

Dielectrics

Introduction

Dielectrics are the materials having electric dipole moment permanently.

Dipole: *A dipole is an entity in which equal positive and negative charges are separated by a small distance..*

DIPOLE moment (μ_{ele}): *The product of magnitude of either of the charges and separation distance b/w them is called Dipole moment.*

$$\mu_e = q \cdot x \rightarrow \text{coul} - m$$

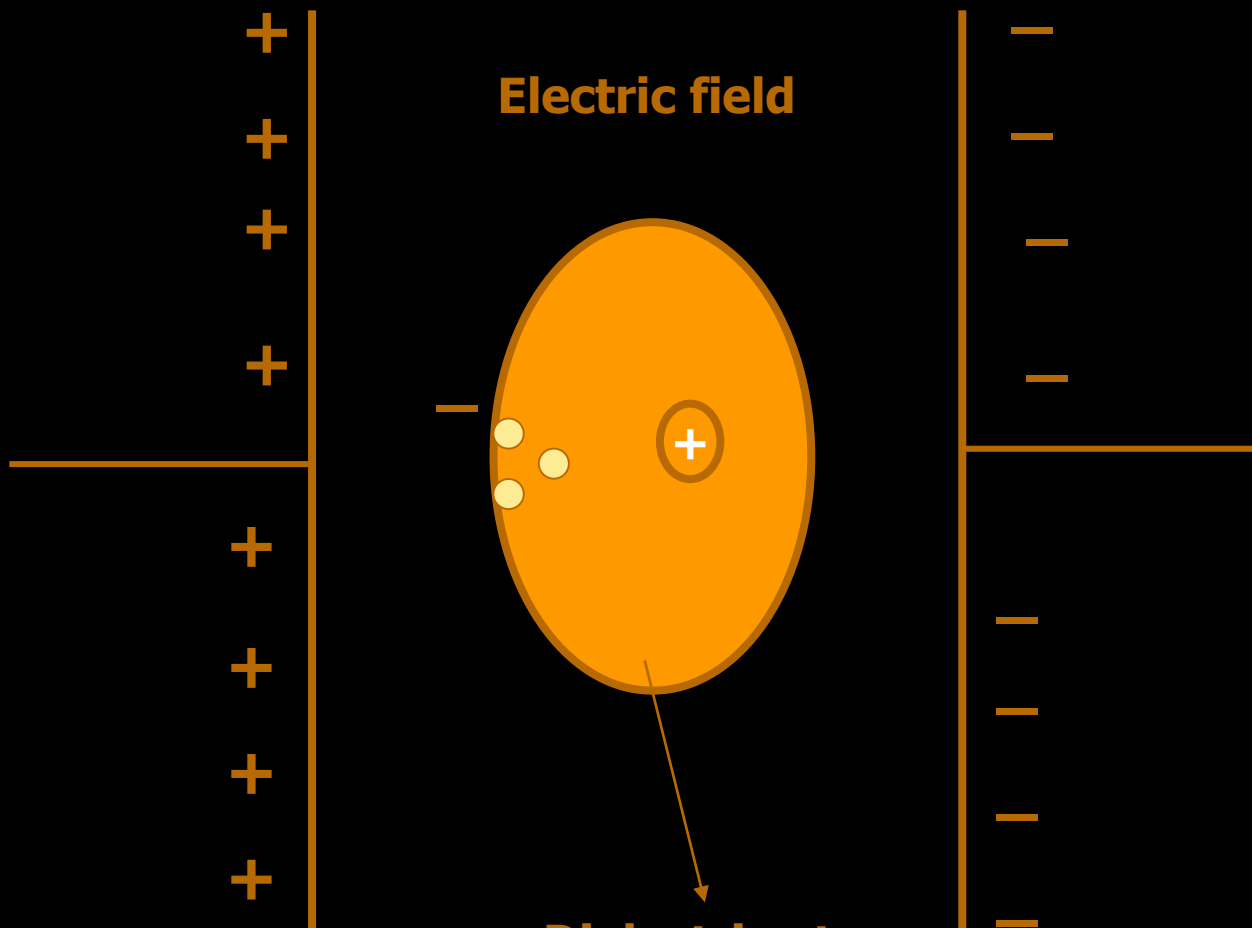


All dielectrics are electrical insulators and they are mainly used to store electrical energy.

Ex: Mica, glass, plastic, water & polar molecules...

dipole

Electric field



Dielectric atom

Dielectric Constant

Dielectric Constant is the ratio between the permittivity of the medium to the permittivity of free space.

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

The characteristics of a dielectric material are determined by the dielectric constant and it has no units.

Electric Polarization

The process of producing electric dipoles by an electric field is called polarization in dielectrics.

Polarizability:

The induced dipole moment per unit electric field is called Polarizability.

The induced dipole moment is proportional to the intensity of the electric field.

$$\mu \propto E$$

$$\mu = \alpha E$$

$\alpha \rightarrow$ polarizability constant

Is a Polarizability constant

Polarization vector:

The dipole moment per unit volume of the dielectric material is called polarization vector.

$$P = \frac{\sum_{i=1}^n q_i x_i}{V}$$

Electric flux Density (D):

Electric flux density is defined as charge per unit area and it has same units of dielectric polarization.

Electric flux density D at a point in a free space or air in terms of Electric field strength is

$$D_0 = \epsilon_0 E \quad \rightarrow (1)$$

At the same point in a medium is given by

$$D = \epsilon E \quad \rightarrow (2)$$

As the polarization measures the additional flux density arising from the presence of material as compared to free space

$$\text{i.e., } D = \epsilon_0 E + P \quad \rightarrow (3)$$

Using equations 2 & 3 we get

$$\epsilon E = \epsilon_0 E + P$$

$$(\epsilon - \epsilon_0) E = P$$

$$(\text{or}) \quad (\epsilon_r \cdot \epsilon_0 - \epsilon_0) E = P$$

$$(\epsilon_r - 1) \epsilon_0 \cdot E = P$$

Electric susceptibility:

The polarization vector \overline{P} is proportional to the total electric flux density and direction of electric field.

Therefore the polarization vector can be written

$$\begin{aligned}\overline{P} &= \varepsilon_0 \chi_e E \\ \chi_e &= \frac{\overline{P}}{\varepsilon_0 E} \\ &= \frac{\varepsilon_0 (\varepsilon_r - 1) E}{\varepsilon_0 E} \\ \chi_e &= \varepsilon_r - 1\end{aligned}$$

Various polarization processes:

When the specimen is placed inside a d.c. electric field, polarization is due to four types of processes....

1. Electronic polarization
2. Ionic polarization
3. Orientation polarization
4. Space charge polarization

Electronic Polarization

When an EF is applied to an atom, +vely charged nucleus displaces in the direction of field and e^- could in opposite direction. This kind of displacement will produce an electric dipole within the atom.

i.e, dipole moment is proportional to the magnitude of field strength and is given by

$$\begin{aligned}\mu_e &\propto E \\ \text{or} \\ \mu_e &= \alpha_e E\end{aligned}$$

where ' α_e ' is called electronic Polarizability constant

It increases with increase of volume of the atom.

This kind of polarization is mostly exhibited in Monatomic gases.

$$\alpha_e = \text{_____} \times 10^{-40} \text{ F-m}^2$$

He	Ne	Ar	Kr	Xe
0.18	0.35	1.46	2.18	3.54

It occurs only at optical frequencies (10^{15}Hz)

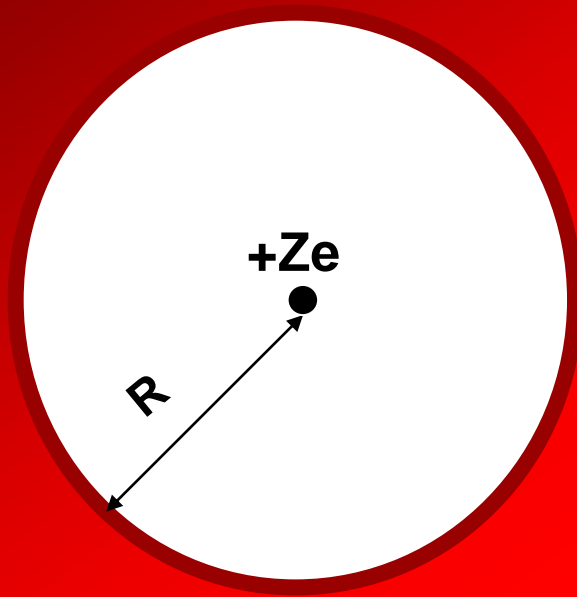
It is independent of temperature.

Expression for Electronic Polarization

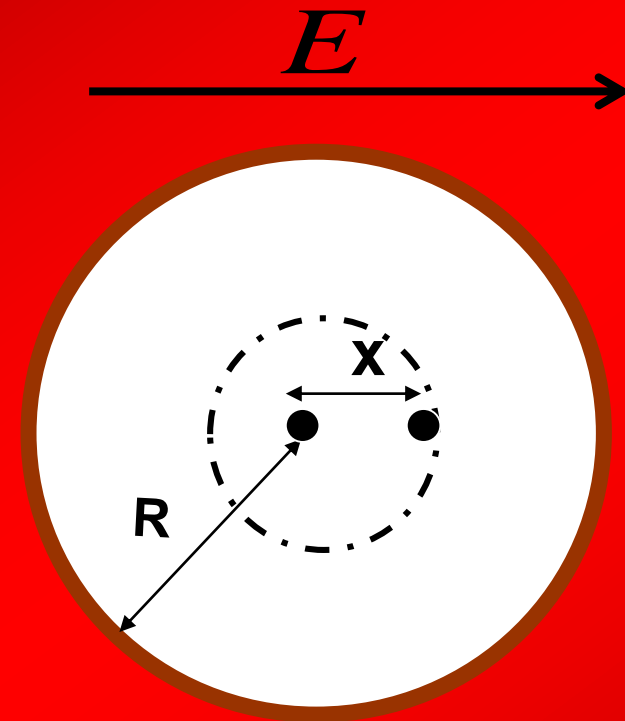
Consider a atom in an EF of intensity 'E' since the nucleus (+Ze) and electron cloud (-ze) of the atom have opposite charges and acted upon by Lorentz force (F_L).

Subsequently nucleus moves in the direction of field and electron cloud in opposite direction.

When electron cloud and nucleus get shifted from their normal positions, an attractive force b/w them is created and the seperation continuous until columbic force F_c is balanced with Lorentz force F_L , Finally a new equilibriums state is established.



No field fig(1)



In the presence of field fig (2)

fig(2) represents displacement of nucleus and electron cloud and we assume that the $-ve$ charge in the cloud uniformly distributed over a sphere of radius R and the spherical shape does not change for convenience.

Let σ be the charge density of the sphere

$$\sigma = \frac{-Ze}{\frac{4}{3}\pi R^3}$$

- Ze represents the total charge in the sphere.

Thus the - ve charge in the sphere of radius 'x' is

$$\begin{aligned} q_e &\Rightarrow \sigma \cdot \frac{4}{3}\pi x^3 \\ &\Rightarrow \frac{-ze}{\frac{4}{3}\pi R^3} \left(\frac{4}{3}\pi x^3 \right) \\ &= \frac{-ze}{R^3} x^3 \quad \text{----- (1)} \end{aligned}$$

$$\text{Now } F_c = \frac{1}{4\pi\epsilon_0} \cdot \frac{q_e \cdot q_p}{x^2} = \frac{1}{4\pi\epsilon_0 x^2} \left(\frac{-ze \cdot x^3}{R^3} \right) (ze) = \frac{-z^2 e^2 x}{4\pi\epsilon_0 R^3} \text{----- (2)}$$

Force experienced by displaced nucleus in EF of Strength E is
 $F_L = Eq = ZeE$ -----(3)

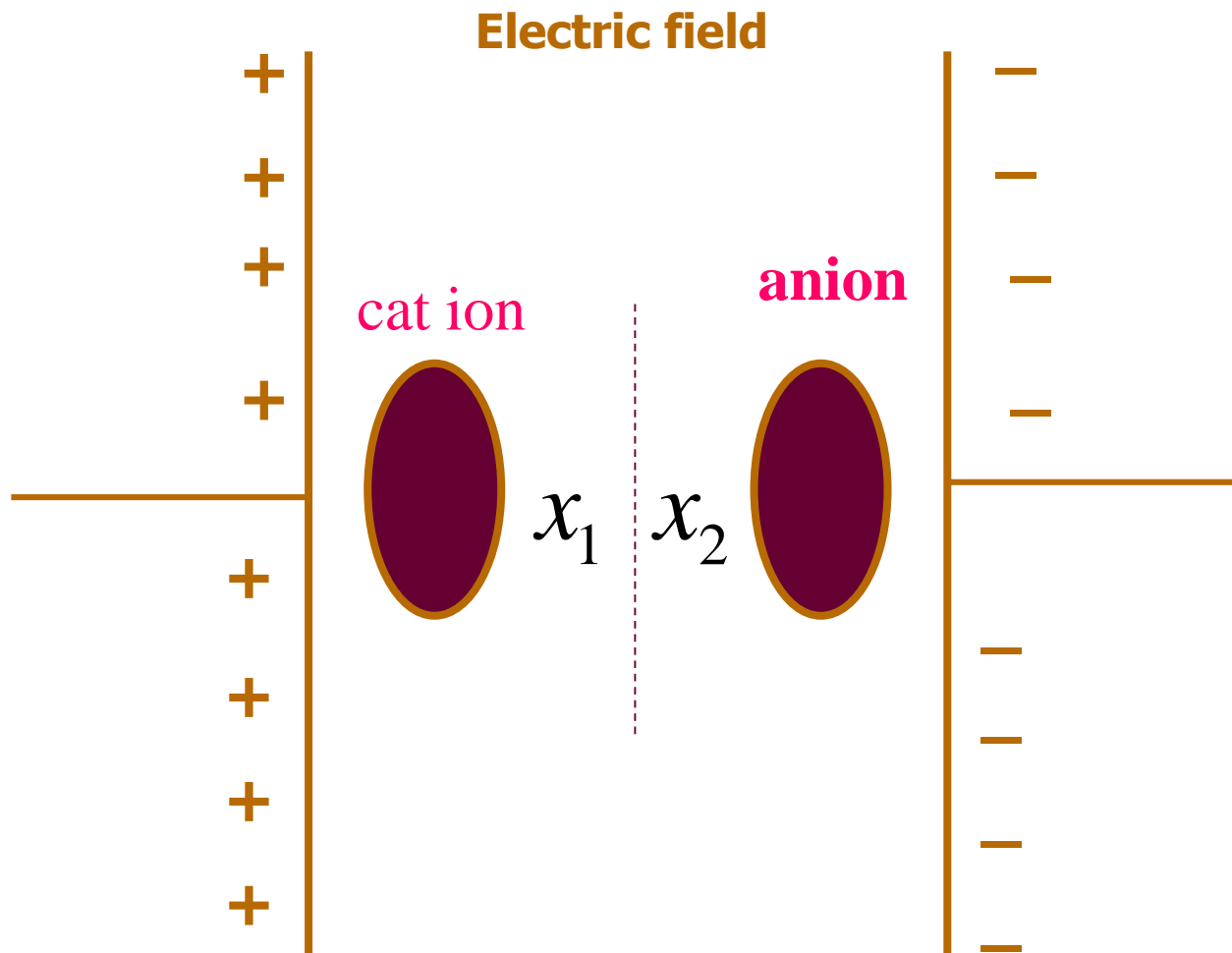
$$\begin{aligned} F_L &= F_c \\ \frac{-z^2 e^2 x}{4\pi\epsilon_0 R^3} &= ZeE \quad \text{----- (4)} \\ \frac{-zex}{4\pi\epsilon_0 R^3} &= E \\ \frac{-zex}{4\pi\epsilon_0 R^3} &= \frac{-zex}{\alpha_e} \quad \therefore E = \frac{\text{dipole moment}}{\alpha_e} \end{aligned}$$

$$\therefore \alpha_e = 4\pi\epsilon_0 R^3$$

Hence electronic Polaris ability is directly proportional to cube of the radius of the atom.

Ionic polarization

- The ionic polarization occurs, when atoms form molecules and it is mainly due to a relative displacement of the atomic components of the molecule in the presence of an electric field.
- When a EF is applied to the molecule, the positive ions displaced by X_1 to the negative side electric field and negative ions displaced by X_2 to the positive side of field.
- The resultant dipole moment $\mu = q (X_1 + X_2)$..



Restoring force constant depend upon the mass of the ion and natural frequency and is given by

$$F = eE = m.\omega_0^2 x$$

or

$$x = \frac{eE}{m.\omega_0^2}$$

$$\therefore x_1 + x_2 = \frac{eE}{\omega_0^2} \left[\frac{1}{m} + \frac{1}{M} \right]$$

Where 'M' mass of anion and 'm' is mass of cat ion

$$\therefore \mu_{ionic} = e(x_1 + x_2) = \frac{e^2 E}{w_0^2} \left[\frac{1}{m} + \frac{1}{M} \right]$$

or $\alpha_{ionic} = \frac{\mu_{ionic}}{E} \Rightarrow \frac{e^2}{w_0^2} \left[\frac{1}{m} + \frac{1}{M} \right]$

This polarization occurs at frequency 10^{13} Hz (IR).

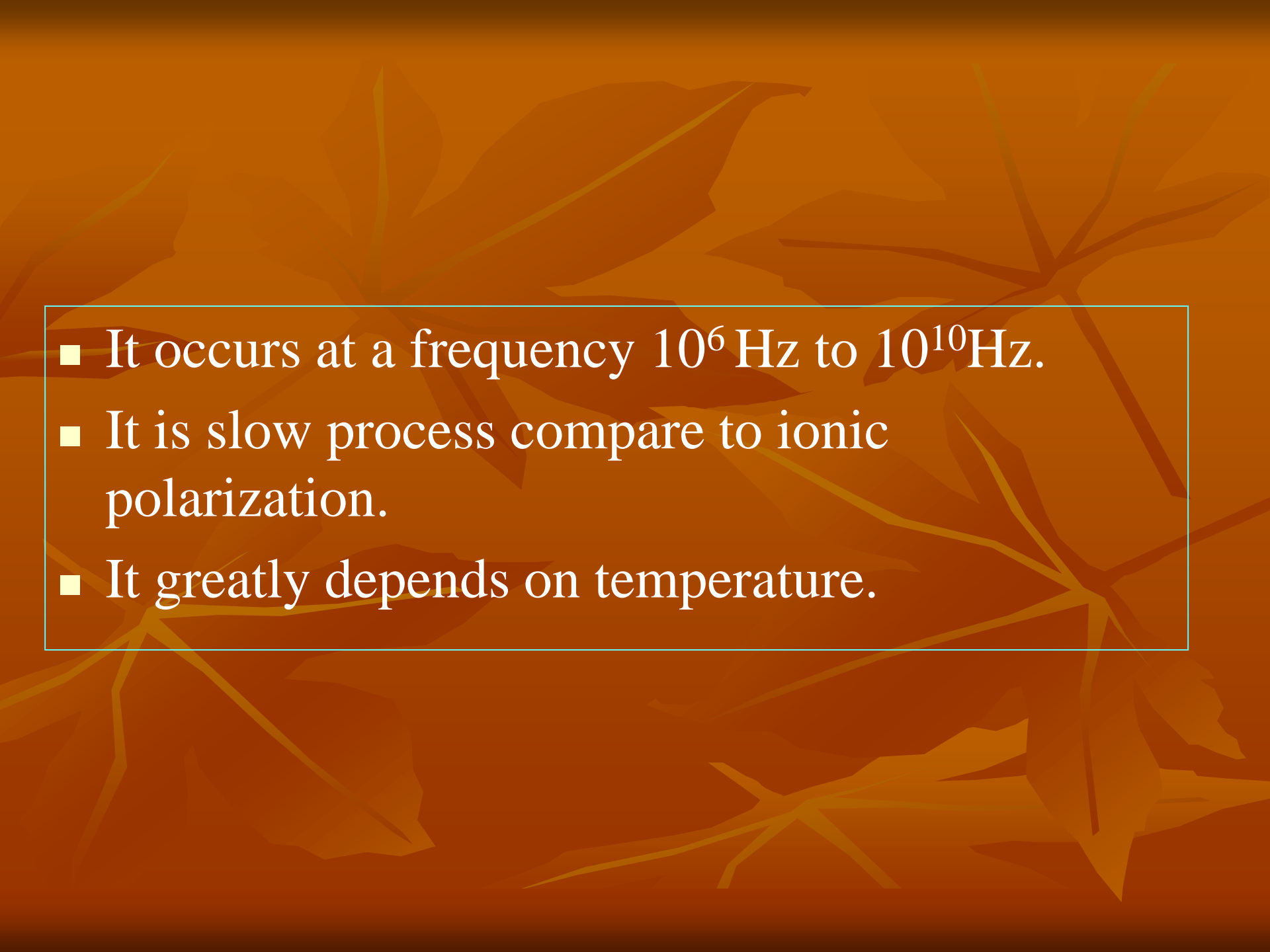
It is a slower process compared to electronic polarization.

It is independent of temperature.

Orientational Polarization

It is also called dipolar or molecular polarization. The molecules such as H_2 , N_2 , O_2 , Cl_2 , CH_4 , CCl_4 etc., does not carry any dipole because centre of positive charge and centre of negative charge coincides. On the other hand molecules like CH_3Cl , H_2O , HCl , ethyl acetate (polar molecules) carries dipoles even in the absence of electric field.

How ever the net dipole moment is negligibly small since all the molecular dipoles are oriented randomly when there is no EF. In the presence of the electric field these all dipoles orient them selves in the direction of field as a result the net dipole moment becomes enormous.

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- The background of the slide features a pattern of stylized, overlapping leaves in various shades of orange and brown, creating a textured, autumnal effect.
- It occurs at a frequency 10^6 Hz to 10^{10} Hz.
 - It is slow process compare to ionic polarization.
 - It greatly depends on temperature.

Expression for orientation polarization

$$P_o = N \cdot \vec{\mu}_{orie} \Rightarrow \frac{N \cdot \mu_{orie}^2 \cdot E}{3kT} = N \cdot \alpha_o \cdot E$$

$$\alpha_o = \frac{\mu_{orie}^2}{3kT}$$

$$\therefore \alpha = \alpha_{elec} + \alpha_{ionic} + \alpha_{ori} = 4\pi\epsilon_o R^3 + \frac{e^2}{w_0^2} \left[\frac{1}{M} + \frac{1}{m} \right] + \frac{\mu_{ori}^2}{3kT}$$

This is called **Langevin – Debye** equation for total Polaris ability in dielectrics.

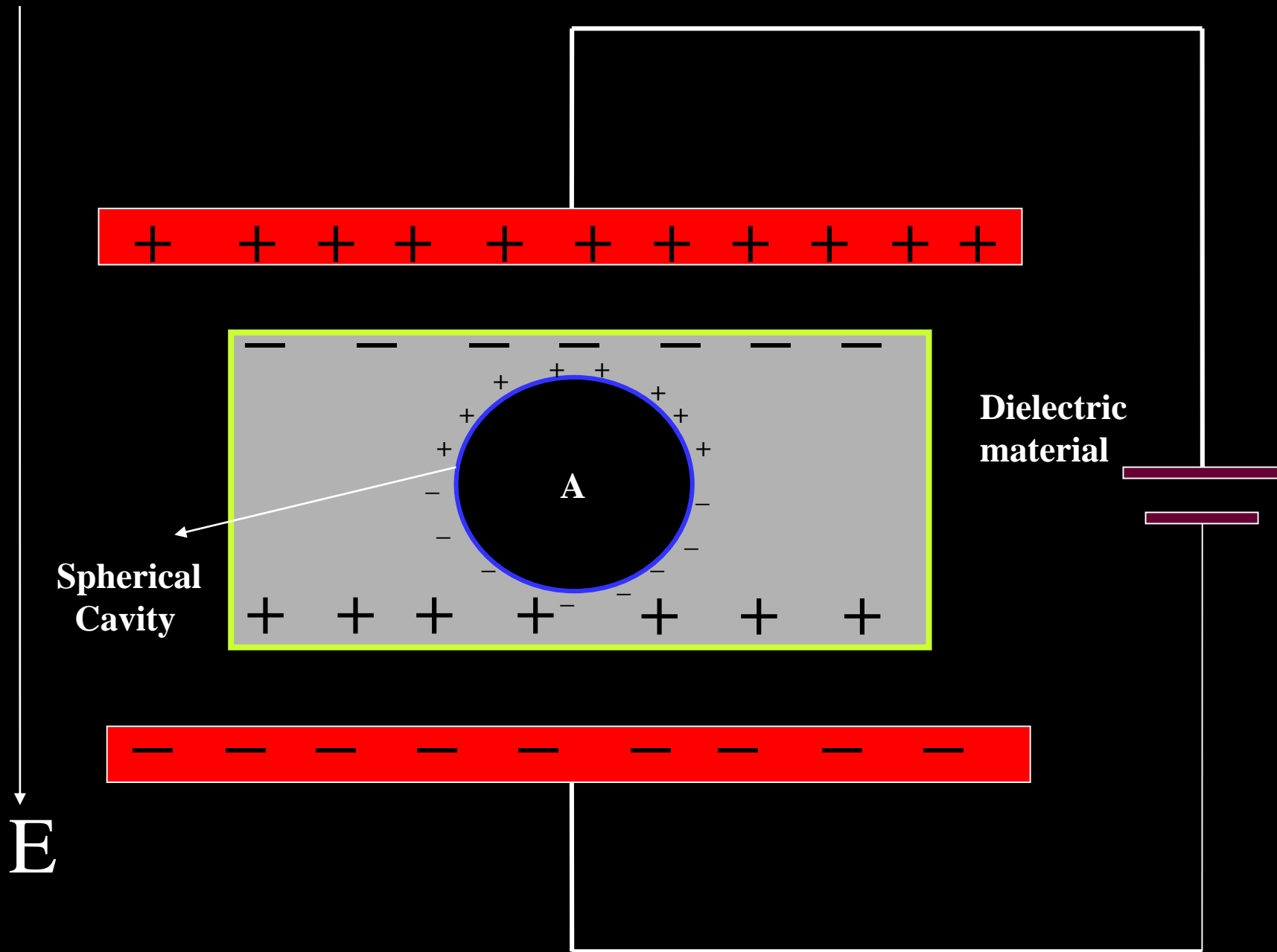
Internal fields or local fields

Local field or internal field in a dielectric is the space and time average of the electric field intensity acting on a particular molecule in the dielectric material.

Evaluation of internal field

Consider a dielectric be placed between the plates of a parallel plate capacitor and let there be an imaginary spherical cavity around the atom A inside the dielectric.

The internal field at the atom site 'A' can be made up of four components E_1 , E_2 , E_3 & E_4 .



Field E_1 :

E_1 is the field intensity at A due to the charge density on the plates

$$E_1 = \frac{D}{\epsilon_0}$$

$$D = \epsilon_0 E + P$$

$$E_1 = \frac{\epsilon_0 E + P}{\epsilon_0}$$

$$E_1 = E + \frac{P}{\epsilon_0} \dots\dots\dots(1)$$

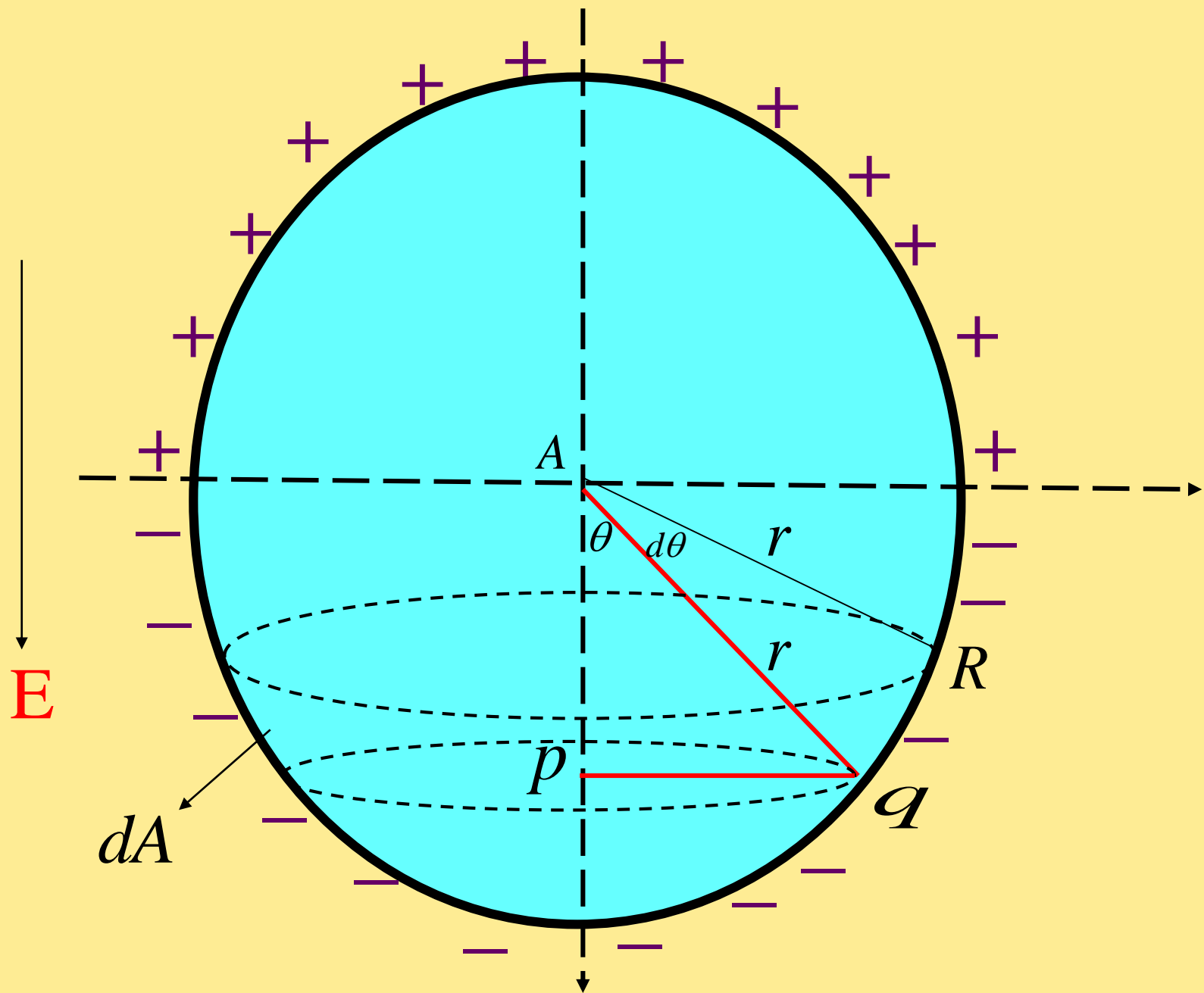
Field E_2 :

E_2 is the field intensity at A due to the charge density induced on the two sides of the dielectric.

$$E_2 = \frac{-P}{\epsilon_0} \dots\dots\dots(2)$$

Field E_3 :

E_3 is the field intensity at A due to the atoms contained in the cavity, we are assuming a cubic structure, so $E_3 = 0$.



Field E_4 :

1. This is due to polarized charges on the surface of the spherical cavity.

$$dA = 2\pi \cdot pq \cdot qR$$

$$dA = 2\pi \cdot r \sin \theta \cdot r d\theta$$

$$dA = 2\pi \cdot r^2 \sin \theta d\theta$$

Where dA is Surface area between θ & $\theta + d\theta$...

2.The total charge present on the surface area dA is...

$dq = (\text{normal component of polarization}) \times (\text{surface area})$

$$dq = p \cos \theta \times dA$$

$$dq = 2\pi r^2 p \cos \theta \cdot \sin \theta \cdot d\theta$$

3. The field due to this charge at A, denoted by dE_4 is given by

$$dE_4 = \frac{1}{4\pi\epsilon_0} \frac{dq}{r^2}$$

The field in $\theta = 0$ direction

$$dE_4 = \frac{1}{4\pi\epsilon_0} \frac{dq \cos \theta}{r^2}$$

$$dE_4 = \frac{1}{4\pi\epsilon_0 r^2} (2\pi r^2 p \cos \theta \cdot \sin \theta \cdot d\theta) \cos \theta$$

$$dE_4 = \frac{P}{2\epsilon_0} \cos^2 \theta \cdot \sin \theta \cdot d\theta$$

4. Thus the total field E_4 due to the charges on the surface of the entire cavity is

$$E_4 = \int_0^\pi dE_4$$

$$= \int_0^\pi \frac{P}{2\varepsilon_0} \cos^2 \theta \cdot \sin \theta \cdot d\theta$$

$$= \frac{P}{2\varepsilon_0} \int_0^\pi \cos^2 \theta \cdot \sin \theta \cdot d\theta$$

$$\text{let } x = \cos \theta \rightarrow dx = -\sin \theta d\theta$$

$$= \frac{P}{2\varepsilon_0} \int_1^{-1} x^2 \cdot dx$$

$$= \frac{-P}{2\varepsilon_0} \left(\frac{x^3}{3} \right)_1^{-1} \Rightarrow \frac{-P}{2\varepsilon_0} \left(\frac{-1-1}{3} \right)$$

$$E_4 = \frac{P}{3\varepsilon_0}$$

The internal field or Lorentz field can be written as

$$E_i = E_1 + E_2 + E_3 + E_4$$

$$E_i = \left(E + \frac{p}{\epsilon_o}\right) - \frac{p}{\epsilon_o} + 0 + \frac{p}{3\epsilon_o}$$

$$E_i = E + \frac{p}{3\epsilon_o}$$

Classius – Mosotti relation:

Consider a dielectric material having cubic structure , and assume ionic Polarizability & Orientational polarizability are zero..

$$\alpha_i = \alpha_0 = 0$$

$$\text{polarization..} P = N\mu$$

$$P = N\alpha_e E_i \dots \text{where.., } \mu = \alpha_e E_i$$

$$\text{where.., } E_i = E + \frac{P}{3\epsilon_0}$$

$$P = N\alpha_e E_i$$

$$P = N\alpha_e \left(E + \frac{P}{3\epsilon_0} \right)$$

$$P = N\alpha_e E + N\alpha_e \frac{P}{3\epsilon_0}$$

$$P - N\alpha_e \frac{P}{3\epsilon_0} = N\alpha_e E$$

$$P \left(1 - \frac{N\alpha_e}{3\epsilon_0} \right) = N\alpha_e E$$

$$P = \frac{N\alpha_e E}{\left(1 - \frac{N\alpha_e}{3\epsilon_0} \right)} \dots\dots\dots(1)$$

We know that the polarization vector

$$P = \epsilon_0 E(\epsilon_r - 1) \dots \dots \dots (2)$$

from eqⁿs (1) & (2)

$$\frac{N\alpha_e E}{(1 - \frac{N\alpha_e}{3\epsilon_0})} = \epsilon_0 E(\epsilon_r - 1)$$

$$1 - \frac{N\alpha_e}{3\epsilon_0} = \frac{N\alpha_e E}{\epsilon_0 E(\epsilon_r - 1)}$$

$$1 = \frac{N\alpha_e}{3\epsilon_0} + \frac{N\alpha_e E}{\epsilon_0 E(\epsilon_r - 1)}$$

$$1 = \frac{N\alpha_e}{3\epsilon_0} + \frac{N\alpha_e}{\epsilon_0(\epsilon_r - 1)}$$

$$1 = \frac{N\alpha_e}{3\epsilon_0} \left(1 + \frac{3}{\epsilon_r - 1}\right)$$

$$\frac{N\alpha_e}{3\epsilon_0} = \frac{1}{\left(1 + \frac{3}{\epsilon_r - 1}\right)}$$

$$\frac{N\alpha_e}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \dots \dots \rightarrow \text{Classius Mosotti relation}$$

Ferro electric materials or Ferro electricity

- Ferro electric crystals exhibit spontaneous polarization I.e. electric polarization with out electric field.
- Ferro electric crystals possess high dielectric constant.
- each unit cell of a Ferro electric crystal carries a reversible electric dipole moment.

Examples: Barium Titanate (BaTiO_3) , Sodium nitrate (NaNO_3) ,Rochelle salt etc..

Piezo- electricity

The process of creating electric polarization by mechanical stress is called as piezo electric effect.

This process is used in conversion of mechanical energy into electrical energy and also electrical energy into mechanical energy.

According to inverse piezo electric effect, when an electric stress is applied, the material becomes strained. This strain is directly proportional to the applied field.

Examples: quartz crystal , Rochelle salt etc.,
Piezo electric materials or peizo electric semiconductors such as Gas, Zno and CdS are finding applications in ultrasonic amplifiers.