Chapter V

The frequency dependent dielectric and AC conductivity properties of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ phosphors were investigated for the frequency range 100 Hz - 2 MHz at room temperature was discussed in this chapter. The value of dielectric constant and dielectric loss decreases with increase in frequency of the applied signal in all the samples. Also the value of dielectric constant and dielectric loss decreased with doping of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ ions. The conductivity of the samples obey Jonscher’s power-law and shows a decrease with increasing doping concentration of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ ions. The higher value of real and imaginary part of impedance at lower frequency indicates the space charge polarization of the material and its absence at higher frequencies was confirmed from the low value of impedance at higher frequency region. The Cole-Cole parameters of the samples were calculated and the semi circle observed indicate a single relaxation process and can be modeled by an equivalent parallel RC circuit.
Dielectric properties of $\text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3$: $\text{Pr}^{3+}$, $\text{Sm}^{3+}$, $\text{Dy}^{3+}$ phosphors

5.1 Introduction

The research and development in the dielectric, piezoelectric and ferroelectric materials have increased due to the availability of new materials with good physical properties in different form like bulk single crystals, ceramics, thin films, thick films, nanotubes, nanowires etc [1]. These materials can find application in the field of sensors, actuators, transducers, micro electromechanical systems, microwave tuners, ferroelectric nonvolatile random access memories, electro optic modulators etc [1-2]. The perovskite structures have recently attracted considerable attention due to their unique electrical and magnetic properties [3]. The most widely used ferroelectrics occur in the perovskite materials has the general formula $\text{ABO}_3$ (where $\text{A} = \text{Sr, Ca, Ba} \& \text{Pb}$ and $\text{B} = \text{Ti}$ ) [3]. The modification in the form of either solid solutions or dopant addition to the simple perovskite materials result in the improvement or tuning of piezoelectric and dielectric properties [3-4]. The perovskite structures with transition metal cation or lanthanides exhibit an interesting combination of conductivity, dielectric and magnetic properties depending on the degree of $\text{TiO}_6$ octahedral tilting [5]. Materials with high dielectric properties find application in the field of miniaturization of microwave devices [6]. The perovskite titanates such as $\text{CaTiO}_3$ and $\text{SrTiO}_3$ are the usually used microwave dielectric material because of their high dielectric constant [7]. The combination of $\text{CaTiO}_3$ and $\text{SrTiO}_3$ with the general formula $\text{Sr}$.
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.xCa.TiO3 binary system have advantageous dielectric, piezoelectric, electrostrictive, pyroelectric and electro-optic properties [8-10]. Depending on the chemical composition and preparation temperature Sr1-xCaTiO3 undergoes structural phase transitions with dramatic effect on the dielectric constant [8]. They also have ferroelectric or antiferroelectric phase transition depends on its exact chemical composition [11].

Dielectric spectroscopy also known as electromechanical impedance spectroscopy is an important tool to study the dielectric properties of any material with the advantage of manual control over frequency and temperature. The measurement of dielectric constant and dielectric loss as a function of frequency and temperature gives information about the polarization mechanism, process of conduction, influence of impurities and phase transition [1]. On combining the data of DC conductivity with the AC conductivity obtained from the dielectric properties will help to understand the information on defect formation, impurities and nature of conduction of a material [12]. Complex impedance analysis helps to analyze the multiple relaxation processes in a polycrystalline material. The complex impedance is mainly described by the Cole-Cole diagram gives the information about the relaxation times arising due to different mechanisms in a material. The luminescence properties of Pr3+, Sm3+ and Dy3+ doped Sr0.5Ca0.5TiO3 perovskite phosphor material was discussed in the previous chapters. In this chapter the dielectric properties of Sr0.5Ca0.5TiO3 and different concentrations of Pr3+, Sm3+ and Dy3+ doped Sr0.5Ca0.5TiO3 perovskite titanate was discussed in detail.
5.2 Experimental

Sr_{0.5}Ca_{0.5}TiO_{3} and Different concentrations of Pr^{3+}, Sm^{3+} and Dy^{3+} doped Sr_{0.5}Ca_{0.5}TiO_{3} samples prepared by solid state reaction method were used for the dielectric and AC conductivity measurements. The preparations of the samples were explained in previous chapters. The powder samples were pelletized for the characterization with 1 cm diameter and 2 mm thickness. The dielectric and AC conductivity measurements were carried out using Agilent E4980A in the frequency range 100 Hz- 2 MHz. All the measurements were carried out at room temperature and represented as a function of frequency.

5.3 Results and Discussion

5.3.1 Dielectric Study of the Samples

The value of dielectric constant is important for the impedance matching in tunable devices so as the dielectric characterization [13]. The complex form of the permittivity of a dielectric material shows the dielectric constant (real part of permittivity) and dielectric loss (imaginary part of permittivity). The real part and the imaginary part of the dielectric constant can be expressed by the equation

$$\varepsilon' = \frac{C_p d}{\varepsilon_0 A}$$  \hspace{1cm} (5.1)

$$\varepsilon'' = \varepsilon' \tan \delta$$  \hspace{1cm} (5.2)

where d is the thickness of the sample, A is the area of the sample, \( \varepsilon_0 \) is the permittivity of free space (= 8.854×10^{-12} F/m), \( C_p \) is the parallel capacitance across the sample and \( \tan \delta \) is the loss tangent or the dissipation factor [14].
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The variation of dielectric constant ($\varepsilon'$) as a function of frequency at room temperature for different concentrations of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped and undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples are represented in Fig.5.1. $\varepsilon'$ describes the relation between the transmission speed of the AC signal and the dielectric material’s capacitance. For Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ and Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples the value of dielectric constant decreases with increasing frequency of the applied signal. In the low frequency region, below 1 kHz, very high value of dielectric constant is obtained due to the electrode effect and polarization mechanisms (electronic, ionic, orientational and space charge polarization). When the frequency is increased the dipole’s movements were restricted and the orientational polarization ceases [15]. This results in the reduction of dielectric constant and reaches a constant value at higher frequency corresponding to the space charge polarization [15]. Thus after a certain frequency the dielectric constant become frequency independent [1]. The dielectric constant, $\varepsilon'$ of prepared samples for selected frequencies is tabulated in Table.5.1. The value of dielectric constant obtained for the prepared samples is comparable with other binary titanate systems [16-19].

We can also see that as the doping concentration of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ ions increases the value of dielectric constant decreases. The samples with higher doping concentration of RE$^{3+}$ ions show a low value of dielectric constant. This may be due to the increased interaction between RE$^{3+}$ ions at higher concentration since the distance between RE$^{3+}$ ions decreases as the concentration increases. Thus the increased interaction between RE$^{3+}$ results in the reduction of dielectric constant [20]. But M. W.
Fig. 5.1 Variation of dielectric constant with frequency for diff. concentration of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples.
Cole et al. explained the reduction in dielectric constant with doping concentration in terms of grain size [13]. Since the sample consists of small granular multigrain with random orientation, implies a near equal polarization in all directions. As the doping concentration of RE$^{3+}$ ions increases the grain size decreases resulting less polarization leading to a reduction in dielectric constant [21]. The decrease in dielectric constant with increase in RE$^{3+}$ concentration was also observed in Sm$^{3+}$ doped CaTiO$_3$, Eu$^{3+}$ doped LaAlO$_3$ and CaTiO$_3$-La(Mg$_{1/2}$Ti$_{1/2}$)O$_3$ ceramics [6, 22-23].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dielectric constant ($\varepsilon'$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f=10$ kHz</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$</td>
<td>844</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 0.05 Pr$^{3+}$</td>
<td>457</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 1.5 Pr$^{3+}$</td>
<td>291</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 0.05 Sm$^{3+}$</td>
<td>576</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 1.5 Sm$^{3+}$</td>
<td>323</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 0.5 Dy$^{3+}$</td>
<td>543</td>
</tr>
<tr>
<td>Sr$<em>{0.5}$Ca$</em>{0.5}$TiO$_3$: 3 Dy$^{3+}$</td>
<td>474</td>
</tr>
</tbody>
</table>

Table 5.1 Dielectric constant of Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ and Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples at selected frequencies.

Fig.5.2 shows the variation of dielectric loss, $\varepsilon''$ with frequency for undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ and Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples at room temperature. The value of dielectric loss shows the amount of energy loss from an AC signal as it passes through the dielectric medium. It is clear from the graph that the value of dielectric loss decreases with increase in the frequency. This decrease in the dielectric loss with frequency is attributed to the facts that, at low frequency range the $\varepsilon''$ is dominated by the influence of ion conductivity. At moderate frequencies, $\varepsilon''$ is due to the
Fig. 5.2 Variation of dielectric loss with frequency for different concentrations of Pr\(^{3+}\), Sm\(^{3+}\) and Dy\(^{3+}\) doped Sr\(_{0.5}\)Ca\(_{0.5}\)TiO\(_3\) samples.
Fig. 5.3 Variation of tan δ with frequency for different concentrations of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples.
contribution of ions jump, conduction loss of ion migration and ions polarization loss. At high frequencies, the dielectric loss in crystalline solids is of two types- intrinsic loss and extrinsic loss [1]. The low frequency phonons cause the intrinsic dielectric loss in solid dielectrics whereas the extrinsic loss is due to the interaction between the charged defects and the microwave fields. So $\varepsilon''$ has a minimum value at high frequency region [15]. The large value of $\varepsilon''$ at lower frequency region can also be due to the space polarization arises from the charged crystal defects, which causes a sudden increase in $\varepsilon''$ at low frequencies [24]. It is reported that the characteristic of low dielectric constant and dielectric loss with high frequency suggest that the sample possesses enhanced optical quality with lesser defects [25].

The variation of tan $\delta$ (also known as loss tangent or dissipation factor) with logarithmic frequency for $\text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3$ and $\text{Pr}^{3+}$, $\text{Sm}^{3+}$ and $\text{Dy}^{3+}$ doped $\text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3$ samples are shown in Fig.5.3. From the figure, it is clear that the value of loss tangent decreases with increase in frequency for all the samples. At low frequencies, due to the high value of resistance more energy is required for ion exchange resulting in high energy loss. But at high frequencies, the polarization due to charge accumulation decreases, as a result the value of loss tangent decreases and the conductivity of the material increases. Also, with the increase in the $\text{RE}^{3+}$ doping concentration, the value of loss tangent decreases due to the increased interaction between the ions.

### 5.3.2 Frequency dependent conductivity study

At low temperatures, the AC conductivity can be expressed as
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\[ \sigma_1(\omega) = \omega \varepsilon_0 \varepsilon'' \]  \hspace{1cm} (5.3)  
\[ \sigma_2(\omega) = \omega \varepsilon_0 \varepsilon' \tan \delta \]  \hspace{1cm} (5.4)

where \( \omega = 2\pi f \) represents the angular frequency of the applied voltage. The plot of AC conductivity with frequency at room temperature for undoped Sr_{0.5}Ca_{0.5}TiO_{3} and Pr^{3+}, Sm^{3+} and Dy^{3+} doped Sr_{0.5}Ca_{0.5}TiO_{3} samples are shown in Fig.5.4. At room temperature frequency dependent conductivity of a material exhibits both low and high frequency dispersion phenomena [26]. The low frequency dispersion is due to the interfacial impedance or space charge polarization. The conductivity at this frequency region is almost constant. As the frequency decreases, more and more charges accumulated at the electrode and the electrode interface resulting in the decrease of mobile charges and a drop in conductivity occurs at low frequency region. In other words at low frequencies, the ac conductivity was almost frequency independent, shows the presence of dc leakage current throughout the sample [27]. At high frequency region, as the frequency increases the conductivity increases due to the hopping of charge carriers [28]. As a result ion exchange process occurs effectively in the high frequency region. That is the conductivity value shows weak dependence at low frequency region and strong dependence at high frequency region [29]. The conductivity of prepared samples obtained is in \( 3\times10^{-8} \) - \( 2.5\times10^{-5} \) S/cm range.

At low frequencies, the conductivity refers to the dc conductivity \( (\sigma_0) \) whereas at higher frequency range the conductivity obeys the power law relation expressed as

\[ \sigma(\omega) = A\omega^\delta \]  \hspace{1cm} (5.5)
So the total conductivity can be obtained by using Jonscher’s power-law relation [30-32] which is a convenient method to understand the frequency dependence of conductivity of a material and is given by

\[ \sigma_T = \sigma_{dc} + \sigma_{ac} \]  
(5.6)

\[ \text{ie. } \sigma_T = \sigma_0 + A\omega^s \]  
(5.7)

where \( \sigma_T \) is the total conductivity and \( \sigma_0 \) (\( \sigma_{dc} \)) is the frequency-independent component i.e. the conductivity at zero frequency. ‘A’ is a constant for a particular temperature and \( s \) is the power law exponent and generally varies from 0 to 1 (0 ≤ \( s \) ≤ 1). The values \( \sigma_0, s \) and A are known as power-law parameters. According to Jonscher, the frequency dependence of conductivity lies in the relaxation phenomena arising due to the mobile charge carriers [33]. At lower frequencies an ion jumps from one site to its neighboring vacant site contributing to D.C conductivity. After jumping from one site to another site, the ion can relax to its original site or to the neighbouring new site. This relaxation of ions in association with conduction gives frequency dispersion in the conductivity spectra.

Using Eqn.5.5-5.7, Jonscher’s power-law parameters were calculated and are presented in Table.5.2. The values of \( s \) are found to be increasing with increasing doping concentration of Pr\(^{3+}\), Sm\(^{3+}\) and Dy\(^{3+}\) ions whereas the values \( \sigma_0 \) and A are found to be decreasing. The value of \( s \) is related to the degree of correlation among moving ions [28]. For the prepared samples the value of \( s < 1 \), which is attributed to the hopping conduction of mobile charge carriers between two sites i.e. barrier hopping [34]. But the value of \( s > 1 \) was also reported, which is due to the quantum mechanical tunneling of mobile charge carriers between asymmetric double well potentials [34-36].
Fig. 5.4 Variation of AC conductivity with frequency for different concentrations of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped $\text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3$ samples.
5.3.3 Complex impedance analysis

The impedance analysis helps to understand the conductive and/or resistive properties of a material [37]. The real part \( (Z') \) and imaginary part \( (Z'\prime\prime) \) of the impedance can be represented as

\[
Z' = Z_{\text{Real}} = |Z| \cos \Theta \\
Z'\prime\prime = Z_{\text{Imag}} = |Z| \sin \Theta
\]  

(5.8) \hspace{1cm} (5.9)

where the phase angle is given by \( \Theta = \tan^{-1}(Z'\prime\prime/Z') \).

Frequency dependence of real part of impedance \( (Z') \) for \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3 \) and \( \text{Pr}^{3+}, \text{Sm}^{3+} \) and \( \text{Dy}^{3+} \) doped \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3 \) samples at room temperature was represented in Fig.5.5. For all the samples the real part of impedance decreases with increase in frequency and shows a frequency independent behavior after 10 kHz, indicate the increase in AC conductivity. This is due to the presence of space charge polarization at lower frequencies, which is eliminated at higher frequencies [38-39]. Also, with the \( \text{RE}^{3+} \) doping concentration, the real part of impedance increases and rapidly decreases.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \sigma \times 10^4 )</th>
<th>( s )</th>
<th>( A \times 10^9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3 )</td>
<td>1.95</td>
<td>0.38</td>
<td>15.86</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 0.05 \text{Pr}^{3+} )</td>
<td>1.33</td>
<td>0.47</td>
<td>0.89</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 1.5 \text{Pr}^{3+} )</td>
<td>0.31</td>
<td>0.50</td>
<td>0.27</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 0.05 \text{Sm}^{3+} )</td>
<td>0.92</td>
<td>0.48</td>
<td>0.82</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 1.5 \text{Sm}^{3+} )</td>
<td>0.96</td>
<td>0.61</td>
<td>0.77</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 0.5 \text{Dy}^{3+} )</td>
<td>1.69</td>
<td>0.52</td>
<td>5.3</td>
</tr>
<tr>
<td>( \text{Sr}<em>{0.5}\text{Ca}</em>{0.5}\text{TiO}_3: 3 \text{Dy}^{3+} )</td>
<td>1.17</td>
<td>0.46</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Table 5.2** Power-law parameters of \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3 \) and \( \text{Pr}^{3+}, \text{Sm}^{3+} \) and \( \text{Dy}^{3+} \) doped \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_3 \) samples.
Fig. 5.5 Variation of real part of impedance with frequency for different concentrations of Pr$^{3+}$, Sm$^{3+}$, and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples.
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Fig. 5.6 Variation of imaginary part of impedance with frequency for different concentration of Pr\(^{3+}\), Sm\(^{3+}\) and Dy\(^{3+}\) doped Sr\(_{0.5}\)Ca\(_{0.5}\)TiO\(_3\) samples.
with increase in frequency. As the doping concentration of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ increases the modification of grain boundary occurs as a result the value of $Z'$ increases at lower frequencies. This indicates the composition dependent electrical relaxation phenomena in the prepared samples [40].

Fig. 5.6 shows the variation of imaginary part of impedance ($Z''$) with frequency for undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ and Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples at room temperature. This plot is suitable for the understanding of the relaxation frequency of the most resistive contribution [40]. For all the samples the value of imaginary part of impedance decreases with increase in frequency and shows a constant value after 10 kHz. As the doping concentration of RE$^{3+}$ ions increases the value of $Z''$ also increases at lower frequency region and merges with the value of the undoped sample at high frequency region.

The Cole-Cole plots represent the real part of the impedance ($Z'')$ as a function of imaginary part of the impedance ($Z'$). Using the Cole-Cole plots we can model the prepared samples as an equivalent parallel resistor-capacitor (RC) circuit by calculating $f_p$, $R_b$, $C_b$ and $\tau$ [41]. The low frequency intercept on the real part of the impedance axis made by the semi-circle gives the value of the bulk resistance ($R_b$) and the peak of the semicircle is used to investigate the value of peak frequency ($f_p$) and the relaxation time ($\tau$). The value of bulk capacitance ($C_b$) is given by the equation

$$C_b = \frac{1}{2\pi f_p R_b} \quad (5.10)$$

and the relaxation time ($\tau$) is given by

$$\tau = R_b C_b = \frac{1}{2\pi f_p} \quad (5.11)$$
Fig. 5.7, 5.8, 5.9 and 5.10 shows the Cole-Cole plot between the real and imaginary part of impedance (\( Z' - Z'' \)) for \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_{3} \) and different concentrations of \( \text{Pr}^{3+}, \text{Sm}^{3+} \) and \( \text{Dy}^{3+} \) doped \( \text{Sr}_{0.5}\text{Ca}_{0.5}\text{TiO}_{3} \) samples respectively. The Cole-Cole plot appears in the form of a semi-circle represents the electrical phenomena in the material due to bulk material, grain boundary effect and interfacial phenomena. Usually, the crystalline materials show single semi-circle corresponding to the single relaxation process due to bulk effect. This bulk effect is due to the parallel combination of bulk resistance \( (R_b) \) and bulk capacitance \( (C_b) \) of the material. But in some cases the polycrystalline material show two semi-circle at high temperature [26]. In this case, the high frequency semi-circle corresponds to the bulk/grain interior property and the low frequency semi-circle corresponds to the grain boundary property.

![Cole-Cole plot for undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ sample.](image)

**Fig. 5.7** Cole-Cole plot for undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ sample.
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The complex impedance plot of the prepared samples shows single semi-circle since the resistance of the grains is larger than the resistance of the grain boundary [26]. The semi-circle corresponding to all samples has its own characteristic features having a unique relaxation frequency attributed to a different component in the sample. The relaxation time ($\tau$) is depending on the intrinsic properties of a material such as grain interior/bulk and grain boundary. Thus, the results obtained from the impedance analysis give a true picture of the electrical behavior of the sample. The Cole-Cole parameters, bulk resistance ($R_b$), bulk capacitance ($C_b$) and relaxation time ($\tau$), obtained from the complex impedance plot at room temperature for the prepared samples are presented in Table.5.3.

Fig.5.8 Cole-Cole plot for 0.05 and 1.5 wt% of Pr$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples.

Fig.5.9 Cole-Cole plot for 0.05 and 1.5 wt% of Sm$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples.
The relaxation time shows an increase with the doping concentration of RE$^{3+}$ ions. In perovskite oxides or in other solid materials, the major mode of charge transport is hopping process [42]. The hopping process generally takes place across the potential barrier set up by the lattice structure and the local environment of other ions. However due to irregularities in the lattice structure near defect sites, the potential barrier will have different magnitudes as well as varied widths [43-44]. This change in hopping

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_0$ (MΩ)</th>
<th>$C_b$ (pF)</th>
<th>$τ$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$</td>
<td>40.58</td>
<td>27.06</td>
<td>1.09</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:0.05 Pr$^{3+}$</td>
<td>63.57</td>
<td>19.12</td>
<td>1.22</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:1.5 Pr$^{3+}$</td>
<td>75.76</td>
<td>17.96</td>
<td>1.36</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:0.05 Sm$^{3+}$</td>
<td>44.73</td>
<td>27.18</td>
<td>1.20</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:1.5 Sm$^{3+}$</td>
<td>70.30</td>
<td>17.98</td>
<td>1.26</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:0.5 Dy$^{3+}$</td>
<td>70.61</td>
<td>17.34</td>
<td>1.21</td>
</tr>
<tr>
<td>Sr$_0.5$Ca$_0.5$TiO$_3$:3 Dy$^{3+}$</td>
<td>73.04</td>
<td>17.17</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Table 5.3 Cole-Cole parameters of Sr$_0.5$Ca$_0.5$TiO$_3$ and Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_0.5$Ca$_0.5$TiO$_3$ samples.
mechanism in the presence of RE$^{3+}$ concentration is responsible for the distribution in the relaxation time [29]. The value of bulk resistance also increases with RE$^{3+}$ doping concentration whereas the value of bulk capacitance decreases.

5.4 Conclusions

The dielectric and AC conductivity studies of undoped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ and different concentrations of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ doped Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ samples were studied at room temperature. The values of dielectric constant and dielectric loss of Sr$_{0.5}$Ca$_{0.5}$TiO$_3$ decrease with increase in the frequency of the applied signal and also with the doping of Pr$^{3+}$, Sm$^{3+}$ and Dy$^{3+}$ ions. The observed increase in the dielectric loss at low frequency region is due to the space charge polarization. The electrical properties such as real part of impedance, the imaginary part of impedance and AC/DC conductivity as a function of frequency have also been studied by impedance spectroscopy. At high frequencies, the AC conductivity increases with increase in frequency due to the hopping of charge carriers. The AC conductivity of the prepared samples obeys Jonscher’s power law and the power-law parameters were calculated. The single semi-circle observed in the Cole-Cole plot shows the single relaxation mechanism due to the bulk properties. The bulk resistance, bulk capacitance and relaxation time of the prepared samples were calculated from the Cole-Cole plot. High dielectric constant and relatively low dielectric loss of the samples indicate their potential application for high frequency microwave devices, capacitor application and miniaturization of electronic devices.
References


