4.1 Introduction

Spinel ferrites form an important class of compounds having large variety of magnetic, electrical and catalytic properties [1-3]. Among the various ferrite materials cobalt ferrite is well known to have high coercivity, moderate saturation magnetization, high chemical stability and mechanical hardness. Hence cobalt ferrite has wide range of technological applications including high density recording media, magnetic fluids, magnetic refrigerants and targeted drug delivery [4, 5]. Magnetic and electrical properties of the ferrite nanoparticles are strongly dependent on their size and size distribution, which are closely related to the method of preparation [6]. In spite of the development of a variety of synthesis routes, the production of cobalt ferrite nanoparticles with desirable size and properties is still a challenge. There are several chemical and physical methods currently in vogue for the synthesis of ferrite nanoparticles. Among these methods, sol-gel technique has the advantages of good control over stoichiometry, crystallite size and particle distribution [7].

Several researchers have investigated the influence of different rare earth ion doping in modifying the properties of ferrites. These studies revealed that the substitution of small percentage of Fe$^{3+}$ ions by rare earth ion induces strain and results in structural distortion which modifies its magnetic and electrical properties [8-10]. Panda et al. [11] indicated that substitution of Fe$^{3+}$ by Pr$^{3+}$ and Gd$^{3+}$ of CoFe$_2$O$_4$ synthesized by citrate precursor method reduces
the grain size of the material and alters the magnetic properties to a larger extent. Rashad et al. [12] studied the change in the magnetic properties of samarium substituted CoFe₂O₄ synthesized by citrate precursor method. Pawan et al. [13] have investigated the effect of La³⁺ doping on the electric, dielectric and magnetic properties of cobalt ferrite by co-precipitation route. In recent years, cobalt based ferrite nanoparticles have attracted the attention of researchers because of their potential applications in high density information storage and targeted transport of drugs. But in order to satisfy the requirements of these applications we must be able to tune the magnetic properties of these materials. Modification in the chemical composition of ferrite by the substitution of divalent or trivalent cations can possibly control the magnetic properties. Rare earth ions are reported to possess a variety of magnetic properties because of the great variation in the number of 4f electrons [14]. Therefore neodymium ions will be a promising candidate for doping cobalt ferrite in order to tune its magnetic properties. The effect of neodymium substitution on the properties of cobalt ferrite nanoparticles synthesized by sol gel technique is not yet reported. The aim of our present study is to investigate the effect of neodymium substitution on the structural and magnetic properties of cobalt ferrite (CoFe₂₋ₓNdₓO₄ with x=0.0 to 0.25 in steps of 0.05) synthesized by sol-gel technique.

4.2 Synthesis

Neodymium doped cobalt ferrite nanoparticles CoFe₂₋ₓNdₓO₄ (with x=0.0 to 0.25 in steps of 0.05) were synthesized by the sol-gel technique. Stoichiometric ratio of cobalt nitrate, neodymium nitrate and ferric nitrate (AR grade MERCK) were dissolved in minimum amount of ethylene glycol using a magnetic stirrer. The solution was then heated at 333K until a wet gel of the metal nitrate was obtained. By increasing the temperature, the gel was
dried and resulted in the self-ignition which produces a highly voluminous and fluffy product. The combustion can be considered as a thermally induced redox reaction of the gel wherein ethylene glycol acts as the reducing agent and the nitrate ion acts as an oxidant. Then, the obtained powder was ground well and sintered for 4 hours in a muffle furnace at 673K.

4.3 Results and Discussion

4.3.1 X-ray Diffraction Analysis

The XRD patterns of CoFe$_{2-x}$Nd$_x$O$_4$ (with $x=0.0$ to $0.25$ in steps of $0.05$) nanoparticles sintered at 673K are depicted in Figure 4.1. The formation of spinel structure was confirmed in all the samples by comparing the XRD pattern with the standard data (JCPDS PDF Card No. 22-1086). A negligible presence of hematite phase ($\alpha$-Fe$_2$O$_3$) is detected in all the samples and the peak corresponding to this phase becomes prominent in the sample with $x=0.25$. Hematite phase is a frequently formed impurity phase in ferrites.
Chapter 4

The interplanar spacing $d_{hkl}$ is calculated using Bragg’s equation which is used to calculate the lattice parameter ‘$a$’ for prominent peak (311). Lattice parameter obtained for undoped sample is in good agreement with that of the bulk cobalt ferrite [4, 15]. The lattice parameters of neodymium doped cobalt ferrite samples increase with increase in neodymium content. The ionic radius of Nd$^{3+}$ (0.0983nm) is large when compared to Fe$^{3+}$ (0.0645nm). Therefore addition of neodymium ions to ferrite lattice causes an expansion of the unit cell and thereby increases the lattice parameter. Similar results have been reported [6, 7]. The average crystallite size of the samples was calculated by drawing Hall-Williamson plots for all the samples [16]. The details of the Hall-Williamson analysis are given in our previous work [8]. The crystallite size shows an increasing trend with the increase in the concentration of neodymium. The lattice parameter, and average crystallite size obtained for all the samples are given in Table 4.1. It can be seen that, the increase in the crystallite size is less pronounced for samples with smaller concentrations of neodymium. But a significant increase is noticed for $x=0.25$. Various researchers [7, 17 & 18] have reported an increase in the grain size of ferrite samples with increase in rare earth concentration. According to Binu et al. [7] and Tahar et al. [18] the observed increase of the grain size can be considered as an indication of great chemical homogeneity of the prepared samples. Jianhong et al. [17] attributed this to the presence of additional phases in the samples. In the present case, additional peaks corresponding to neodymium oxides are not observed in the XRD pattern. However, the significant increase in the crystallite size for $x=0.25$ may be due to the presence of secondary phase of iron oxide ($\alpha$-Fe$_2$O$_3$). The theoretical (X-ray) density was calculated using...
the equation (2.9) given in section 2.3.1. Bulk density and percentage of porosity of the samples were also determined [19, 20].

<table>
<thead>
<tr>
<th>Nd content X</th>
<th>Lattice parameter (Å)</th>
<th>Crystallite size (nm)</th>
<th>X-ray density (g/cm³)</th>
<th>Bulk density (g/cm³)</th>
<th>Porosity (%)</th>
<th>Particle size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>8.399</td>
<td>11.26</td>
<td>5.260</td>
<td>2.662</td>
<td>48.96</td>
<td>15 ± 3</td>
</tr>
<tr>
<td>0.05</td>
<td>8.422</td>
<td>13.00</td>
<td>5.315</td>
<td>2.716</td>
<td>48.27</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>8.424</td>
<td>13.38</td>
<td>5.408</td>
<td>2.690</td>
<td>50.23</td>
<td>18 ± 3</td>
</tr>
<tr>
<td>0.15</td>
<td>8.425</td>
<td>14.04</td>
<td>5.504</td>
<td>2.581</td>
<td>53.12</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>8.428</td>
<td>14.69</td>
<td>5.598</td>
<td>2.461</td>
<td>56.02</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>8.432</td>
<td>17.64</td>
<td>5.689</td>
<td>2.665</td>
<td>53.14</td>
<td>23 ± 3</td>
</tr>
</tbody>
</table>

The X-ray density ($\rho_x$), bulk density ($\rho_m$) and percentage porosity of the studied samples are tabulated in Table 4.1. The X-ray density increases with neodymium content as it depends mainly on the molecular weight of the sample, whereas bulk density shows an irregular variation. Porosity is expected to decrease with increase in particle size; however in the present system of doped cobalt ferrites, porosity increases. This may be ascribed to the increase in X-ray density with Nd$^{3+}$ concentration. For higher concentration of Nd$^{3+}$ such as $x=0.25$, decrease in porosity is noticed and this may be due to the significant increase in crystallite size for that sample.

4.3.2 TEM Analysis

Figures 4.2(a) - (c) show TEM images of CoFe$_{2-x}$Nd$_x$O$_4$ samples with $x=0.0, 0.1$ and $0.25$ respectively. In these figures most of the nanoparticles appear with an almost spherical shape and some of them are agglomerated. The size distribution of the nanoparticles as observed in TEM images are
shown in Figures 4.3(a) - (c). It can be seen that the samples have narrow size distribution. The average particle sizes determined from TEM analysis are shown in Table 4.1.

Figure 4.2(a) TEM image of $\text{CoFe}_2\text{O}_4$

Figure 4.2(b) TEM image of $\text{CoFe}_{0.9}\text{Nd}_{0.1}\text{O}_4$
Effect of Neodymium Substitution on Structural, Magnetic and Electrical Characterization of Nano Cobalt Ferrites and Studies on their Antibacterial Activity

Figure 4.2(c) TEM image of CoFe_{0.75}Nd_{0.25}O_{4}

Figure 4.3(a) The size distribution of CoFe_{2}O_{4} nanoparticles

Characterization of Nano Cobalt Ferrites and Studies on their Antibacterial Activity
Chapter 4

Characterization of Nano Cobalt Ferrites and Studies on their Antibacterial Activity

Figure 4.3(b) The size distribution of CoFe$_{0.9}$Nd$_{0.1}$O$_4$ nanoparticles

Figure 4.3(c) The size distribution of CoFe$_{0.75}$Nd$_{0.25}$O$_4$ nanoparticles
4.3.3 FTIR Spectra Analysis

In the wave number range 1000-300 cm\(^{-1}\), the infrared bands of solids are usually assigned to vibration of ions in the crystal lattice. Two prominent metal-oxygen bands are seen in the IR spectra of all spinel ferrites. According to Waldron [21] the vibrations of unit cell of cubic spinel can be constructed in the tetrahedral site (A) and octahedral site (B). The formation of spinel structure in the prepared samples can be confirmed by the presence of characteristic absorption bands in the FTIR spectrum.

The absorption bands of the investigated CoFe\(_{2-x}\)Nd\(_x\)O\(_4\) samples in wave number range 900-400 cm\(^{-1}\) are shown in Figure 4.4. Two prominent absorption bands are found in the IR spectra. The absorption band \(\nu_1\) observed in the range 600-550 cm\(^{-1}\), corresponds to intrinsic stretching vibrations of the metal at the tetrahedral site. The band \(\nu_2\) observed in the range 450-400 cm\(^{-1}\), is assigned to octahedral-metal stretching. The values of \(\nu_1\) and \(\nu_2\) are observed to shift to lower frequency side with increasing neodymium content. The shifting of bands towards lower frequency can be attributed to the increase in unit cell dimension and the substitution of cations with large ionic radii. The shift in the absorption band \(\nu_2\) may be attributed to the substitution of Fe\(^{3+}\) ions on octahedral B sites by Nd\(^{3+}\) ions. It is known that increasing site radius reduces the fundamental frequency and therefore the central frequency should shift towards the lower frequency side [22, 23]. An increase in site radius may be expected due to the replacement of smaller Fe\(^{3+}\) ions on the octahedral site by larger Nd\(^{3+}\) ions.
4.3.4 WD-XRF Elemental Analysis

The stoichiometry of the powder samples were checked by WD-XRF analysis. The composition of the elements present in CoFe$_{2-x}$Nd$_x$O$_4$ samples with $x=0.0$, $x=0.1$ and $x=0.25$ are given in Table 4.2. The samples show the expected stoichiometry. No trace of any impurity was found indicating the good chemical homogeneity of the samples.

<table>
<thead>
<tr>
<th>Elements present</th>
<th>$X=0.0$ Expected (wt.%</th>
<th>WD-XRF (wt.%)</th>
<th>$X=0.10$ Expected (wt.%</th>
<th>WD-XRF (wt.%)</th>
<th>$X=0.25$ Expected (wt.%</th>
<th>WD-XRF (wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>25.110</td>
<td>25.25</td>
<td>24.205</td>
<td>24.090</td>
<td>22.950</td>
<td>22.200</td>
</tr>
<tr>
<td>Nd</td>
<td>0</td>
<td>0</td>
<td>0.924</td>
<td>0.516</td>
<td>1.046</td>
<td>15.051</td>
</tr>
<tr>
<td>Fe</td>
<td>47.608</td>
<td>47.30</td>
<td>43.586</td>
<td>42.810</td>
<td>38.072</td>
<td>37.080</td>
</tr>
</tbody>
</table>

4.3.5 Magnetic Properties

The magnetic characterizations of the samples were done using vibrating sample magnetometer and magnetic hysteresis loops were drawn for
all the samples. The magnetic parameters such as the saturation magnetization \( M_s \), coercivity \( H_c \) and remanent ratio \( R \) were determined for all the samples. Figure 4.5 shows the magnetic hysteresis loops of CoFe\(_{2-x}\)Nd\(_x\)O\(_4\) system. The inset of the figure shows the loops in the field of -1.5kOe to 1.5kOe. The magnetization does not attain saturation even at the maximum applied field of 20kOe for reasons including the presence of antiferromagnetic or paramagnetic impurities. Therefore the saturation magnetization of all the samples were determined by extrapolating the inverse of the field versus magnetization graph to \( 1/H=0 \). The saturation magnetization \( M_s \), coercivity \( H_c \) and remanent ratio \( R \) of all the samples are presented in Table 4.3. The value of \( M_s \) at room temperature for the undoped sample is 52.24emu/g and it is about 35% lower than that reported for the bulk cobalt ferrite [4]. The low value of saturation magnetization compared with that of the bulk may be due to canting of spins on the surface of the nanoparticles which reduces the net magnetization [24].
With the increase in Nd$^{3+}$ doping the saturation magnetization value decreases from 52.24 emu/g to 31.74 emu/g. The net magnetic moment of ferrites is directly related to the distribution of magnetic ions over tetrahedral and octahedral sites. Owing to the large ionic radii, neodymium ions preferably occupy octahedral sites. The magnetic moments of rare earth ions generally originate from the localized $4f$ electrons and the ordering of their moments is observed at very low temperatures [25]. Therefore, the effect of Nd$^{3+}$ ions in the cobalt ferrite materials seems to be similar to the substitution of non-magnetic atoms in the octahedral Fe sites of the spinel lattice, which decreases Fe$^{3+}$–Fe$^{3+}$ interactions causing $M_s$ to decrease. Therefore as the neodymium concentration increases, the exchange interaction between octahedral and tetrahedral sites deteriorates, which results in the decrease of magnetization of doped cobalt ferrite. The decrease in magnetization can also be attributed to the presence of hematite phase, which is a canted antiferromagnetic at room temperature with only feeble magnetism.

<table>
<thead>
<tr>
<th>Nd Content $x$</th>
<th>$M_s$ (emu/g)</th>
<th>$M_r$ (emu/g)</th>
<th>$H_c$ (Oe)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>52.24</td>
<td>20.07</td>
<td>1379.20</td>
<td>0.3842</td>
</tr>
<tr>
<td>0.05</td>
<td>37.64</td>
<td>15.57</td>
<td>961.01</td>
<td>0.4137</td>
</tr>
<tr>
<td>0.10</td>
<td>36.65</td>
<td>12.00</td>
<td>863.67</td>
<td>0.3274</td>
</tr>
<tr>
<td>0.15</td>
<td>35.59</td>
<td>12.65</td>
<td>852.15</td>
<td>0.3554</td>
</tr>
<tr>
<td>0.20</td>
<td>32.21</td>
<td>09.32</td>
<td>803.29</td>
<td>0.2894</td>
</tr>
<tr>
<td>0.25</td>
<td>31.74</td>
<td>08.64</td>
<td>686.37</td>
<td>0.2722</td>
</tr>
</tbody>
</table>

The coercivity $H_c$ which measures the magnetic field strength required for overcoming anisotropy to flip the magnetic moments is clearly affected by
the Nd$^{3+}$ substitution. The coercivity values of the samples are in the range of 1379-686Oe which is higher than that obtained for rare earth doped cobalt ferrite synthesized by other methods and sintered at 673K [26, 12]. It is reported that coercivity depends on factors such as magneto-crystallinity, microstrain, size distribution, anisotropy and the magnetic domain size [27-29]. Also it is well known that in the multi domain regime, the coercivity is inversely proportional to the grain size. A larger grain size makes the motion of domain walls easier, and thereby decreases the coercivity. This may be the reason for the decrease in the coercivity. The decrease of $H_c$ value with the increase in Nd$^{3+}$ content can also be related to the probable migration of Co$^{2+}$ ions from octahedral to tetrahedral sites. However, further studies are required to confirm this. The remanent ratio ($R=M_r/M_s$) is an indication of the ease with which the direction of magnetization reorients to the nearest easy axis after the removal of the magnetic field. The values of the remanent ratio of the prepared samples are in the range 0.2-0.4. The low value of $R$ is an indication of the isotropic nature of the material [30]. Thus the above study suggests that the magnetic properties of the cobalt ferrite nanoparticles can be tuned by the appropriate choice of neodymium ion concentration.

4.3.6 Electrical Properties

4.3.6.1 DC Resistivity

Variation of DC resistivity with temperature for the four samples (x=0.0, 0.05, 0.1, 0.15) is presented in Figure 4.6. The resistivity of the samples was found to increase with neodymium content. The replacement of Fe$^{3+}$ ions by Nd$^{3+}$ ions causes a decrease in Fe$^{3+}$/Fe$^{2+}$ ion pairs at the octahedral sites.
resulting in enhancement in the electrical resistivity of the doped cobalt ferrite. Thus the increase in resistivity can be attributed to the decrease in charge carrier mobility and increase in B-site hopping length. The variation in electrical resistivity with temperature follows Arrhenius equation given in section 2.4.1, which is typical behaviour of semiconductors. The decrease in electrical resistivity with temperature is due to the enhanced thermal mobility of the charge carriers. At higher temperatures lesser amount of energy is required for the hopping of electron between two equivalent lattice sites [31, 32]. The activation energy for hopping is calculated from the slope of the linear plot of $\ln \rho$ versus $1000/T$ and it varies from 0.65 eV to 0.74 eV.

![Figure 4.6 Compositional variation of DC resistivity of CoFe$_2-x$Nd$_x$O$_4$ with inverse temperature](image)

**Figure 4.6** Compositional variation of DC resistivity of CoFe$_2-x$Nd$_x$O$_4$ with inverse temperature

### 4.3.6.2 Relative Dielectric Permittivity

Figure 4.7 shows the variation of real part of dielectric permittivity with frequency at room temperature.
The value of dielectric constant is very high at lower frequencies and decreases rapidly with the increase of frequency. This is the normal dielectric behaviour of spinel ferrites and is also observed by several investigators [33-36]. The decrease in permittivity with frequency can be explained on the basis of Koop’s theory [37] which considers the dielectric structure as an inhomogeneous medium of two layers of the Maxwell-Wagner type [38]. Ferrites are dipolar due to the presence of ferrous and ferric ions. The hopping of electrons between these ions under the influence of an external electrical field may be visualized as the rotation of dipoles and this result in orientation polarization. At low frequencies the electronic, ionic, dipolar and space charge polarizations contribute to the net polarization of the ferrite material. But at higher frequencies the electron exchange between ferrous and ferric ions cannot follow the alternating field, which results in a decrease in the contribution of dipolar polarization in dielectric constant. Therefore, the
dielectric constant of the samples decreases as the frequency is increased. When neodymium is incorporated into spinel cobalt ferrite, it occupies the octahedral site, decreasing the Fe$^{3+}$ ion number responsible for polarization in the ferrite system. In magnitude the rate of hopping decreases and hinders the conduction mechanism. Hence the value of dielectric permittivity decreases with increase of Nd$^{3+}$ content in the present system.

Temperature dependence of dielectric permittivity at selected frequencies for the sample with $x=0.1$ is shown in Figure 4.8. The dielectric permittivity increases with increase in temperature at all the selected frequencies. The increase in $\varepsilon_r$ with increase in temperature can be related to the increase in drift mobility of charge carriers. Also the thermal activation increases the hopping of electrons and so the hopping frequency increases. This results in an increase in the polarization, leading to an increase in the dielectric constant with increase in temperature [39, 40]. The dipolar, interfacial, electronic and ionic polarizations contribute towards the dielectric permittivity of the ferrite material. Dipolar and interfacial contributions are dominant at low frequencies and both of these polarizations are temperature dependent. This explains the rapid increase in dielectric constant with temperature at low frequencies. While at higher frequencies, electronic and ionic polarizations dominate and their temperature dependence is insignificant [41].
It is evident from Figure 4.9 that the dielectric permittivity is decreased with increase in Nd$^{3+}$ concentration. There is a decrease in $\varepsilon_r$ for
x=0.1 and thereafter a slight increase is noticed. We know that the mechanism of dielectric polarization in ferrites is similar to that of electric conduction. Substitution of Nd$^{3+}$ ions for Fe$^{3+}$ ions in the octahedral sites decreases the rate of hopping of electrons and consequently hinders the conduction mechanism [42-44]. Hence the decrease in conductivity with neodymium content explains the decrease in $\varepsilon_r$ with composition.

4.3.6.3 Dielectric Loss

The dielectric loss tangent (\(\tan \delta\)) represents the energy loss within the dielectric medium. The variation of tan $\delta$ with frequency at room temperature for the present ferrite system is depicted in Figure 4.10. Dielectric loss decreases rapidly in the low frequency region. As the frequency increases, a decline in the rate of decrease is observed and finally it becomes frequency independent. In the low frequency region more energy is required for electron hopping and this can be the reason for the observed high loss. In the high frequency region, since the energy required for the hopping of electrons is less, the dielectric loss decreases [45]. A peak is observed in the dielectric loss angle plot of the doped samples. This peak is observed when the hopping frequency of electron between Fe$^{2+}$ and Fe$^{3+}$ is approximately equal to that of the external applied field [46]. The lowering of dielectric constant and dielectric losses along with enhancement in resistivity of these materials are promising for use in transformer cores and in motors that work at low frequency.
4.3.6.4 AC Conductivity

The variation of AC conductivity as a function of frequency at room temperature is represented in Figure 4.11. The change in AC conductivity with frequency is very small in the low frequency region for most of the samples but exhibits dispersion at high frequencies and this is consistent with the equation (2.33). In most of the disordered solids, AC conductivity is directly proportional to frequency. In ionic lattice the conduction occurs due to the hopping of electrons between the same elements existing in different oxidation states. AC conductivity decreases with frequency in the case of large polaron hopping, whereas in small polaron hopping, it increases with frequency [47, 48]. In the present case, AC conductivity is increasing with frequency and the plots are almost linear at high frequencies. This indicates that conduction is due to small polaron hopping. The formation of small polaron may be due to the defect levels or oxygen
vacancies created during sintering. The frequency dependence of $\sigma_{ac}$ can be explained with the help of Maxwell-Wagner two layer model of polycrystalline ferrites [38, 49].

![Graph showing frequency dependence of AC conductivity ($\sigma_{ac}$)](image)

**Figure 4.11** Frequency dependence of AC conductivity ($\sigma_{ac}$)

The correlation between AC conductivity and absolute temperature at selected frequencies for the doped sample with $x=0.1$ is shown in Figure 4.12. Dispersion is observed in the low temperature region and conductivity become less temperature dependent at high temperatures. As expected, the AC conductivity profiles are similar to those of the real part of dielectric permittivity because the dielectric permittivity is directly proportional to the square root of conductivity [50].
The mobility and hopping frequency increases with increase in temperature and hence the conductivity rises rapidly. However, at high temperatures, thermal energy is enough to cause large lattice vibrations. This leads to scattering of charge carriers which is expected to damp the mobility and hence the conductivity becomes less temperature dependent. Similar results are reported [46, 47]. Figure 4.13 depicts the variation of AC conductivity with composition. The observed decrease in AC conductivity can be explained in terms of the decrease in hopping rate due to the substitution of Fe$^{3+}$ ions by Nd$^{3+}$ ions on the octahedral sites. However, a slight increase is noticed for the sample with concentration $x=0.2$ and this may be attributed to the occupancy of rare earth ion in tetrahedral site.

![Figure 4.12 Relation between AC conductivity and absolute temperature](image)

Figure 4.12 Relation between AC conductivity and absolute temperature
4.4 Conclusions

A series of neodymium doped cobalt ferrites, CoFe$_{2-x}$Nd$_x$O$_4$ with $x=$0.0, 0.05, 0.1, 0.15, 0.2, 0.25 were successfully synthesized by sol-gel technique. XRD analysis confirmed the formation of single phase spinel structure. Neodymium doping has resulted in an increase in lattice parameter, which can be explained on the basis of the large ionic radius of Nd$^{3+}$ compared with the Fe$^{3+}$. The crystallite size of the cobalt ferrite nanoparticles increased with the increase in neodymium concentration. The TEM analysis reveals that the prepared nanoparticles have spherical morphology, narrow size distribution and slightly agglomerated. The chemical homogeneity of the samples was confirmed by the XRF elemental analysis. The absorption bands in FTIR spectra are found in the expected range and this corroborates the spinel characteristics of the prepared samples. The absorption band $\nu_2$ shifts to the lower frequency side indicating the substitution of Fe$^{3+}$ ions at the octahedral sites by Nd$^{3+}$ ions. The saturation magnetization decreased with an
increase in neodymium content and this is attributable to the decrease in the net magnetic moment in the octahedral site. Further, the doping of rare earth metal ions in ferrites is generally known to decrease the saturation magnetization because of their paramagnetic nature and lower magnetic moment as compared to ferromagnetic Fe$^{3+}$ ions. The effect of neodymium doping on coercivity is explained based on the particle size dependence of coercivity in the multidomain regime. The DC electrical resistivity of the doped samples increased with neodymium concentration up to $x=0.15$ and showed a decrease for further increase in the concentration. From the analysis of the dielectric properties of the neodymium doped samples it can be concluded that the addition of smaller concentrations of Nd$^{3+}$ ions has caused a decrease in the dielectric permittivity and dielectric loss. Further, the dielectric constant and dielectric loss of all the samples decreased with increase in the frequency of the applied AC field and it is explained on the basis of Maxwell-Wagner interfacial polarization and electron hopping mechanism. The dielectric constant and AC conductivity increase with temperature and this is related to the increase in drift mobility resulting in an enhancement in the hopping frequency of charge carriers. The linear increase observed in the AC conductivity at high frequencies suggests that the conduction is due to small polaron hopping. Thus we can tailor the magnetic and electrical properties of the cobalt ferrite nanoparticles by appropriate choice of the neodymium ion concentration and make them suitable for technological applications.
Chapter 4

References

Effect of Neodymium Substitution on Structural, Magnetic and Electrical Characterization of Nano Cobalt Ferrites and Studies on their Antibacterial Activity


Chapter 4


Effect of Neodymium Substitution on Structural, Magnetic and Electrical Characterization of Nano Cobalt Ferrites and Studies on their Antibacterial Activity


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