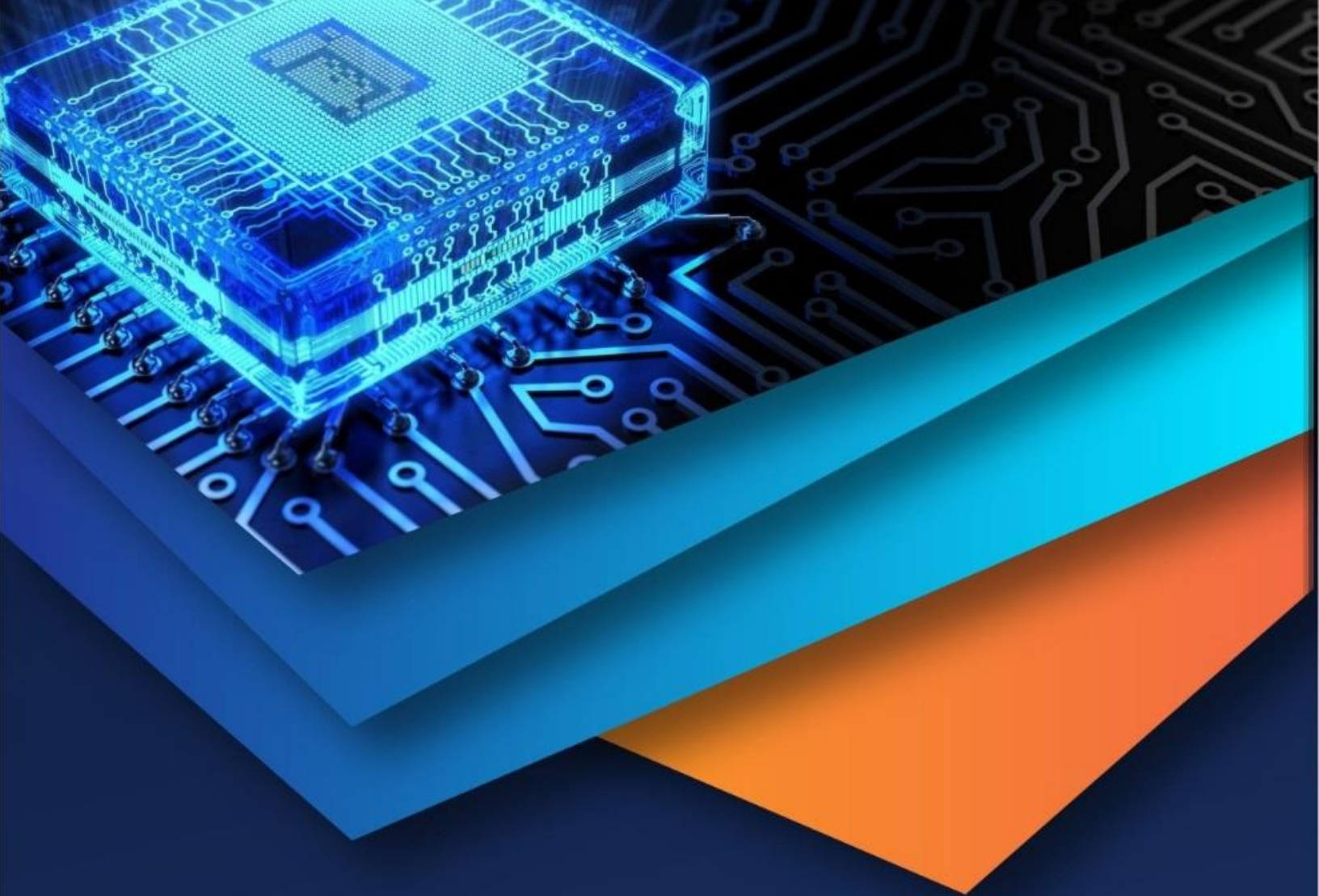
IV. CONCLUSION

In the present investigation, influence of partial substitution of Nd^{3+} and Cr^{3+} at the Pb^{2+} site in $PbFe_{12}O_{19}$ on the structural, morphological, luminescence, magnetic and dielectric have been studied and reported with stoichiometric proportion of $Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ and $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$ synthesized using Auto combustion approach. X-ray diffraction data shows that increase in crystallite size, crystallite cell volume, strain reveals influence of substituent with larger ionic radii as comparison with lower ionic radii. Irregular shaped with inter-granular regions with increased grain growth along with dense polycrystalline morphology with substitution of Nd^{3+} & Cr^{3+} resulted with discernible differences in grain morphology and packing. Magnetic measurements confirmed ferromagnetic behaviour for both compositions. $Pb_{0.8}Nd_{0.2}Fe_{12}O_{19}$ exhibited higher remanent magnetization ~ 7.049 emu g^{-1} , saturation magnetization ~ 96.1 emu g^{-1} , effective Bohr magneton 20.149 & anisotropy constant ~ 6939.01 as compare with $Pb_{0.8}Cr_{0.2}Fe_{12}O_{19}$, for which the corresponding values were 6.582 emu g^{-1} , 92.3 emu g^{-1} , 19.052 and 6552.33, respectively. Conversely, the Cr-substituted composition exhibited slightly higher coercivity 68.15 Oe than the Nd-containing composition 67.32 Oe. The squareness ratio decreased marginally from 0.073 to 0.071 with Cr substitution. The dielectric measurements demonstrated strong frequency dispersion of both the real and imaginary components of dielectric permittivity, particularly in the low-frequency region, followed by reduced frequency dependence at higher frequencies. The AC conductivity remained comparatively low at lower frequencies but increased markedly in the higher-frequency region, indicating enhanced localized charge-carrier hopping. The Nd-substituted composition exhibited higher high-frequency AC conductivity than the Cr-substituted composition. The results demonstrate that substitution of Nd^{3+} and Cr^{3+} provides an effective route for tailoring the coupled magnetic, dielectric and electrical properties of Pb-based hexaferrites for potential high-frequency electronic and magneto-dielectric applications.

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