4.1: INTRODUCTION

Ferrite materials are important magnetic material in technological and industrial applications owing to their combination of electrical and magnetic properties. They possess very high electrical resistivity, high saturation magnetization, high permeability, low eddy current, dielectric loss and other properties which makes them usable in different applications.

Many different ferrites have been developed to meet the diversity of requirements that occur in microwave engineering, permanent magnet, transformer core, memory chips etc.[1-2]. Among the three types of ferrites, spinel ferrites are important and commonly used magnetic materials. The properties of the spinel ferrites are modified by number of ways viz. method of preparation, nature and valence of the substituent or dopant etc. [3].

On account of their use in desirable applications they have been intensively studied by many workers [4-7]. Different methods like ceramic technique [8], chemical co-precipitation [9], sol-gel [10] etc. were used for the preparation and modification in properties of spinel ferrites. The divalent, trivalent and tetravalent cations like Zn$^{2+}$[11], Al$^{3+}$[12] and Mn$^{4+}$[13] or Ti$^{4+}$[14] were commonly used for modifying the electrical and magnetic properties of spinel ferrites. The rare earth ions are found to be promising substituent for modifying the properties of ferrites. Due to their large ionic radii they cannot be completely
replaces Fe$^{3+}$ ions, only partial replacement is possible. In the literature various rare earth ions were doped into the spinel lattice with a view to improve their structural, electrical and magnetic properties [15-17].

Nickel and substituted nickel ferrites are important magnetic materials due to their remarkable properties and therefore they have been widely studied [18,19]. The modifications in the properties of Ni-Zn spinel ferrites were carried out by substituting divalent cations like Cu$^{2+}$ [20]. Ni-Cu-Zn ferrites have been investigated in the recent years for multilayer chip inductors (MLCIs) applications due to their good electrical and magnetic properties at high frequency and relatively low sintering temperature. Now days, they become an important components for the domestic electronic applications like cellular phones, video camera etc. [21]. Ni-Cu-Zn spinel ferrites can also be used as a surface mounting device (SMD) for miniaturization of electronic devices [22]. It is revealed from the literature studies that Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_{2-x}$RE$_x$O$_4$ spinel ferrite shows good electrical and magnetic properties that can be useful for multilayer chip inductor (MLCIs) devices. To further improve the properties of Ni-Cu-Zn spinel ferrite, the doping of rare earth ions like Gd$^{3+}$, Nd$^{3+}$, Sm$^{3+}$, Y$^{3+}$ was carried out in the present investigation. It is reported in the literature that, the doping of rare earth ions strongly influences on the structural, electrical, dielectric as well as magnetic properties of spinel ferrites.

4.2: EXPERIMENTAL SECTION

Preparation of ferrite sample

Polycrystalline samples of the nominal formula Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_{2-x}$RE$_x$O$_4$ (R = Y$^{3+}$, Gd$^{3+}$, Sm$^{3+}$ and Nd$^{3+}$ where x = 0.10) were prepared by standard ceramic technique [23] using analytical reagent grade oxides
(99.99%) materials: NiO, CuO, ZnO, Gd$_2$O$_3$, Sm$_2$O$_3$, Nd$_2$O$_3$, Y$_2$O$_3$, Fe$_2$O$_3$. Weighing of compounds was accurately taken in molecular weight percentage with a single pan microbalance. The mixed powders were ground and presintered at 950°C for 24 h. The solid state reaction for these is as follows

$$x\text{NiO} + y\text{ZnO} + z\text{CuO} + 1.90\text{Fe}_2\text{O}_3 + 0.10\text{RE}_2\text{O}_3 \rightarrow \text{Ni}_x\text{Zn}_y\text{Cu}_z\text{Fe}_{0.95}\text{RE}_{0.05}\text{O}_4$$

For the perfect iron Stoichiometric composition, the mol ratio of

$$\text{Fe}_2\text{O}_3 + \text{RE}_2\text{O}_3 = 1 \text{ and } x + y + z = 1$$

The sintered powder is again re-ground and pelletized. Polyvinyl alcohol was used as a binder in making disc shaped pellets of 10 mm diameter and 3 mm thickness. The pellets were finally sintered in muffle furnace for 1050°C for 24 h and then slowly cooled to the room temperature.

**Characterizations**

X-Ray diffraction (XRD) patterns were taken at room temperature to confirm the crystal structure of the prepared samples. The XRD patterns were recorded in the angle 2θ range from 20° to 80° using Cu-Kα as a target having wavelength $\lambda = 1.54056$ Å with scanning rate 2° per minute.

The Fourier Transform infrared (FTIR) spectral data was collected using α-FTIR Bukar spectrophotometer in the wave number range 400 cm$^{-1}$ to 1000 cm$^{-1}$ by KBr pellet method.

The magnetic properties were studied using pulse field hysteresis loop technique at room temperature. a. c. susceptibility measurement was carried out by instrument supplied by Magenta Company (Mumbai).
D. C. electrical resistivity measurements were carried out using two-probe method in the temperature range 300-800 K in the steps of 10 K. For electrical measurement, surface of the pellets were well polished and coated with silver paste for good electrical contact. The samples were placed between two electrodes inside of silica tube which was supported with a furnace. The temperature of the samples was controlled and measured using chromel-alumel thermocouple with an accuracy of ±5K.

The dielectric constant ($\varepsilon'$), dielectric loss ($\varepsilon''$) and dielectric loss tangent ($\tan \delta$) all the samples in the pellet form were measured using a Hioki 3532-50 (JAPAN) impedance analyzer in the frequency range 100 Hz to 1 MHz at room temperature.

### 4.3: RESULTS AND DISCUSSIONS

#### 4.3.1: Structural Characterization

**X-ray diffraction**

Figure 4.1(a, b and c) represents the X-ray diffraction (XRD) pattern for Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_{1.90}$RE$_{0.10}$O$_4$ spinel ferrite (with RE = Nd$^{3+}$, Sm$^{3+}$, Gd$^{3+}$, Y$^{3+}$) recorded at room temperature using Regaku (Miniflex-II) X-ray diffractometer. The XRD patterns were collected in the range 2$\theta$ = 20$^0$ to 80$^0$. All the reflections seen in the XRD patterns are sharp clear and intense. The presence of the strong diffraction peaks corresponding to the planes (220), (311), (222), (400), (422), (511), (440) and (533) indexed using Bragg’s law indicates that the presence of cubic spinel ferrite family. The secondary phases are observed in rare earth ions added Ni-Cu-Zn ferrites. The observed secondary phase identified as 2$\theta$ is 32.85$^0$ Gadolinium iron oxide (GdFeO$_3$), 33.12$^0$ Yttrium iron oxide (YFeO$_3$), 32.54$^0$ Neodymium iron oxide (NdFeO$_3$) and 32.74$^0$ Samarium
iron oxide (SmFeO$_3$) observed in XRD pattern (indicate by * in Figure 4.1, b and c). Similar XRD patterns were reported for other rare earth doped spinel ferrite [23-25]. The occurrence of these peaks can be attributed to large ionic radii of rare earth ions compared to Fe$^{3+}$ ions. The additional peak belongs to GdFeO$_3$, NdFeO$_3$, SmFeO$_3$ and YFeO$_3$ as confirmed from the JCPDS card numbers (78-0451), (82-2421), (39-1490) and (39-1489) respectively. The presence of the secondary phase in the Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_{1.90}$RE$_{0.10}$O$_4$ ferrites indicated that the RE$^{3+}$ doped had a solubility limit in the spinel lattice. A possible explanation was that the radius of rare earth RE$^{3+}$ ions was larger than that of Fe$^{3+}$ ions had a solubility limit of Gd$^{3+}$ (0.938Å), Sm$^{3+}$ (0.964Å), Nd$^{3+}$ (0.995Å) and Y$^{3+}$ (0.893Å) ion in the spinel lattice due to its ionic radius [26,27]. The redundant RE$^{3+}$ ions will aggregate on grain boundaries forming the secondary phase (REFeO$_3$).

Using the XRD data inter-planer spacing d-values were calculated and are presented in Table 4.1 along with their respective (h k l) planes. It is observed from Table 4.1 that minimum d-value was observed for Gd$^{3+}$ ions and maximum value is obtained for Nd$^{3+}$.

**Lattice constant**

The unit cell parameter (lattice constant) was calculated using the relation [28]. The values of lattice constant for different rare earth doped Ni-Cu-Zn ferrite are given in Table 4.2. It is clear from Fig 4.2 that maximum lattice constant was observed for Nd$^{3+}$ doped Ni-Cu-Zn spinel ferrite whereas minimum value of lattice constant was observed for Gd$^{3+}$ doped Ni-Cu-Zn ferrite. The lattice constant depends upon the ionic radii of the dopant ions. The difference in lattice constants is due to difference in ionic radii of the dopant rare earth ions. Table 4.2 also
includes the values of molecular weight (M), unit cell volume (V). Similar type of behaviour of lattice constant as a function of different rare earth dopant was reported in the literature [29].

**Bulk density**

The bulk density ($d_B$) of the samples was measured by using Archimedes principle [30]. The values are given in Table 4.2. It is observed from Table 4.2 that, the bulk density $d_B$ increases with doping of the rare earth ($\text{RE}^{3+} = \text{Y}^{3+}, \text{Gd}^{3+}, \text{Sm}^{3+}$ and $\text{Nd}^{3+}$) ions in Ni-Cu-Zn ferrite.

**X-ray density**

X-ray density ($dx$) was calculated for all the samples using the relation discussed elsewhere [30]. The values of X-ray density are listed in Table 4.2. X-ray density of Gd doped Ni-Cu-Zn spinel ferrite found to maximum. The minimum value of X-ray density is observed for Nd$^{3+}$ doped Ni-Cu-Zn spinel ferrite. The change in X-ray density values are attributed to the change in lattice constant of the rare earth dopant. The molecular weight of Gd (157.25 amu) [31] doped Ni-Cu-Zn is more as compared to Nd (144.24 amu) doped Ni-Cu-Zn ferrites. The difference in molecular weight also leads to difference in X-ray density of Gd and Nd doped Ni-Cu-Zn ferrite.

**Porosity**

The percentage porosity ($P\%$) of each rare earth doped Ni-Cu-Zn ferrite was calculated by using X-ray density and bulk density values of respective ferrite and by using the relation [32]. The porosity varies between 25 to 37 % (Table 4.2). The large values of porosity may be due to the presence of secondary peak in the XRD pattern, it can be also be
related to the lower sintering temperature (1050°C) and high atomic weights of rare earth ions.

**Particle size**

The particle size was estimated by using Scherrer’s formula [33] taking into consideration the highest intense peak (311) appeared in the XRD patterns. The values of particle size are also given in Table 4.2. The particle sizes of samples doped with RE$^{3+}$ ions are smaller than that of Ni-Cu-Zn ferrites (692-295 Å). The RE$^{3+}$ ions have empty or half-filled or fully-filled 4f electron shell with stable structure, so the sample with RE$^{3+}$ ions has high thermal stability. The larger bond intensity of RE$^{3+}$-O$^{2-}$ is compared with that of Fe$^{3+}$-O$^{2-}$. The bond intensity of Fe$^{3+}$-O$^{2-}$, Gd$^{3+}$-O$^{2-}$, Nd$^{3+}$-O$^{2-}$ and Y$^{3+}$-O$^{2-}$ are 390.4 ±17.2 (kJ mol$^{-1}$), 715 ±13 (kJ mol$^{-1}$), 709 ±15 (kJ mol$^{-1}$) and 725 ±15 (kJ mol$^{-1}$) respectively. More energy is needed to make RE ions enter into lattice and from the bond of RE$^{3+}$-O$^{2-}$. Bond energy is a part of inner energy. During the process of bond break or formation, inner energy will be changed in the reaction. Therefore, RE$^{3+}$ doped ferrites had higher thermal stability related to pure Ni-Cu-Zn ferrite, and more energy was needed for the RE$^{3+}$ doped samples to complete crystallization and grow grains [29,34]. Similar type of behaviour as a function of different rare earth dopant was reported in the literature [35, 36].

**Hopping length**

The distance between magnetic ions (hopping length) in the tetrahedral (L$_A$) and octahedral sites (L$_B$) was determined according to the relation [37]. The variation of the hopping length for A sites (L$_A$) and the B sites (L$_B$) with the RE$^{3+}$ dopant is tabulated in Table 4.3. It is observed that
the distance between magnetic ions (hopping length) of $L_A$ and $L_B$ exhibits similar behaviour as that of lattice constant.

**Tetrahedral bond, octahedral bond, tetra edge and octa edge**

The values of the tetrahedral and octahedral bond length ($d_{AL}$ and $d_{BL}$), the tetrahedral edge ($d_{AE}$) and the shared and unshared octahedral edge ($d_{BE}$ and $d_{BEU}$) were calculated by using the relations [37] and their values are presented in Table 4.3. These structural parameters are found to depend on lattice parameter. In the present case, the lattices constant changes with doping of rare earth ($RE^{3+} = Y, Gd, Sm$ and $Nd$) ions in Ni-Cu-Zn ferrites hence $d_{AL}$, $d_{BL}$, $d_{AE}$ and $d_{BE}$, $d_{BEU}$ (shared, unshared) all these structural parameters changes.

**Cation distribution**

The structural, electrical and magnetic properties of spinel ferrites also depend on the distribution of cations at available A and B site. The occupancy of cations depends on their site preference energy. Usually, an ion with larger ionic radii prefers to occupy octahedral B site. Rare earth ions have larger ionic radii more than 0.89Å and therefore prefer to occupy octahedral site in spinel lattice. The exact distribution of cations can be estimated using the method of X-ray intensity ratio calculations. The method is used by several researchers [38, 39].

In this method, the X-ray intensity of few selected planes (422), (440), (422) and (400) was calculated using Buerger’s formula [40]. In calculating the intensity the temperature and absorption factors are not taken into account as they do not affect much the intensity calculation [41]. The ratios of intensity for various planes were then compared with observed intensity ratio. The intensity ratios of planes $I(220)/I(400)$, $I(422)/I(440)$ and $I(400)/I(440)$ are considered to be sensitive to the
cation distribution [42]. The distribution of Ni\(^{2+}\), Cu\(^{2+}\), Zn\(^{2+}\), Fe\(^{3+}\) and RE\(^{3+}\) cation amongst the octahedral and tetrahedral sites in the \(\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{Fe}_{1.90}\text{RE}_{0.10}\text{O}_4\) was determined from the X-ray intensity ratio calculations. The intensity ratios were calculated for number of combinations of cations occupying tetrahedral and octahedral B site. It is true that calculated intensity ratio do not perfectly agree with each other. A close agreement between calculated intensity ratio and observed intensity ratio is assumed to be its cation distribution. The cation distribution determined using X-ray diffraction method is presented in Table 4.4. The intensity ratio corresponding to these cation distribution data is presented in Table 4.5. It can be observed the results of cation distribution data suggest that the all RE\(^{3+}\) ions, Ni\(^{2+}\) and Cu\(^{2+}\) ions showed a strong preference for the octahedral [B] sites, respectively, the Fe\(^{3+}\) ions show partial distribution among (A) and [B] sites, Zn\(^{2+}\) ions occupy tetrahedral (A) sites. Finally the cation distribution is estimated for the best-fit X-ray intensity ratio.

**Tetrahedral radius**

The radius of tetrahedral sites \(r_A\) can vary, depending upon the nature and ionic radii of the constituent ions. The tetrahedral A-site ionic radii can be calculated using the values of lattice constant ‘a’ and oxygen positional parameter ‘u’ \((u = 0.381\text{Å})\). Table 4.6 gives the values of tetrahedral radius \(r_A\), the values of ‘\(r_A\)’ increases with substitutions of rare earth (RE\(^{3+}\) = Y\(^{3+}\), Gd\(^{3+}\), Sm\(^{3+}\) and Nd\(^{3+}\)) ions in Ni-Cu-Zn ferrites.

**Octahedral radius**

The octahedral radius ‘\(r_B\)’ of all the samples under investigation was calculated using the values of lattice constant ‘a’ and oxygen parameter ‘u’. Octahedral radius ‘\(r_B\)’ increases with doping of rare earth (RE\(^{3+}\) =
\( \text{Y}^{3+}, \text{Gd}^{3+}, \text{Sm}^{3+} \text{and} \text{Nd}^{3+} \) ions in NI-Cu-Zn ferrite. The values of octahedral radius for each sample were found to be greater than tetrahedral radius which can be observed from Table 4.6. The theoretical lattice parameter \( (a_{th}) \) can be calculated using this equation [42]. The values of \( a_{th} \) are shown in table 4.6. The variation of theoretical values of lattice constant is similar to that of experimentally determined lattice parameter.

**Fourier Transform infrared (FTIR) Spectroscopy**

Figure 4.3 (a, b and c) represents the Fourier Transform infrared spectra (FTIR) of all RE\(^{3+}\) substituted Ni-Cu-Zn ferrite. The FTIR spectra show two main absorption bands of the iron ions on both tetra and octahedral positions \( \nu_1 \) and \( \nu_2 \) in the range (582-587 cm\(^{-1}\)) and (464-493 cm\(^{-1}\)) respectively depending on RE\(^{3+}\) concentration. The third vibrational frequency band \( \nu_3 \), in the range from (420-470 cm\(^{-1}\)) is corresponds to the divalent octahedral metal ion and oxygen complexes [43]. From Figure 4.3 (a, b and c) it can be understand that the \( \nu_1 \) and \( \nu_2 \) shifted slightly due to substitution of RE\(^{3+}\) ions in Ni-Cu-Zn spinel ferrite. The difference in band positions is attributed to Fe\(^{3+}\)-O\(^2-\). The higher frequency absorption band \( \nu_1 \) is assigned to vibrations of the tetrahedral metal complexes which is the bond between the oxygen ion and tetrahedral site metal ion. Lower frequency band \( \nu_2 \) is assigned to vibration of octahedral metal complexes which is the bond between oxygen ion and octahedral site metal ion [44]. The Values of \( \nu_1 \) and \( \nu_2 \) are used to determine force constant \( K_0 \) and \( K_t \). \( K_0 \) and \( K_t \) were calculated by using the known values of cation mass. The values are given in Table 5.6. It is observed from Table 5.6 that, values of force constant decreases with Gadolinium content \( x \).
4.3.2 Magnetic Properties

The magnetic properties of the present rare earth doped Ni-Cu-Zn ferrites were investigated using pulse field hysteresis loop technique. The plot of magnetization (M) verses applied magnetic field (H) is shown in Fig 4.4 (a, b and c) The values of saturation magnetization (Ms), coercivity (Hc), remanence magnetization (Mr) and magneton number (n_B) are summarized in Table 4.8. It can be seen from Table 4.8 that the saturation magnetization decreases with rare earth doping of Sm, Y, Nd and Gd, but for The decrease in saturation magnetization is due to the substitution of nonmagnetic and magnetic Y^{3+}, Sm^{3+}(1.78\mu_B), Gd^{3+}(7.98\mu_B) and Nd^{3+}(3.45\mu_B) in Ni-Cu-Zn spinel ferrite. The rare earth ions owing to their large ionic radii occupy octahedral site by replacing Fe^{3+} ions. The main contributions of magnetic properties come from Fe^{3+} on octahedral B site. The net magnetic moment is given by [45]

\[ M = M_B - M_A \]

Where, M_A and M_B represent the total magnetic moment of the A and B sublattices, respectively. The doping of rare earth ions reduces the super-exchange interaction and therefore saturation magnetization decreases. Further, the decrease in magnetization can be attributed to the fact that due to substitution of rare earth ions spin canting takes place. The collinear ferrimagnetic arrangement into non-collinear arrangement. Overall, the substitution of selected rare earth ions in Ni-Cu-Zn spinel ferrite reduces saturation magnetization, coercivity and remanence magnetization (Table 4.8).

Magneteton number were calculated by using the equation 3.20 (chapter III) [46] and their values presented in Table 4.8. Like saturation
magnetization, magneton number of rare earth doped sample decreases compared to pure Ni-Cu-Zn ferrite.

**A.C. Susceptibility**

The temperature dependence of A.C. susceptibility was studied in the temperature range from 300K to 600K using double coil set-up. The plots of normalized ac susceptibility \( \chi_T/\chi_{RT} \) against temperature (T) are shown in Fig 4.5 (a, b and c). All the samples exhibit normal ferrimagnetic behaviour. The susceptibility increases with increase in temperature showing the hump near Curie temperature and then suddenly falls to zero. Using these plots Curie temperature was obtained and their values are given in Table 4.9. It is observed from Table 4.9 that Curie temperature decreases with \( \text{RE}^{3+} \) substitution with respect to the parent Ni-Cu-Zn spinel ferrite. The lowest Curie temperature of 404 K was observed for \( \text{Gd}^{3+} \) doped Ni-Cu-Zn spinel ferrite. \( \text{Y}^{3+} \) doped spinel ferrite shows maximum Curie temperature of 425 K as compared to other rare earth ions under investigation. The decrease in Curie temperature is related to decrease in magnetic linkages. The substitution of non magnetic \( \text{RE}^{3+} \) ions in place of magnetic \( \text{Fe}^{3+} \) ions leads to a decrease in active magnetic linkages. Our results on magnetic properties are in good agreement with the literature reports [47, 48].

Variations of Curie temperature are used to determine Curie temperature of all the samples. The values of Curie temperature are given in Table 4.10. It can be observed from Figure 4.7 that, Curie temperature decreases with doping of rare earth \( \text{RE}^{3+} = \text{Y}, \text{Gd}, \text{Sm and Nd} \) content as compeer to pure Ni-Cu-Zn sample [29].
4.3.3: D.C. Electrical Resistivity

The temperature dependence of electrical resistivity was studied using standard two-probe method. The D.C. electrical resistivity of all the samples under investigation was measured from room temperature to well beyond Curie temperature. Fig 4.6(a, b and c) shows the variation of the electrical resistivity log $\rho$ against reciprocal of temperature $1000/T$. It is clear from the resistivity plots that the electrical resistivity of all investigated RE$^{3+}$ doped Ni-Cu-Zn spinel ferrite decreases with increase in temperature, thus exhibiting semiconducting behaviour obeying the well-known relation [49]. It is also seen from Fig 4.6 (a, b and c) that there are two regions of conduction with different activation energies. The change in slope is observed in each resistivity plots at a particular temperature which may correspond to Curie temperature of the sample.

**Activation Energy**

The activation energy $E_g$ for each sample was calculated and slope of the resistivity plots. The values of activation energy for different rare earth doped Ni-Cu-Zn ferrite are listed in Table 4.10. It is found Table 4.10 that activation energy increases with doping of Gd$^{3+}$, Y$^{3+}$, Sm$^{3+}$, Nd$^{3+}$ rare earth ions as compared to activation energy of Ni-Cu-Zn parent spinel ferrite. The activation energy is found to be more (0.4 eV) for Gd$^{3+}$ doped Ni-Cu-Zn spinel ferrite and it is less for Nd$^{3+}$ doped Ni-Cu-Zn spinel ferrite (0.228 eV). It is also evident from Table 4.10 that the activation energy in paramagnetic region is greater than ferrimagnetic region. The small values of change in activation energy exhibits semiconducting behavior of properties samples.
**Room Temperature Resistivity**

The room temperature dc resistivity of Ni-Cu-Zn ferrite was measured by two probe method. The results of resistivity as a function of different rare earth ions are listed in Table 4.10. It is observed from Table that room temperature resistivity of $1.24 \times 10^5 \ \Omega \text{cm}$ to $9.68 \times 10^6 \ \Omega \text{cm}$ is found to be increased. The maximum resistivity was observed for Gd$^{3+}$ doped Ni-Cu-Zn spinel ferrite and it is a minimum for Y$^{3+}$ doped Ni-Cu-Zn ferrite. It is reported that and from our cation distribution studies that the rare earth ions occupy octahedral sites owing to its large ionic radius. The concentration of Fe$^{3+}$ ions on octahedral B-site decreases with doping of rare earth ions. The hopping rare of electron transfer will decrease the decrease of Fe$^{3+}$ ions. As a result, the dc resistivity increases with doping of different rare earth ions. Our results on room temperature resistivity are in good agreement with the literature reports [50, 51]. Conduction mechanism in present sample may be attribute to hopping of electron Fe$^{2+}$ to Fe$^{3+}$ and hole transfer from Ni$^{3+}$ to Ni$^{2+}$ ions.

\[
\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^- \\
\text{Ni}^{3+} + e \rightarrow \text{Ni}^{2+}
\]

Combining these two equations,

\[
\text{Ni}^{2+} + \text{Fe}^{3+} \rightarrow \text{Ni}^{3+} + \text{Fe}^{2+}
\]

**4.3.3: Dielectric Properties**

Figure 4.8 (a, b) shows the variation of the real and imaginary part of the dielectric constant ($\varepsilon'$ and $\varepsilon''$) as a function of frequency at room temperature for all the rare earth dopant (RE$^{3+} = \text{Y, Gd, Sm and Nd}$) under investigation. It is seen from these figures that both the $\varepsilon'$ and $\varepsilon''$ show dispersion with frequency. The values of $\varepsilon'$ and $\varepsilon''$ both are high at low frequency and low at high frequency. At low frequency both $\varepsilon'$ and
\( \varepsilon'' \) decreases very rapidly whereas at high frequency they decrease very slowly rather remains constant. The decrease in \( \varepsilon' \) and \( \varepsilon'' \) is exponential in nature. The behaviour of \( \varepsilon' \) and \( \varepsilon'' \) of the present samples is similar to other spinel ferrites [52, 53] and it depicts the dispersion due to Maxwell Wagner type interfacial polarization in agreement with Koops phenomenological theory [54]. The phenomena of electron exchange between \( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \) ions gives local displacement of electrons in the direction of an applied electric field which subsequently determines the polarization. The polarization decreases with increase in frequency and reaches a constant value beyond a certain frequency of external field, the electron exchange between \( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \) ions cannot follow the alternating field.

Fig. 4.8 (c) shows the variation of dielectric loss tangent (\( \tan \delta \)) with frequency at room temperature. Table 4.11; observed that dielectric loss decreases with the increasing frequency which is a normal behavior of any ferrite material. It is clear from Fig.4.8(c) that the dielectric loss tangent decreases with doped \( \text{RE}^{3+} \) content. First of all, the doped in \( \text{RE}^{3+} \) resistivity may give rise to the reduction in \( \tan \delta \), because the loss factor can be written in terms of the electrical conductivity [55]. Such a result was observed by several investigators [56].
4.4 CONCLUSIONS

The Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_{1.90}$RE$_{0.10}$O$_4$ spinel ferrites have been synthesized successfully using sintered ceramic method. The conclusions are summarized as follows:

- X-ray studies, all the samples with rare earth (Gd$^{3+}$, Sm$^{3+}$, Nd$^{3+}$ and Y$^{3+}$) ions exhibit a cubic spinel structure with the appearance of a small peak representing secondary phases. The addition of rare earth ions to the system leads to better applicable ferrites with high resistivity.

- The change in the values of lattice constant of Y$^{3+}$, Gd$^{3+}$, Sm$^{3+}$ and Nd$^{3+}$ rare earth ions doped in Ni-Cu-Zn ferrite is due to larger ionic radii of the RE$^{3+}$ ions as compared to the Fe$^{3+}$ ions.

- The X-ray density and bulk density increases with RE$^{3+}$ (Gd, Sm, Nd and Y) doped in Ni-Cu-Zn spinel ferrites; however, decreasing trend in porosity was attributed to the substitution of RE$^{3+}$ thereby making all samples denser.

- The X-ray intensity ratio calculations were carried out to determine cation distribution of the present system which suggests that Fe$^{3+}$ ion occupies tetrahedral (A) and octahedral [B] sites. RE$^{3+}$ (Gd, Sm, Nd, Y), Ni$^{2+}$ and Cu$^{2+}$ ions showed a strong preference for the occupied only octahedral [B] site, whereas Zn$^{2+}$ ions occupy tetrahedral A-site.

- The analysis of FTIR spectra, it was found that when Fe$^{3+}$ is replaced with RE$^{3+}$ ions, almost minor changes are observed in the band position of FTIR spectra.
The saturation magnetization and the magneton number decreases with increasing of RE$^{3+}$ (Gd, Sm, Nd, Y) content as compared to pure Ni-Cu-Zn spinel ferrite.

The Curie temperature obtained from A.C. susceptibility, Loria technique and D.C. electrical resistivity are in the reported range and decreases with increase in doping content RE$^{3+}$ (Gd, Sm, Nd, Y) ions all Curie temperature good agreement which is other

It is observed that the samples having high resistivity have activation energy and vice versa. The activation energy in paramagnetic region is more than that of ferrimagnetic region. The variation of DC resistivity with temperature shows change in conduction behavior at Curie temperature.

The room temperature resistivity of RE$^{3+}$ substituted Ni-Cu-Zn ferrites is higher than pure spinel ferrite.

The dielectric constant, dielectric loss and dielectric loss tangent decreased with the increase of RE$^{3+}$ content. The decrease in ($\varepsilon'$) and increase in resistivity is required for high frequency application.
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Fig 4.1(a): X-ray diffraction patterns of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_2$O$_4$ system.
Fig 4.1(b): X-ray diffraction patterns of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ system. (RE = Gd, Y)
Fig 4.1(c): X-ray diffraction patterns of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ system. (RE = Sm, Nd)
Fig 4.2: Variation of lattice constant ‘a’ with substitution of RE$^{3+}$ of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system. (RE = Gd, Y, Sm, Nd)
Fig 4.3(a): FTIR Spectra of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{Fe}_2\text{O}_4$. 
Fig 4.3(b): FTIR Spectra of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ system.

($\text{RE}^{3+} = \text{Gd, Nd}$)
Fig 4.3(c): FTIR Spectra of $Ni_{0.25}Cu_{0.20}Zn_{0.55}RE_{0.10}Fe_{1.90}O_4$ system.

$\text{(RE}^{3+} = \text{Sm, Y})$
Fig 4.4(a): Hysteresis loop of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_2$O$_4$. 
Fig 4.4(b): Hysteresis loop of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$.  

(RE$^{3+}$ = Gd, Nd)
Fig 4.4(c): Hysteresis loop of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$.

(RE$^{3+}$ = Sm, Y)
Fig 4.5(a): Variation of a.c. Susceptibility ($\chi_T/\chi_{RT}$) with temperature (T) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_2$O$_4$. 
Fig 4.5(b): Variation of a.c. Susceptibility ($\chi_T/\chi_{RT}$) with temperature (T) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ (RE$^{3+} =$ Gd, Y).
Fig 4.5(c): Variation of a.c. Susceptibility ($\chi_T/\chi_{RT}$) with temperature (T) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.58}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ ($\text{RE}^{3+} = \text{Sm, Nd}$).
Fig 4.6(a): Variation of $\log \rho$ Vs $1000/T$ (K$^{-1}$) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$Fe$_2$O$_4$. 
Fig 4.6(b): Variation of $\log \rho$ Vs $1000/T$ (K$^{-1}$) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$. (RE$^{3+} =$ Gd, Nd)
Fig. 4.6(c): Variation of log $\rho$ Vs $1000/T$ ($K^{-1}$) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ ($\text{RE}^{3+} = \text{Sm, Y}$)
Fig 4.7: Variation of Curie temperature ($T_c$) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ with content $\text{RE}^{3+}$. ($\text{RE}^{3+} = \text{Gd, Nd, Sm, Y}$).
Fig. 4.8 (a): Variation of dielectric constant ($\varepsilon'$) with logarithm of frequency (Log $F$) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ with content $\text{RE}^{3+}$. ($\text{RE}^{3+} = \text{Gd}, \text{Nd}, \text{Sm}, \text{Y}$).
Fig. 4.8 (b): Variation of dielectric loss ($\varepsilon''$) with logarithm of frequency (Log $f$) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ with content RE$^{3+}$.

(RE$^{3+}$ = Gd, Nd, Sm, Y).
Fig. 4.8 (c): Variation of dielectric loss tangent (tan $\delta$) with logarithm of frequency (Log F) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ with content RE$^{3+}$.
(RE$^{3+}$ = Gd, Nd, Sm, Y).
Table 4.1

Miller indices (hkl) and Inter planner spacing (d) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system. (RE$^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Plane (h k l)</th>
<th>d (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>Gd</td>
</tr>
<tr>
<td>2 2 0</td>
<td>2.9569</td>
</tr>
<tr>
<td>3 1 1</td>
<td>2.5239</td>
</tr>
<tr>
<td>2 2 2</td>
<td>2.4175</td>
</tr>
<tr>
<td>4 0 0</td>
<td>2.0952</td>
</tr>
<tr>
<td>4 2 2</td>
<td>1.7120</td>
</tr>
<tr>
<td>3 3 3</td>
<td>1.6148</td>
</tr>
<tr>
<td>4 4 0</td>
<td>1.4835</td>
</tr>
<tr>
<td>5 3 3</td>
<td>1.2802</td>
</tr>
</tbody>
</table>
### Table 4.2:

Molecular weight (M), lattice constant (a), volume (V), X-ray density (d_x), bulk density (d_B), Particle size (t) and Porosity (P) of Ni_{0.25}Cu_{0.20}Zn_{0.55}RE_{0.10}Fe_{1.90}O_4 system. (RE^{3+} = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>M</th>
<th>a (Å)</th>
<th>V</th>
<th>d_x (gm/cm³)</th>
<th>d_B (gm/cm³)</th>
<th>P (%)</th>
<th>t (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>239.03</td>
<td>8.369</td>
<td>586.21</td>
<td>5.416</td>
<td>3.360</td>
<td>37.96</td>
<td>692</td>
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<tr>
<td>Gd</td>
<td>249.17</td>
<td>8.386</td>
<td>589.74</td>
<td>5.612</td>
<td>4.083</td>
<td>27.25</td>
<td>492</td>
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<tr>
<td>Y</td>
<td>242.34</td>
<td>8.428</td>
<td>598.65</td>
<td>5.392</td>
<td>4.083</td>
<td>24.28</td>
<td>375</td>
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<tr>
<td>Sm</td>
<td>248.48</td>
<td>8.406</td>
<td>593.89</td>
<td>5.558</td>
<td>4.164</td>
<td>25.08</td>
<td>345</td>
</tr>
<tr>
<td>Nd</td>
<td>247.87</td>
<td>8.433</td>
<td>599.82</td>
<td>5.490</td>
<td>4.102</td>
<td>25.28</td>
<td>295</td>
</tr>
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</table>
Table 4.3

Hopping length \((L_A, L_B)\), Tetrahedral bond \((d_{AL})\), Octahedral bond \((d_{BL})\), Tetra edge \((d_{AE})\) and Octa edge \((d_{BE})\) for different doping types.

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>(L_A) (Å)</th>
<th>(L_B) (Å)</th>
<th>(d_{AL}) (Å)</th>
<th>(d_{AE}) (Å)</th>
<th>(d_{BL}) (Å)</th>
<th>(d_{BE}) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>2.525</td>
<td>2.446</td>
<td>1.899</td>
<td>3.101</td>
<td>2.047</td>
<td>2.817</td>
</tr>
<tr>
<td>Gd</td>
<td>2.529</td>
<td>2.450</td>
<td>1.903</td>
<td>3.107</td>
<td>2.047</td>
<td>2.823</td>
</tr>
<tr>
<td>Y</td>
<td>2.538</td>
<td>2.459</td>
<td>1.910</td>
<td>3.120</td>
<td>2.056</td>
<td>2.834</td>
</tr>
<tr>
<td>Sm</td>
<td>2.534</td>
<td>2.455</td>
<td>1.907</td>
<td>3.114</td>
<td>2.052</td>
<td>2.829</td>
</tr>
<tr>
<td>Nd</td>
<td>2.541</td>
<td>2.462</td>
<td>1.913</td>
<td>3.120</td>
<td>2.059</td>
<td>2.833</td>
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</table>
Table 4.4

Estimated cation distribution in Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system.
(RE$^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>A-Site</th>
<th>B-Site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zn</td>
<td>Cu</td>
</tr>
<tr>
<td>NiCuZn</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>Gd</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>Y</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>Sm</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>Nd</td>
<td>0.55</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 4.5

X-ray intensity ratios of \( \text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{Fe}_{1.90}\text{RE}_{0.10}\text{O}_4 \) system.

\( \text{RE}^{3+} = \text{Gd}, \text{Y}, \text{Sm}, \text{Nd} \)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>I (220)/I(400)</th>
<th>I (422)/I(440)</th>
<th>I (400)/I(440)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (cal)</td>
<td>I (obs)</td>
<td>R</td>
</tr>
<tr>
<td>\text{NiCuZn}</td>
<td>1.69</td>
<td>1.57</td>
<td>0.12</td>
</tr>
<tr>
<td>\text{Gd}</td>
<td>1.13</td>
<td>1.19</td>
<td>0.06</td>
</tr>
<tr>
<td>\text{Y}</td>
<td>1.52</td>
<td>1.99</td>
<td>0.47</td>
</tr>
<tr>
<td>\text{Sm}</td>
<td>1.90</td>
<td>1.55</td>
<td>0.35</td>
</tr>
<tr>
<td>\text{Nd}</td>
<td>1.89</td>
<td>1.09</td>
<td>0.80</td>
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</table>
Table 4.6

Ionic radii ‘r_A’, ‘r_B’, average ionic radii r (Å) and Theoretical Lattice Constant ‘a_th’ of Ni_{0.25}Cu_{0.20}Zn_{0.55}RE_{0.10}Fe_{1.90}O_4 system. (RE^{3+} = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>r_A (Å)</th>
<th>r_B (Å)</th>
<th>r (Å)</th>
<th>a_th (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>0.5789</td>
<td>0.7221</td>
<td>0.6505</td>
<td>8.3691</td>
</tr>
<tr>
<td>Gd</td>
<td>0.5827</td>
<td>0.7261</td>
<td>0.6544</td>
<td>8.3855</td>
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<tr>
<td>Y</td>
<td>0.5923</td>
<td>0.7364</td>
<td>0.6643</td>
<td>8.4279</td>
</tr>
<tr>
<td>Sm</td>
<td>0.5871</td>
<td>0.7309</td>
<td>0.6590</td>
<td>8.4052</td>
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<tr>
<td>Nd</td>
<td>0.5935</td>
<td>0.7377</td>
<td>0.6656</td>
<td>8.4332</td>
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</table>
Table 4.7

Vibrational band frequency ($\nu_1$, $\nu_2$, $\nu_3$) and Force constant ($K_t$, $K_o$) of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system. ($\text{RE}^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>$\nu_1$ (cm$^{-1}$)</th>
<th>$\nu_2$ (cm$^{-1}$)</th>
<th>$\nu_3$ (cm$^{-1}$)</th>
<th>$K_t \times 10^5$ (dyne/cm)</th>
<th>$K_o \times 10^5$ (dyne/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>587</td>
<td>464</td>
<td>411</td>
<td>1.604</td>
<td>1.015</td>
</tr>
<tr>
<td>Gd</td>
<td>585</td>
<td>493</td>
<td>462</td>
<td>1.593</td>
<td>1.397</td>
</tr>
<tr>
<td>Y</td>
<td>584</td>
<td>483</td>
<td>445</td>
<td>1.587</td>
<td>1.051</td>
</tr>
<tr>
<td>Sm</td>
<td>582</td>
<td>473</td>
<td>415</td>
<td>1.576</td>
<td>1.128</td>
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<tr>
<td>Nd</td>
<td>586</td>
<td>474</td>
<td>421</td>
<td>1.598</td>
<td>1.155</td>
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</table>
### Table 4.8

Saturation magnetization ($M_s$), Remanance magnetization ($M_r$), Coercivity ($H_c$), Remanence ratio ($M_r/M_s$) and Magneton number ($n_B$) of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ system. (RE$^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>$M_s$ (emu/gm)</th>
<th>$M_r$ (emu/gm)</th>
<th>$H_c$ (Oe)</th>
<th>$M_r/M_s$</th>
<th>$n_B$ ($\mu_B$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>68.676</td>
<td>17.542</td>
<td>63.340</td>
<td>0.255</td>
<td>2.939</td>
</tr>
<tr>
<td>Gd</td>
<td>58.594</td>
<td>2.939</td>
<td>11.410</td>
<td>0.050</td>
<td>2.614</td>
</tr>
<tr>
<td>Y</td>
<td>62.108</td>
<td>2.037</td>
<td>10.917</td>
<td>0.032</td>
<td>2.694</td>
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<tr>
<td>Sm</td>
<td>65.040</td>
<td>1.017</td>
<td>19.526</td>
<td>0.015</td>
<td>2.893</td>
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<tr>
<td>Nd</td>
<td>69.432</td>
<td>1.206</td>
<td>17.302</td>
<td>0.017</td>
<td>2.081</td>
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Table 4.9

Curie temperature (Tc) data measured from Loria Technique, DC Resistivity and A.C. Susceptibility of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system (RE$^{3+} = $ Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>Tc (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loria Technique</td>
</tr>
<tr>
<td>NiCuZn</td>
<td>456</td>
</tr>
<tr>
<td>Gd</td>
<td>410</td>
</tr>
<tr>
<td>Y</td>
<td>430</td>
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<tr>
<td>Sm</td>
<td>436</td>
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<tr>
<td>Nd</td>
<td>418</td>
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Table 4.10

Activation energy in paramagnetic ($E_p$), Ferrimagnetic ($E_f$), activation energy ($\Delta E$) and Room temperature Resistivity of $\text{Ni}_{0.25}\text{Cu}_{0.20}\text{Zn}_{0.55}\text{RE}_{0.10}\text{Fe}_{1.90}\text{O}_4$ system (RE$^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>$E_p$ (eV)</th>
<th>$E_f$ (eV)</th>
<th>$\Delta E$ (eV)</th>
<th>$\rho \times 10^6$ (Ω-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuZn</td>
<td>0.885</td>
<td>0.666</td>
<td>0.218</td>
<td>0.124</td>
</tr>
<tr>
<td>Gd</td>
<td>0.724</td>
<td>0.324</td>
<td>0.400</td>
<td>9.68</td>
</tr>
<tr>
<td>Y</td>
<td>0.751</td>
<td>0.523</td>
<td>0.228</td>
<td>2.35</td>
</tr>
<tr>
<td>Sm</td>
<td>0.695</td>
<td>0.398</td>
<td>0.296</td>
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<td>Nd</td>
<td>0.569</td>
<td>0.312</td>
<td>0.256</td>
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Table 4.11

Room Temperature Dielectric constant ($\varepsilon'$), Dielectric loss ($\varepsilon''$) Dielectric Loss tangent ($\tan \delta$) at varying frequency of Ni$_{0.25}$Cu$_{0.20}$Zn$_{0.55}$RE$_{0.10}$Fe$_{1.90}$O$_4$ system. (RE$^{3+}$ = Gd, Y, Sm, Nd)

<table>
<thead>
<tr>
<th>Content (RE=0.10)</th>
<th>$\varepsilon'$ × $10^4$</th>
<th>$\varepsilon''$× $10^4$</th>
<th>tan $\delta$</th>
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<tbody>
<tr>
<td></td>
<td>100 Hz</td>
<td>1 KHz</td>
<td>10 KHz</td>
</tr>
<tr>
<td>NiCuZn</td>
<td>29.7</td>
<td>8.98</td>
<td>0.26</td>
</tr>
<tr>
<td>Gd</td>
<td>13.2</td>
<td>2.03</td>
<td>0.37</td>
</tr>
<tr>
<td>Y</td>
<td>23.2</td>
<td>7.30</td>
<td>0.19</td>
</tr>
<tr>
<td>Sm</td>
<td>16.4</td>
<td>3.10</td>
<td>0.65</td>
</tr>
<tr>
<td>Nd</td>
<td>19.5</td>
<td>4.60</td>
<td>0.11</td>
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