International Journal of Physical Sciences

Volume 10 Number 20 October 2015
ISSN 1992-1950

Academic Journals

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International Journal of Physical Sciences

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academicJournals

Vol. 10(20), pp. 549-553, 30 October, 2015
DOI: 10.5897/IJPS2015.4395
Article Number: F96BFCD55973
ISSN 1992 - 1950
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International Journal of Physical Sciences

Full Length Research Paper

A statistical analysis of Lorentz invariance in entropy

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Received 4 August, 2015; Accepted 10 October, 2015

After relativity was introduced by Einstein in 1905, several attempts were made to reformulate the other fields of physics to make them consistent with the postulates of Relativity. However, relativistic reformulation remains a bone of contention even today after over a hundred years since Einstein's epoch making papers. This is mainly due to seemingly conflicting yet consistent ways of defining the macroscopic variables to be Lorentz invariant. Here, it will be shown from statistical origins that the current definition of entropy is untenable in relativistic scenarios.

Key words: Statistical mechanics, relativistic thermodynamics, entropy, Lorentz invariance.

INTRODUCTION

There are various ways to go about transforming the first and second laws of thermodynamics. One approach (Plank-Einstein) is to consider the invariance of pressure and obtain (Callen and Horwitz, 1971):

$$V = \frac{V_0}{\gamma}$$

From standard length contraction formulation. We are going to use standard notation implying:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

P is the pressure, U is the internal energy, Q is the Heat content, V is the volume and T is the temperature. In the γ term, v is the relative velocity of the frame while c is the speed of light. Also, the subscript $_0$ has been used to indicate the macroscopic variables in the rest frame). And therefore from standard Charles' Law:

$$T = \frac{T_0}{\gamma}$$

Also extending using the first law ($dU = dQ + PdV$):

$$Q = \frac{Q_0}{\gamma}$$

The second approach (Ott) is to consider the conservation of momentum before and after the thermodynamic process to get inverse of the above relations (Dunkel et al., 2009).

Simply by considering the energy transferred as seen from a moving frame (Rothenstein and Zaharie, 2003):

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PACS: 51.10+y. 05.70.Ce, 03.30+p, 05.20.Dd

$$Q = Q_0 \gamma$$

And therefore by the invariance of entropy

$$T = T_0 \gamma$$

This will also lead to:

$$V = V_0 \gamma$$

Note, that since the first law has been used to obtain these relations, none of them violate it or provide any inconsistencies to the definition of entropy which is considered invariant in both the cases. The problem of course arises when we choose to consider the results of an observation. Thus here, we choose to look at a more fundamental way by looking at the statistical origins of entropy.

REFORMULATING ENTROPY

Let's begin with Boltzmann's ubiquitous equation:

$$S = k \ln W$$

There was a great deal of controversy, when this equation was introduced by Boltzmann a century ago (Campisi and Kobe, 2010). Succinctly Einstein had said, the equation lacks proper theoretical basis and the concept of microstates is heuristic at best. However, nevertheless it does simplify quite a lot of scenarios and a relativistic reformulation is much needed.

Modified H-Theorem

A most straightforward quasi-derivation comes from Boltzmann's own H-Theorem which states:

$$\frac{dH}{dt} \leq 0$$

$If\ f_1\ satisfies\ the\ \mathrm{Boltzmann\ Equations},$ Where H(f) is defined as:

$$H[f] = \int d^3p\, d^3q\, f_1(p, q, t) \ln(p, q, t)$$

The Boltzmann equations which can easily be derived from Louiville's theorem which states:

$$\frac{\partial f}{\partial t} = \left(\frac{\partial f}{\partial t}\right)_{force} + \left(\frac{\partial f}{\partial t}\right)_{diffusion} + \left(\frac{\partial f}{\partial t}\right)_{collision}$$

Applying the Louiville's theorem here, for phase space distributions gives us the compact form:

$$\frac{\partial f}{\partial t} + \frac{p}{m}.\nabla\mathrm{f} + \mathbf{F}.\frac{\partial f}{\partial t} = \left(\frac{\partial f}{\partial t}\right)_{collision}$$

Extending, this to make it Lorentz invariant gives us (Clemmow and Wilson, 1957):

$$\frac{1}{c\beta}\frac{\partial f}{\partial t} + u_\lambda \frac{\partial f}{\partial x_\lambda} + \frac{1}{mc^2\beta} F_\lambda \frac{\partial f}{\partial u_\lambda} + \frac{1}{mc^2\beta} f \frac{\partial F_\lambda}{\partial u_\lambda} = 0;\ for \left(\frac{\partial f}{\partial t}\right)_{collision} = 0$$

Here, $\begin{cases} u_\lambda\ is\ the\ three\ velocity \\ F_\lambda\ is\ the\ three\ force \\ \beta \equiv \sqrt{1 - v^2/c^2} \end{cases}$

Compared to the original non-relativistic scenario, the below equation due to Clemmow and Wilson contain the additional $\frac{1}{mc^2\beta} f \frac{\partial F_\lambda}{\partial u_\lambda}$ term which although not apparent is simply due to the first order Taylor-Expansion of the Jacobian of transformation from $f(t, x_\lambda, u_\lambda) \rightarrow f(t + \delta t, x_\lambda + \delta x_\lambda, u_\lambda + \delta u_\lambda)$. However, what is important is that this term will have a non-trivial effect on the resulting H-Theorem.

Coming back to the H-theorem, we see that the only physically useful function f which satisfies the Boltzmann equations is a probability distribution. Note, that there might be other functions which also satisfy the above criteria but are not relevant in this context. Thus, this function must be an invariant. However, engaging in a simple Jacobian of transformations from:

$$\begin{cases} q \rightarrow q' \\ p \rightarrow p' \\ t \rightarrow t' \end{cases}$$

Where the primed co-ordinates denote the relativistic scenario, we see that the integral is no longer of the same form.

Thus, as pointed out, because of the additional factor, H(f) does not retain its form and needs suitable modifications, although the moot idea remains same. It's important to note though that f is still invariant due to our above made assumption.

There is an important caveat to make here: Namely the Loschmidt paradox wherein Boltzmann supposedly obtains irreversibility using Louiville's theorem based on Newton's equations which are time symmetric. However, we will not digress and it will suffice to say here that this was resolved by assuming that initial states have low entropy which evolve to higher entropy over time.

Modified Helmholtz theorem

Campisi and Kobe (2010) demonstrated that for a Hamiltonian of a system given by (Campisi and Kobe, 2010):

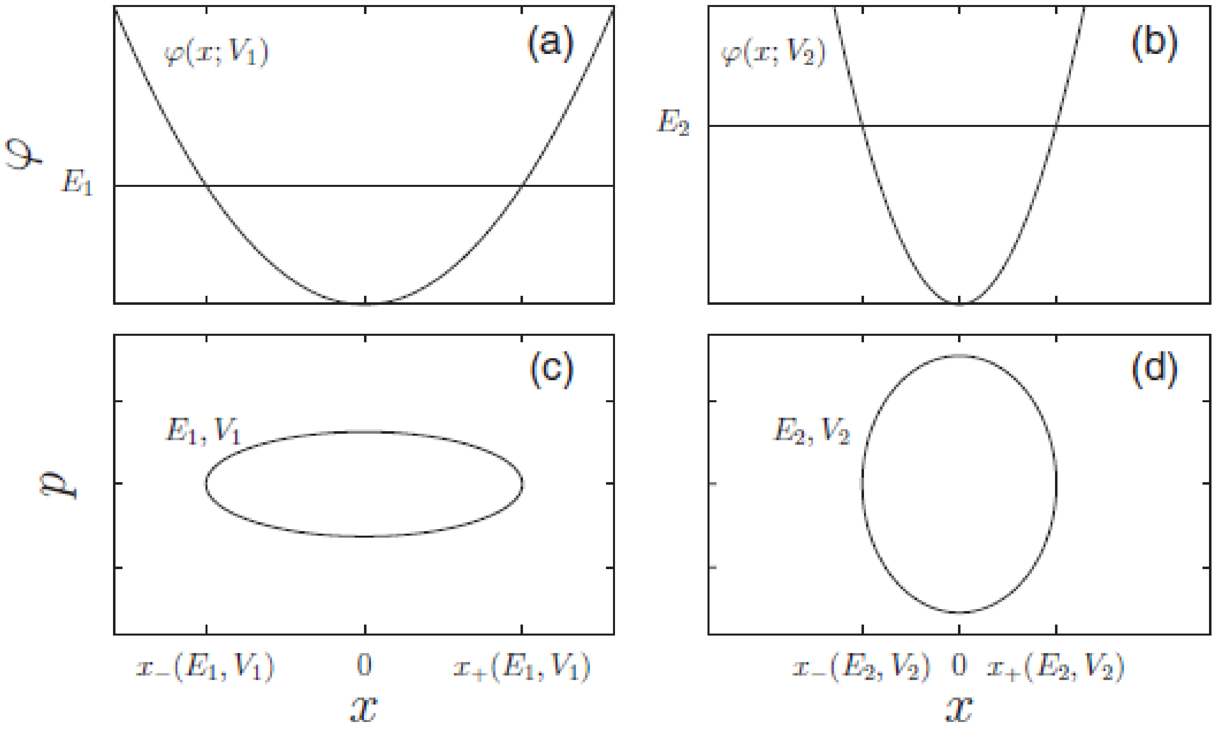

Figure 1. Point particle in the U-shaped potential $\phi(x;V)$=$mV^2x^2/2$. (a) Shape of the potential for a V=V_1. (b) Shape of the potential for a V=V_2. (c) Phase space orbit corresponding to the potential $\phi(x;V)$ at energy E_1. (d) Phase space orbit corresponding to the potential $\phi(x;V)$ at energy E_2. The two quantities *E,V,* uniquely determine one "state," that is, one closed orbit in phase space.

$$H(x,p;V) = K(p) + \phi(x;V)$$

Here $K(p) = \frac{p^2}{2m}$ is the kinetic energy and p is the momentum. The particle is considered to be moving in a U-shaped potential $\phi(x)$ as illustrated subsequently. Also note that V is some externally controllable parameter so that $\phi = \phi(x;V)$. Figure 1 is due to Campisi and Kobe (2010).

For a fixed V, the particle's energy E is a constant of motion. For simplicity, we define the zero energy in such a way that the minimum potential is 0, regardless of the value of V.

Once E and V are specified, the orbit of the particle in phase space is fully determined. Now applying Helmholtz theorem (Campisi and Kobe, 2010):

A function S(E,V) satisfying the following equations exist and is given by:

$$S(E,V) = k \ln 2 \int_{x_{-}(E,V)}^{x_{+}(E,V)} \sqrt{(2m(E-\phi(x;V))}\,dx$$

Where the equations to be satisfied are:

$$\begin{cases} \dfrac{\partial S(E,V)}{\partial E} = \dfrac{1}{T(E,V)} \\ \dfrac{\partial S(E,V)}{\partial V} = \dfrac{P(E,V)}{T(E,V)} \end{cases}$$

The entropy can be written more compactly as:

$$S(E,V) = k \ln \oint p\,dx$$

Where $p = \sqrt{(2m(E-\phi(x;V))}$ which is called the reduced action (Campisi and Kobe, 2010). It is basically the area θ in phase space enclosed by the orbit of energy E and parameter V,

$$S(E,V) = k \ln \theta(E,V)$$

Where, $\theta(E,V) = \int_{H(x,p;V)\leq E} dp\,dx.$

What is remarkable about the above result is that it suggests that there exists a consistent one dimensional mechanical counterpart of entropy given by the logarithm of the phase space volume enclosed by the curve of constant energy $H(x,p;V) = E.$

To generalize the model to more degrees of freedom, we find:

$$< f >_t = \frac{2m}{\tau}\int_{x_-}^{x_+}\frac{dx}{p(x)}f\left(x,p(x)\right);\ using\ dt = \frac{m dx}{p(x)}$$

Also using:

$$\int dp\,\delta\left(\frac{p^2}{2m}+\phi(x;V)-E\right)=\frac{2m}{p(x)}$$

Further, this allows us to define the normalized space probability density function as:

$$\rho(x,p;E,V)=\frac{1}{\tau(E,V)}\delta\left(\frac{p^2}{2m}+\phi(x;V)-E\right)$$

Thus to make a meaningful formulation, we extend to N-particle system in 3 dimensions with 3N degrees of freedom.

Thus the Hamiltonian for a N-particle system is (Campisi and Kobe, 2010):

$$H_N(\boldsymbol{q},\boldsymbol{p};V)=K_N(\boldsymbol{p})+\phi_N(\boldsymbol{q};V)$$

Thus in further analogy, we define the micro canonical probability distribution as:

$$\rho_N(\boldsymbol{q},\boldsymbol{p};E,V)=\frac{1}{\Omega_N(E,V)}\delta(E-H_N(\boldsymbol{q},\boldsymbol{p};V))$$

Where the normalization, Ω_N is given by:

$$\Omega_N(E,V)=\int\dots\int\delta(E-H_N(\boldsymbol{q},\boldsymbol{p};V))d\boldsymbol{q}\,d\boldsymbol{p}$$

Generalized Helmholtz theorem

From the above we obtain the generalised Helmholtz theorem (Campisi and Kobe, 2010):

$$S_N(E,V)=k\ln\phi_N(E,V)$$

Where, $$\phi_N(E,V)=\int\dots\int_{H(x,p;V)\le E}dp\,dx$$

Boltzmann principle

For a system composed of a large number of particles that interact through short range forces, the phase space volume approaches $\phi_N(E)\propto e^E$. Because $\Omega_N=\frac{\partial\phi_N}{\partial E}$, we also have $\phi_N\propto\Omega_N$ (From above definition of normalization).

Since Ω_N is a measure of the shell constant energy $H_N(\boldsymbol{q},\boldsymbol{p};V)=E$, it is proportional to the number of microstates (W) (Campisi and Kobe, 2010).

This therefore proves Boltzmann's equation to an arbitrary constant which is irrelevant anyway.

Relativistic formulation

Now, for the adiabatic scenario, $E^2-p^2c^2$ is an invariant and conserved quantity. Replacing back in:

$$S(E,V)=k\ln\oint p\,dx$$

We get,

$$S(E,V)=k'\ln\oint\sqrt{E^2-m_0^2c^4}\,dx$$

Here, k' is the modified constant term after dividing by the factor proportional to the speed of light term.

If we stick to the above formulation, since the energy doesn't remain constant, the orbit of energy E in phase space varies leading to an unbounded orbit potentially leading to an untenable definition for entropy. Even more important is that the phase space volume adds another exponential factor to the above, giving us a different definition for Boltzmann's eponymous equation. However, all of the above is based on our tacit assumption that entropy should be a relativistic invariant. Moreover, what is important is that to note is we find that simply making a relativistic reformulation without changing our definition makes Boltzmann's definition of entropy void in high velocity domains.

CONCLUSION

The above text shows that the current definition of entropy is untenable in the relativistic limit and needs to be suitably modified. Further, from above the distributions have also been shown to be derivable for high speed limits from a statistical perspective.

Conflict of Interest

The authors have not declared any conflict of interest.

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Vol. 10(20), pp. 554-561, 30 October, 2015
DOI: 10.5897/IJPS2015. 4406
Article Number: 20E142C55975
ISSN 1992 - 1950
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International Journal of Physical Sciences

Full Length Research Paper

A study of structural, optical and dielectric properties of Eu_2O_3 doped borate glass

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Received 27 August, 2015; Accepted 28 September, 2015

Recent technological applications have generated more interest in the studies of different types of glasses. The wide applications of glasses take place due to their interesting properties such as low thermal expansion, high softening temperature, high resistance to chemical attack, high refractive index with low dispersion and mechanical strength. Eu_2O_3 doped borate glasses were successfully synthesized by melt quenching method. The X-ray diffraction (XRD) spectra revealed that these glasses had amorphous nature. Optical properties of prepared samples were characterized by photoluminescence studies. The dielectric properties of glass samples were studied for different frequencies and different temperatures.

Key words: Glass, melt quenching method, europium oxide, X-ray diffraction (XRD), photoluminescence and dielectric studies.

INTRODUCTION

The rare earth (RE) doped borate glasses are among those materials which have a number of optics and photonics applications (Marimuthu et al., 2009). Borate based glasses are the best choice, which more clearly show the relationship between glass structure and optical properties of RE ions (Hai et al., 2005). An interesting characteristic of the borate glass is the appearance of variations in its structural properties when RE cations is introduced. Borate glass is a suitable optical material for RE ions with high transparency, low melting point, high thermal stability, good RE ion solubility (Hai et al., 2005); Deva and Madhukar, 2012) and shows more clear relationship between glass structure and physical properties. When rare earth elements are added to a glass matrix as dopant, a change in its electronic energy level structure is induced and also its absorption characteristics get modified. Among these the Borate glasses exhibit a more complex action of alkali ions than the silicate glasses and have Boric acid as the major component. The promising characteristic of borate is to produce the materials with small coefficient of thermal expansion and make it superior in glass industry to the silicate glasses. Also Boric acid is used in the manufacture of special type of fiberglass as it prevents devitrification in glass production, increases the durability and can be used as a heterogeneous catalyst (Sakashita

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and Shimoda, 1991). Boric acid improves glass melting besides enhancing the glass properties. Addition of Boric acid can increase the refractive index of glass. Due to the presence of alkali ions, Boric acid can dissolve uniformly in simulated physiological liquids at normal temperature. But with the addition of other cations in small amount, the dissolution becomes non uniform and it is likely that a new compound is obtained. For example, by adding Yttrium oxide as one of the components, it modifies the structure of glass and makes it resistant to heat or chemical attack. In this non-silicate glass composition, Boric acid acts as network former and lithium carbonate plays the role as a modifier. Lithium carbonate here helps to lower the melting point. It has to be emphasized that recent studies have focused on Borate glasses due to their remarkable properties like low melting temperature, thermal stability and radiation, which make it more advantageous in communication field. Even though by nature borates are easily crystallized and fairly stable, by adding some reagents like rare earth elements, they can overcome the demerits and improve their optical characteristics. Europium doped glasses belong to an important class of materials because they can be employed in a variety of applications such as two-dimensional x-ray imaging sensors, high-density memory devices, blue emitting phosphors for plasma display panels, and x-ray storage (Aitasalo et al., 2003; Qiu et al., 1997). Divalent Europium doped materials find applications as luminescent sources in the UV to blue-green region of the electromagnetic spectrum, as well as sensor devices, because the divalent Eu emission intensity is strongly dependent on the temperature (Shelby, 1994). On the other hand, the trivalent Eu doped materials present optical properties of interest in the orange-red region. The advantage of using glasses as hosts for such dopants in relation to crystals lies in their homogeneity and ease of fabrication into various shapes, such as flat boards, fibers, and rods. In this paper, the structural, optical, and dielectric properties of Eu_2O_3 doped borate glass system have been presented.

EXPERIMENTAL PROCEDURE

In order to substantiate the study and compare how the addition of rare elements can change glass structure and its characteristics, the common technique of melt quenching was followed. It is based on the principle of melting the oxide so as to reduce the temperature suddenly below the transition temperature. For the purpose of comparison, two samples were prepared using the melt quenching method. In the first sample (Sample 1), Alkaline earth borate glasses of composition 60.5 H_3BO_3+xZnO+xLi_2CO_3 +x $Sr_2O_{3+}x_1Y_2O_3$ were bought (x in molecular % ranging from 10 to 50 and x_1 in molecular % of 0.01) from Aldrich 99.995% pure. Next the required quantities were thoroughly mixed together with a constant proportion and finely ground using mortar and pestle for 10 min. After this the ground raw materials were placed in a silica crucible and kept in the electronic furnace to melt the mixture under nearly 1150°C, with the continuous examination over a time of 3 h. After 3 h, the melted sample was transported to another furnace with temperature below 400°C in order to prevent breakage during the processing and placed for 3 h. This process is called annealing. After this annealing process, the sample was gradually cooled at the room temperature. The second sample (Sample 2) was also prepared following the same procedure but with the addition of 0.5% of Europium oxide in the composition as a dopant. Finally, the samples were polished for further characterization.

RESULTS AND DISCUSSION

XRD characterization

The XRD pattern of the samples was recorded by using a powder X-ray diffractometer (Schimadzu model: XRD 6000 using CuKα radiation, λ=0.154 nm), with a diffraction angle between 20° and 0°. Figure 1 show the characteristic X-ray diffraction spectra of the glass samples. The spectra of each glass sample contain a broad bump located at 2 θ value 21.005° and 'd' spacing 4.22595 Å for both the samples and no sharp lines are observed in the spectra which suggest that all the prepared glass samples confirm the amorphous (glassy) nature.

Optical characterization

The optical properties of the samples were studied by means of photoluminescence characterization. The fluorescent emission and absorption were performed with time correlated single photon counting instrument (purchased from Horiba Jobin Yvon, New Jersey). The xenon arc lamp was used as an excitation source at 450 Watt Power. The entire system consisted of two separate excitation and emission monochromators and detectors with red sensitive photomultiplier tube (R928p). The Luminescence spectra for samples under excitation at 260 nm were recorded. The photoluminescence studies revealed that by increasing the concentration of $Eu^{3+,}$ the spectrum gradually shifted from red to near UV region. The position of the excitation purely depended on Eu^{3+} concentration in glass. The emission and excitation spectra of the divalent Eu ions mainly contained two types of electronic transitions, 4f -5d transition for high energy region and weak 4f-4f transition at low energies.

The excitation spectra for the samples recorded from 240 to 420 nm at an emission wavelength of 260 nm are shown in Figure 2. The excitation spectra for sample 2 consisted of several bands of wavelength 250, 320, 352, and 415 nm. The excitation spectra of Eu^{3+} were monitored at $^5D_0$-$^7F_2$ transitions with a sharp peak at 262 nm. At the same time in sample 1 excitation bands appeared at 261, 343, and 350 nm. From the study it could be concluded that on the addition of dopants to sample1, the excitation wavelength slightly changed. Depending on the type of host material, the optical properties vary. Several emission bands were observed

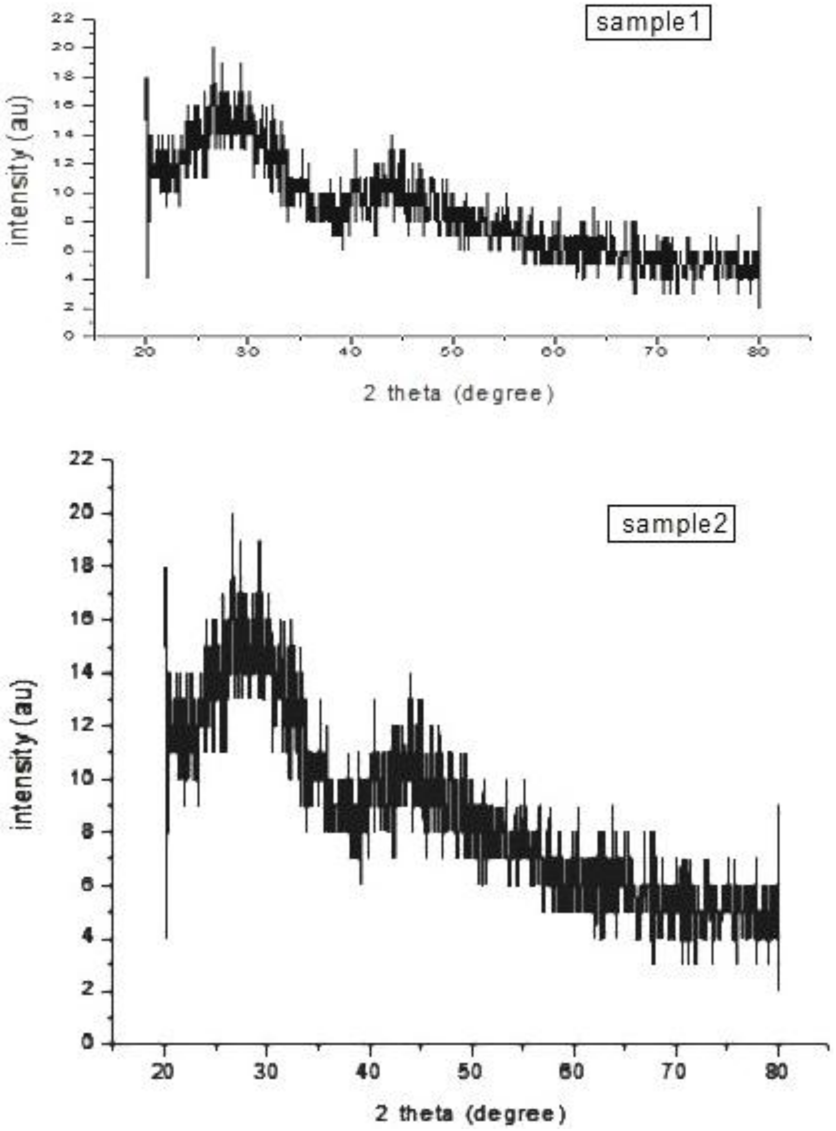

Figure 1. XRD pattern of sample 1(pure) and sample 2 (doped).

as shown in Figure 4. The excitation spectra show the characteristic features of Eu^{3+} excitation without any spectral shift in all samples under 613 nm emission. Swapna et al. (2015) reported that among all excitations in Eu^{3+} high intense emission peaks were observed at 364, 383, 395, 413, 467, 528, and 532 nm with the corresponding transitions being $^7F_0 \rightarrow ^5D_4, ^2G_5, ^5L_6, ^5D_3, ^5D_2, ^7F_1 \rightarrow ^5D_1$ transitions of Eu^{3+} (Swapna et al., 2015). In the present study, the observed emission spectra of Eu^{3+} showed excitation peaks at 391,412,436, and 452 nm (Figure 2 and 3). In general Eu^{3+} characteristics emission lay between 540 and 780 nm. But in the emission spectra of Eu^{3+}, among all bands, band near 436 nm showed a sharper peak than the other bands in the glass. The sharper the emission wavelength, the more intense the emission will be. It suggests that the glass provides more intensity at 436 nm. The emission spectra of sample 1 consisted of peaks at 388, 413, 437, and 453 nm wavelengths as shown in Figure 3. On the addition of dopant like Europium oxide, the peak positions slightly changed.

In this case, the intrinsic excitation bands of Eu^{3+} were placed near UV spectral range (~ 360 nm to 420 nm). From the graph, it is clear the highest peak value of Eu_2O_3 is 436 nm. The Parity-forbidden nature of Eu^{3+} absorption results only in low absorption cross-section. Yang et al. (2004) reported that the emission spectra of the different morphologies of Eu^{3+} sample exhibited orange and red emission, where the luminescence intensity of orange was approximately equal to red emission (Yang et al., 2004). The orange and red light emissions were associated with transitions of $^5D_0 \rightarrow ^5F_1$

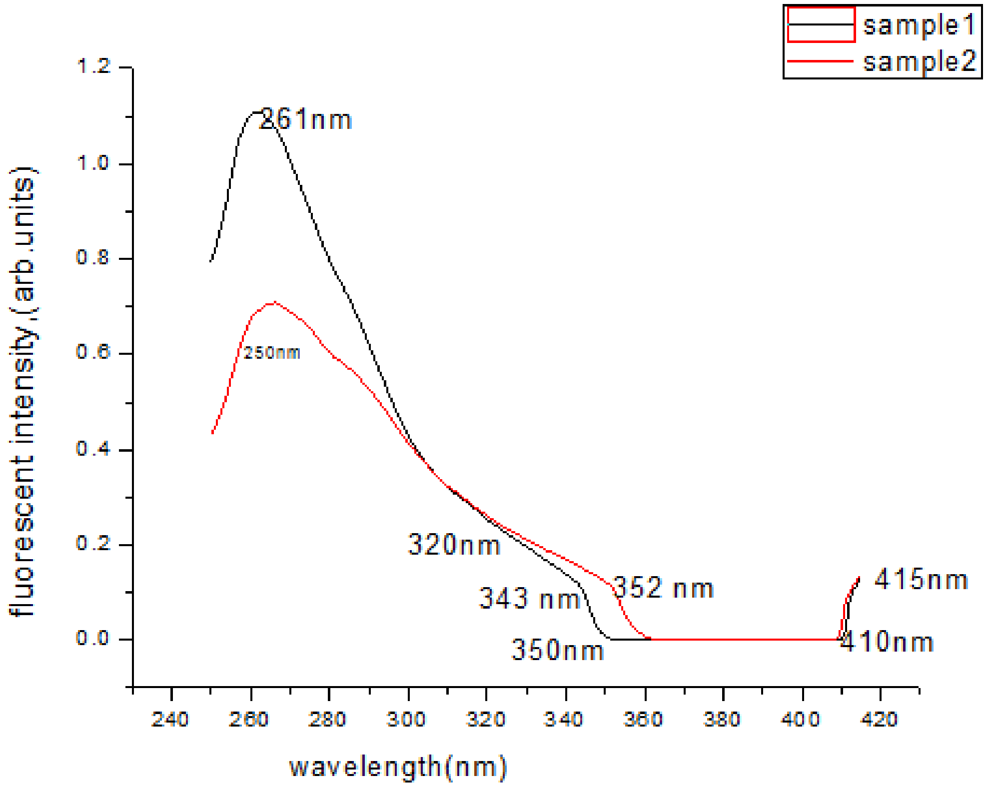

Figure 2. Excitation spectra for sample 1 and sample 2.

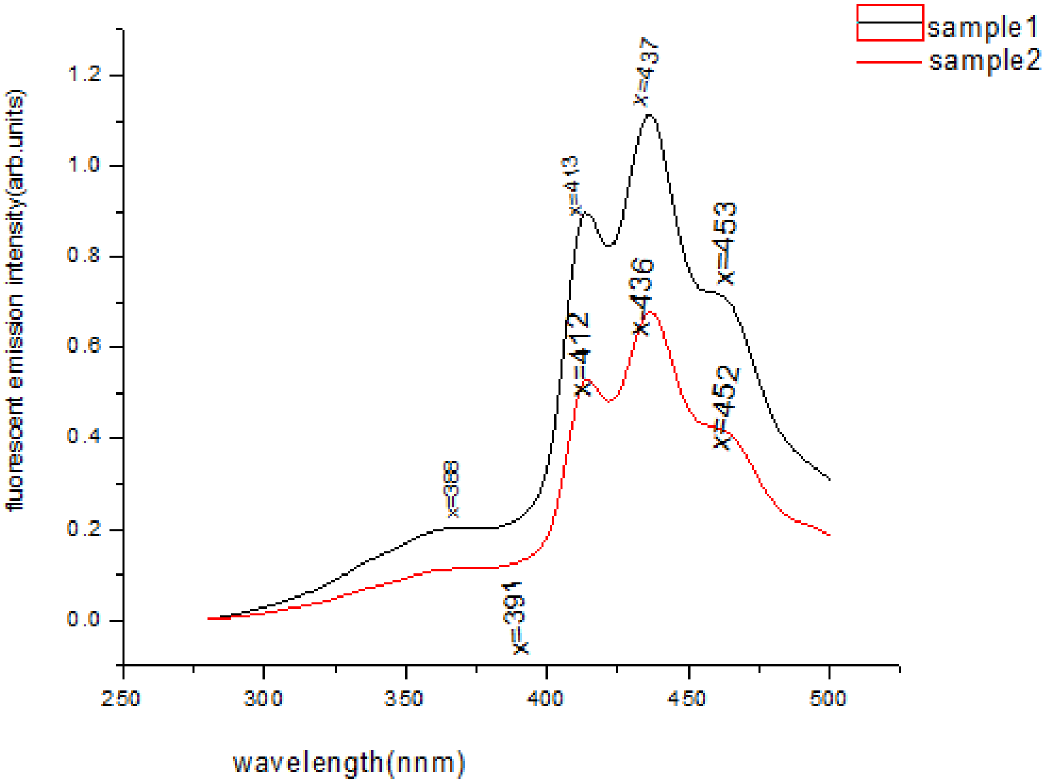

Figure 3. Emission spectra for sample 1 and sample 2.

and $^5D_0 \rightarrow {}^5F_2$ respectively. The present work suggests that the excitation spectra arises from the transition of $^5D_2 \rightarrow {}^5F_0$ and also agrees with the studies done by Lourenc-o et al. (2011). It confirms the feasibility of using this glass for UV green LED excitation.

Dielectric properties

The dielectric constant and the dielectric loss of the glass samples were studied at different temperatures using a HIOKI 3532-50 LCR HITESTER in the frequency range of 50 Hz to 5 MHz. The dielectric constant of a material may be defined as the ratio of the field strength in vacuum to that in the material for the same distribution of charge. The dielectric constant of a substance is a property of the constituent ions. The dielectric constant or relative permittivity can be defined as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{1}$$

We know that

$$\varepsilon = \frac{Cd}{A} \tag{2}$$

Thus, we have

$$C = \varepsilon_r \varepsilon_0 A / d \tag{3}$$

Where A is the area of the sample and d is the thickness of the sample. The relative permittivity (ε_r) is usually known as dielectric constant. It is always greater than unity. Suppose a parallel plate condenser has a capacitance of C_0 in air; then its capacitance, when the space between the plates is filled by a medium of dielectric constant (ε_r), is given by:

$C = C_0 \varepsilon_r$

$$\varepsilon_r = \frac{C}{C_0} \tag{4}$$

When a dielectric is subjected to an alternating electric field, the electric field strength changes as:

$$E = E_0 \cos \omega t \tag{5}$$

The induced current in the dielectric does not change exactly with the applied voltage. The current is found to lead the potential in phase. In a similar way, the electrical displacement (D) is also not in phase with respect to E. Now the expression for D becomes

$$D = D_0 \cos(\omega t - \delta)$$
$$D = D_0 \cos \omega t \cos \delta + D_0 \sin \omega t \sin \delta \tag{6}$$

The factor sin δ is a measure of the energy absorbed by the dielectric. It is known that in a capacitor the dielectrics usually have a resistance R and impedance Z that are related to the phase angle. Assuming R to be very large,

$$\sin \delta \approx \tan \delta = 1/\omega RC \tag{7}$$

The factor tan δ is referred to as the dielectric loss. Dielectric constant can be found from the measurement of capacitance. The dielectric constant in any direction of the medium can be considered as a measure of electrostatic binding strength between the ions in the direction. The higher the dielectric constant, the lower the electrostatic binding and hence higher is the lattice energy. Dielectric properties of pure and doped glasses are due to the contribution of electronic, ionic, dipole orientations and space charge polarizations. The charge carriers in a glass cannot move freely through but they could be displaced and thus become polarized depending upon the applied alternating field. The variation of dielectric constant and the dielectric loss with frequency and temperature for pure and doped glasses is shown in Figures 4 and 5. It can be seen that the dielectric constant and the dielectric loss gradually decrease with increase in frequency and decrease in temperature. Increase in dielectric constant and dielectric loss is more pronounced at lower frequencies. This behavior can be attributed to the applied electric field, which assists electrons hopping between two different sites in glasses. At high temperatures, the jump frequency of the charge carrier becomes large and comparable with the frequency of the applied field. Accordingly at low frequency the charge carriers hop easily out of the sites with low free energy and tend to accumulate at sites with high free energy barriers. This leads to a net polarization and gives an increase in the dielectric constant and the dielectric loss. However, at high frequency, the charge carriers will no longer be able to rotate sufficiently rapidly, so their oscillation will begin to lie behind this field resulting in a decrease of dielectric constant and dielectric loss. At low temperatures, jump frequency of the charge carries becomes smaller than the frequency of the applied field. The periodic reversal of the applied field takes place so rapidly that there are no excess charge carriers jumping in the field direction and the polarization is due to the disappearance of the charges piling up at high free energy barrier sites, which leads to a decrease in the values of the dielectric constant and the dielectric loss (Sindhu, et al., 2005; Szu and Lin, 2003). Similar variation of the dielectric constant and the dielectric loss

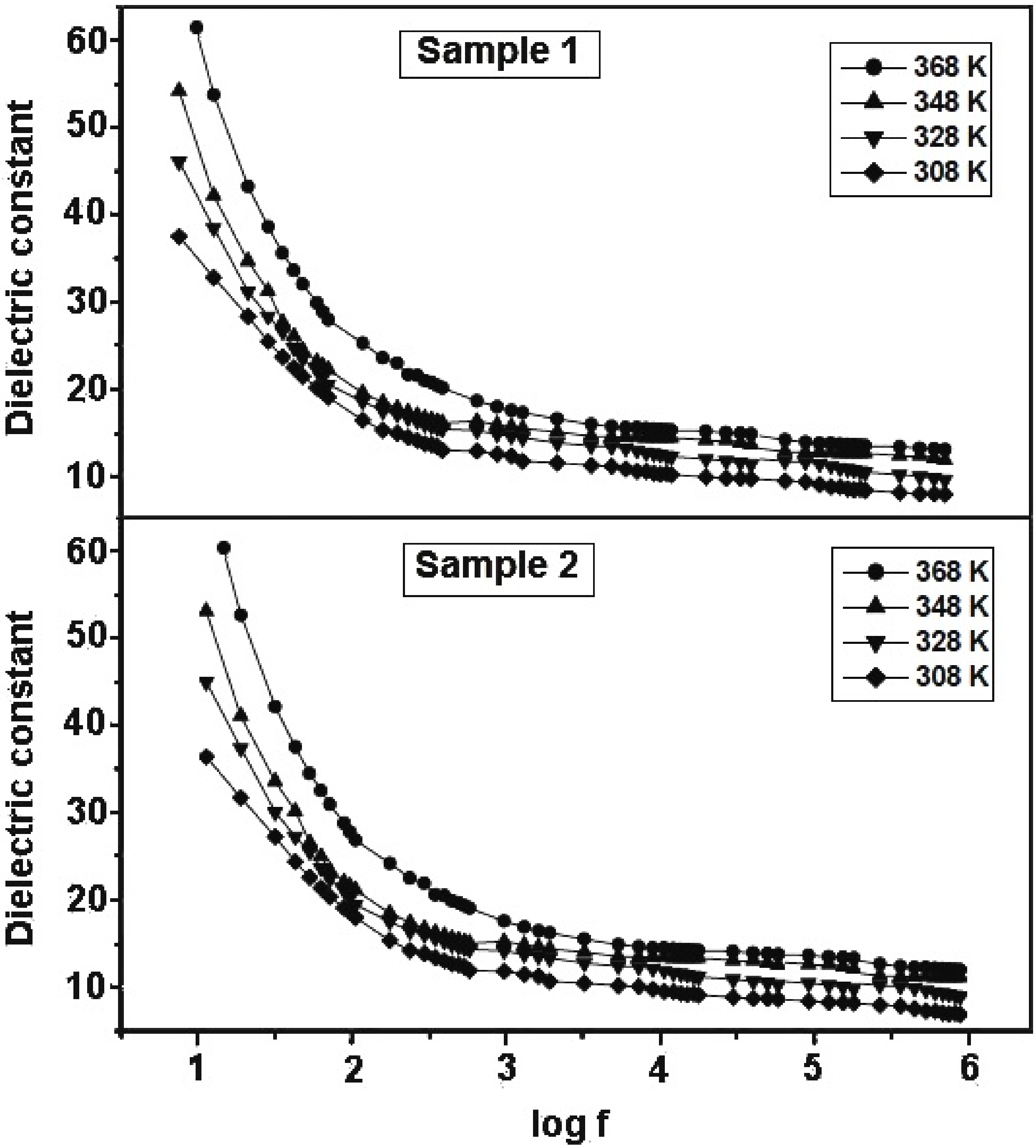

Figure 4. Variation of dielectric constant with log frequency.

was observed for other glass samples.

Conclusion

Eu_2O_3 doped Borate glasses were successfully synthesized by melt quenching method. The X-ray diffraction characterization strongly indicated the amorphous nature of the prepared glasses. The photoluminescence graph made it clear that the small variation in the peak value occurred when the sample was doped with a rare earth element. This indicated that the wavelength of excitation purely depended upon the material composition. The dielectric properties of glass samples were studied for different frequencies and different temperatures.

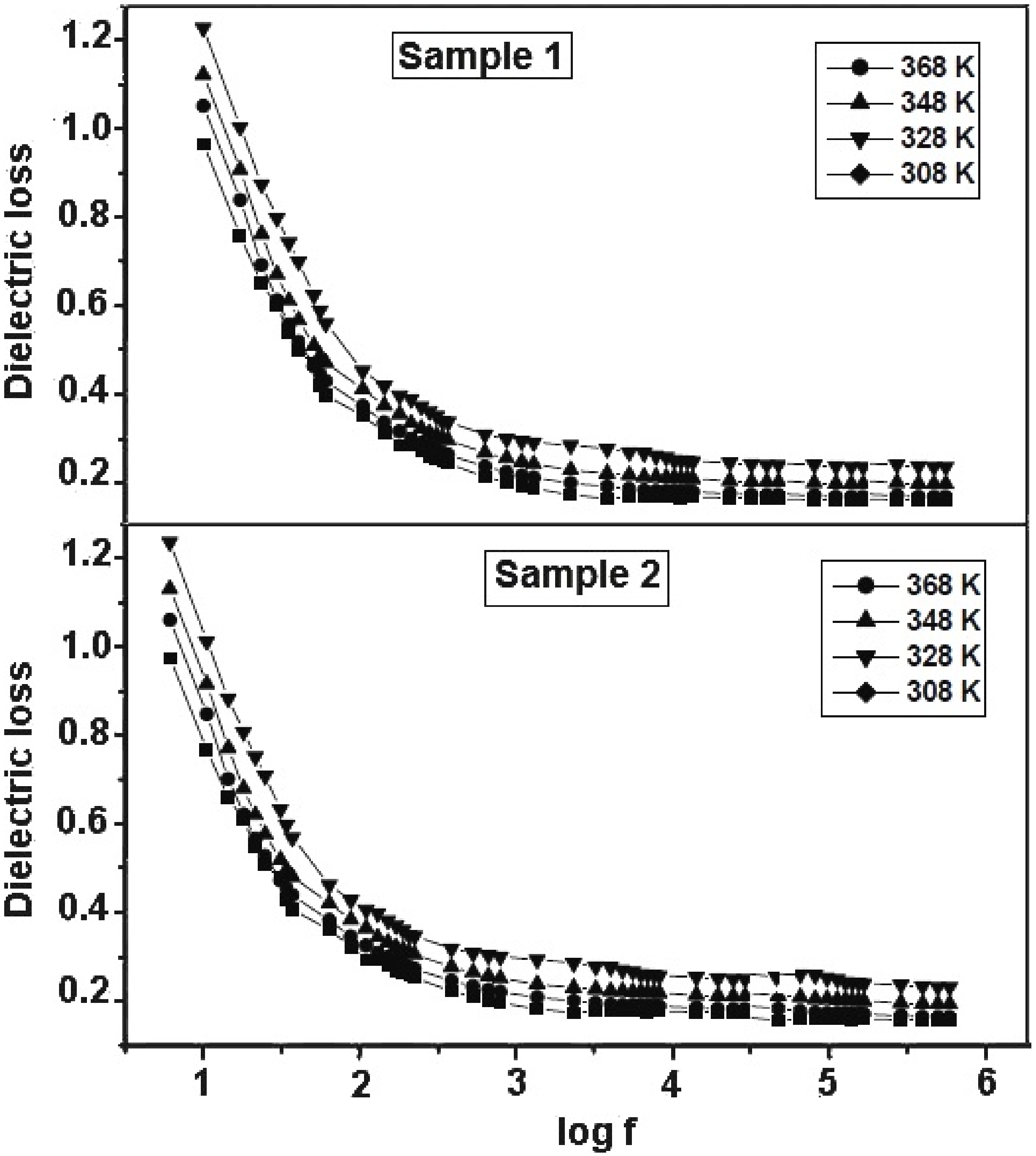

Figure 5. Variation of dielectric loss with log frequency.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGMENT

The author Dr. M. Priya would like to thank the Board of Research in Nuclear Sciences (BRNS) for funding this major research project.

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