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Study of Magneto electric effect in barium ferrite and Barium titanate composite

Basuki Nath Mishra,[1] **and Dr. Shuchitangshu Chatterjee.**[2]

1. Reasearch Scholar of RKDF University, Ranchi, RKDF university , Ranchi, Jharkhand (India)
2. Vice Chancellor, RKDF University, Ranchi, Jharkhand (India)

Abstract

Magnetoelectric composites are important functional materials in recent time. In this composite the mechanical strain mediates magnetoelectric (ME) coupling between the magnetic and the electric subsystems**.** This literature review discusses the progress in research in the field of ME composite. The ME composites shows M E effect which is characterized by Magneto electric voltage coefficient (dE/dH). In the past few decade, a number of research has been processed in the study of magnetoelectric functional materials. The basic electric and magnetic properties like permittivity and permeability as well as elastic properties like modulus of elasticity of magneto electric functional materials are associated with ME voltage coefficient(dE/dH). The Variation of ME coefficient (α =dE/dH) with dc magnetic field was also studied for all composite samples. In this article authors want to formulate Magneto electric voltage coefficient in a BT – BHF bilayer (Barium titanate as FE and Barium hexa ferrite as FM) through mathematical modeling and simulation. Authors verified the derived formula by using well established data for Barium titanate and Barium Hexaferrite and tried to design optimum thickness of the barium titanate and barium hexaferrite for maximum ME coefficient (α =dE/dH)

Keywords : Magnetoelectric, piezoelectric, magnetostrictive , ME Coefficient

1. Introduction: The electric polarisation induced by applied magnetic field or vice versa is termed as magneto electric effect. In the past few decade, comprehensive research has been conducted on ME effect in two phase magnetoelectric composite materials as well as single phase magnetoelectric composite materials. The Permittivity, Permeability and the modulus of elasticity of magnetoelectric composites are influenced by a physical quantity known as magnetoelectric voltage coefficient. The Composite with high permittivity, high permeability and large coefficient of elasticity are essential parameters to acheive high ME coefficient [1]. Barium hexaferrite ($BaFe_{12}O_{19}$) is a permanent magnetic material . It can also be categorize as a ferri-magnetic material. It has a number of properties such as high saturation magnetization(72) , high curie temperature (450^0c), fairly high coercivity(1236 Oe), better magneto crystalline anisotropy(3.3×10^5 J/m^3) better chemical stability, anti-erosion etc. Due to these properties, It has a very wide range of application like in a high-density recording media and

electromagnetic wave absorber [2], [3]. Barium ferrite has hexagonal structure. It can be characterized in magneto-plumbite oxide group , and It can be categorised as hard magnetic materials [4] It is well known fact that the Fe^{3+} ion occupies five different sites on the sub lattice structure of $BaFe_{12}O_{19}$, and each arrangement shows different magnetic properties. Thus the addition of nonmagnetic materials into barium ferrite influences its sub lattice and magnetic properties. [5] . Xue Li and Guo-Long Tan reported the co-existence of enhanced Ferro electricity and excellent magnetic performance in M-type barium hexaferrite($BaFe_{12}O_{19}$) in their research paper [6]. According to them, Barium hexaferrite demonstrates a classic electric polarization (P-E) hysteresis loop with full saturation. Barium hexaferrite ($BaFe_{12}O_{19}$) shows two nonlinear current peaks in the v-I curve for polarization. It indicates abnormal change of dielectric constant near Curie temperatures . . It holds a large remnant polarization of 55.7 $\mu C/cm^2$. Two peaks in the temperature-dependent dielectric spectrum of Barium hexaferrite ($BaFe_{12}O_{19}$) was found, which indicates the phase transition from ferro-to antiferro- and antiferro-to para-electric structures. On the other hand a conventional strong magnetic hysteresis loop was also observed in Barium hexaferrite. The magnetically induced electric polarization on Barium ferrite shows alternating spin current waves. [6] But, doubtful ferroelectricity of $BaFe_{12}O_{19}$ ceramics has been reported by various research groups [7]. The electric hysteresis loops mainly show linear feature without saturation due to big current leakage and appear large difference in shape from typical ferroelectrics [7]. The source of current leakage may arise from the high density of oxygen vacancies and Fe^{3+} ions inside the bulk crystals. Therefore, the ferroelectricity of $BaFe_{12}O_{19}$ compound still remains controversial [7,8] But, Barium ferrite is one of the ferromagnetic oxide that has both dielectric and magnetic properties under high frequency suitable for microwave applications [9]. The Fe^{3+} ions occupy the sub-lattice at different sites which is responsible for different magnetic properties of Barium ferrite. The addition of nonmagnetic materials into barium ferrite ceramic may influence its sub lattice and their magnetic properties[10].

Titanium Alloy Manufacturing Company studied the properties of a number of titania ceramic and noticed anomalous polarization effects in barium titanate [11].After report of titanium Alloy Manufacturing company, The laboratory for Insulation Research again studied the properties of Barium titanate and pointed out the ferroelectric properties of Barium titanate. The origin of ferroelectricity in the perovskite type crystals is the ionic shifts of the body centered ion, Ti- ion. It is also reported that the strong local field upon the Ti ion is essential to realize the Ferro electricity in Barium titanate [12,13]. The dipole interaction between the Ti - ion and the oxygen ion is very strong . Thus, the spontaneous ionic shifts, which causes the spontaneous polarization appears BaTiO3. In this condition, the force which is responsible to displace the ion is too strong to overcome the impacts of repulsive force between the ions[14,15]. The ionic radius of the Ti ion is very small. So, the ionic shifts of the Ti ions in the oxygen octahedra can be seen in BaTiO3 . Barium titanate is an excellent material for induced piezoelectric transducer due to its high polarization (0.26 C/m^2), curie temperature (120-130^{0}c) ,high permittivity (6140) at curie temprature and high induced strain (>0.2% at 60 kV) [15]. Fully dense nanocrystalline barium titanate has 40% higher permittivity than the same material prepared in classic ways[16]

The interaction between piezoelectric and piezomagnetic properties of the composite through elastic deformations is termed as magnetoelectric (ME) effect [17]. when an external magnetic field is applied to the composite, the piezomagnetic component of the composite material is deformed. This deformation is transmitted to the piezoelectric component of that composite material, Due to piezoelectric effect the electric polarisation appears with respect to mechanical stresses . The inverse ME effect is also considerable in magneto electric composite material. In the inverse effect the deformation of the piezoelectric component is developed by an external electric field. This deformation is transmitted to the piezomagnetic component which is magnetized due to the piezomagnetic effect. Thus, multiferroic has an excellent property which is commonly known as the magnetoelectric effect.

The most common composite used in magneto electric nanoparticle is a combination of Barium hexa ferrite (BF) and barium titanate (BTO) due to its good compatibility and high magnetoelectric coupling coefficient even at room temperature [18],

So, we have studied the composite of these two materials (Barium titanate and Barium Hexaferrite)and tried to know about the improvement of the composite system properties compared to the parent materials using simulation.

This paper is a theoretical frame and mathematical analysis for studying and understanding the magneto electric response of the Barium titanate and Barium hexa ferrite bi-layer mode bar structure composite.

2. Theoretical approach for the formulation of magnetoelectric effect :

Since magneto – electric effect is the combination of piezoelectric effect and magnetostriction effect. So we have used piezoelectric constitutive equation, Magnetostrictive constitutive equation and newton's second law of motion simultaneouslyto formulate the magnetoelectric effect in bilayer of a ferroelectric material and a ferromagnetic material.

we have considered a bilayer bar structure of a ferroelectric material of thickness (t_e)and a f erromagnetic material of thickness (t_m). $t = t_e + t_m$. the length and width of bar is l and w respectively.

Figure -1

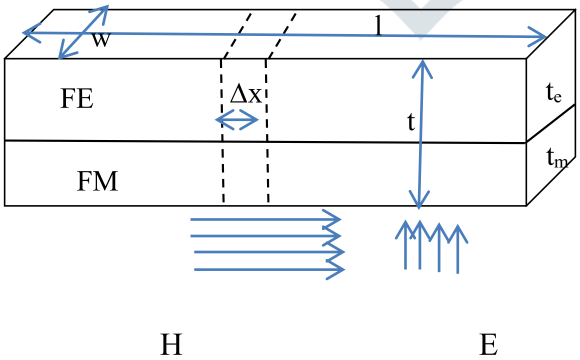

Figure 1 : Multiferroic composites bi-layer of a ferroelectric and a ferromagnetic material

In this model, we have assumed that the external magnetic field is applied along longitudinal direction which induces the mechanical strain in the same direction. According to Hook's law Stress is directly proportional to the strain. Therefore stress (σ) = Elastic compliance (s) x strain (χ). If d^m is the ferromagnetic constant for applied Magnetic field(H), then, we can write the constitutive equation for magnetostriction as

$$\chi_{11} = s^{m}_{11}\sigma^{m}_{1} + d_{11} H_1 \qquad \text{----------------------------[1]}$$

Where superscript “m” refers to ferromagnetic material and the subscript “1” refers to the longitudinal direction.

In piezoelectric effect, the applied electric field (E) induces strain . The mechanical relation between stress (σ) & strain (χ) is derived by using Hook’s Law as stress (σ) = Elastic compliance (s) x strain (χ).If d^e is the ferroelectric constant for applied electric field(E), then, we can write the constitutive equation for piezoelectric effect as

$$\chi_1 = s_{11}^{e}\sigma_1^{e} + d_{31}^{e} E_3 \qquad \text{----------------------------[2]}$$

$$D_3 = d_{31}^{e}\sigma_1^{e} + \varepsilon_{33} E_3 \qquad \text{----------------------------[3]}$$

Where superscript “e” refers to ferroelectric material and the subscript “3” refers to the transversal direction (direction is shown in figure-1) ε is the electric permittivity and D is the electric displacement. In considered variable H,E,D ,χ and σ are dependent variables .these variables are the function of a point along its designated direction.

In this formulation, we have assumed that there is a perfect physical bonding between the ferroelectric and ferromagnetic material in the bilayer. Thus, when the magnetic field ‘H’ is applied to the bilayer in longitudinal direction, it induces mechanical stress in the same direction which results equal elastic displacement (X) in both the layer.

Therefore the mechanical strain (χ_1) = $\frac{dX_1}{dx}$

According to newton’s law of force, Force = mass . acceleration

Therefore $dF = M\,\frac{d^2X_1}{dt^2} = \rho\, dv\, .\, \frac{d^2X_1}{dt^2} = \rho\, dx\, .\, dy.dz\, \frac{d^2X_1}{dt^2}$ -----------[4]

In term of stress (σ),

$$dF = \sigma_1 dA = \sigma_1 dy\, .\, dz \qquad \text{---[5]}$$

From equation [4] and [5] $\sigma_1 dy\, .\, dz = \rho\, dx\, .\, dy.dz\, \frac{d^2X_1}{dt^2}$

$$(\sigma_1/dx)\, dy\, .\, dz = \rho\ \ dy.dz\, \frac{d^2X_1}{dt^2} \text{ --------------[6]}$$

In piezoelectric effect, the stress – strain relation is written as $\chi_1 = s_{11}^{e}\sigma_1^{e}$

$$\text{Therefore ,} \quad \sigma_1^{e} = \frac{\chi_1}{s_{11}^{e}}$$

Thus equation -6 may be written as $\frac{1}{s_{11}^{e}} . \frac{d\chi_1^{e}}{dx} . dy\, .\, dz = \rho_e\ \ dy.dz\, \frac{d^2X_1}{dt^2}$

$$\therefore \frac{1}{s_{11}^{e}} . \frac{d\chi_1^{e}}{dx} . w\, .\, t_e = \rho_e\ \ w\, .\, t_e \frac{d^2X_1}{dt^2} \text{ -----------------(7)}$$

In magnetostriction, the stress – strain relation is written as $\chi_1 = s_{11}^{m}\, \sigma_1^{m}$

$$\text{Therefore ,} \quad \sigma_1^{m} = \frac{\chi_1}{s_{11}^{m}}$$

Thus equation -6 may be written as $\frac{1}{s_{11}^{m}} . \frac{d\chi_1^m}{dx}$. dy . dz = ρ_m dy.dz $\frac{d^2X_1}{dt^2}$

$$\therefore \frac{1}{s_{11}^{m}} . \frac{d\chi_1^m}{dx} . \text{ w . } t_m = \rho_m \text{ w . } t_m \frac{d^2X_1}{dt^2} \text{ ------------------(8)}$$

On adding equation -7 and equation -8 , we get

$$\left(\frac{t_m}{s_{11}^{m}} + \frac{t_e}{s_{11}^{e}} \right) \frac{d\chi_1}{dx} = (\rho_e . t_e + \rho_m . t_m) \frac{d^2X_1}{dt^2} \text{ ---------------(9)}$$

This equation has been modified in term of thickness ratio ($\eta = \frac{t_e}{t}$) ,

$$\frac{(1-\eta).s_{11}^{e} + \eta .s_{11}^{e}}{s_{11}^{m} s_{11}^{e}} . \frac{d^2X_1}{dx^2} = [\eta\rho_e . +(1-\eta)\ \rho_m] \frac{d^2X_1}{dt^2}$$

In term of frequency we can express the second order differential equation as

$$\frac{d^2X_1}{dt^2} = -\ \omega^2 X_1$$

Thus the equation -10 may be expressed in term of angular frequency as

$$\frac{(1-\eta).s_{11}^{e} + \eta .s_{11}^{e}}{s_{11}^{m} s_{11}^{e}} . \frac{d^2X_1}{dx^2} = -\ \omega^2 [\eta\rho_e . +(1-\eta)\ \rho_m] . X_1$$

$$\Rightarrow \frac{d^2X_1}{dx^2} = \frac{-\ \omega^2[\eta\rho_e + (1-\eta)\rho_m]}{(1-\eta)\ s_{11}^{e} + \eta\ s_{11}^{m}}\ s_{11}^{m}.s_{11}^{e} \ . X_1$$

$$\Rightarrow \frac{d^2X_1}{dx^2} = -\ k^2 .X_1 \qquad \text{Where } k^2 = \frac{\omega^2[\eta\rho_e + (1-\eta)\rho_m]}{(1-\eta)\ s_{11}^{e} + \eta\ s_{11}^{m}}\ s_{11}^{m}.s_{11}^{e}$$

The general solution of second degree equation is

X_1 (x) = A Sin (kx) + B Cos (kx): where A & B are arbitrary constant

$$\frac{dX1}{dx} = \text{k \{A cos (kx) – B Sin(kx)\}}$$

$$\chi_1 = \text{k \{A cos (kx) – B Sin(kx)\}}$$

According to constitutive equation :

$$\chi_{11} = s_{11}^{m}.\sigma_1^{m} + d_{11} H_1$$

$$\Rightarrow \quad s_{11}^{m}.\sigma_1^{m} = \chi_{11} - d_{11} H_1$$

$$\Rightarrow \quad \sigma_1^{m} = \frac{1}{s_{11}^{m}} (\chi_{11} - d_{11} H_1)$$

$$\Rightarrow \quad \sigma_1^{m} = \frac{1}{s_{11}^{m}} [\text{k\{A cos (kx) – B Sin(kx)\}} - d_{11}^{m} H_1]$$

Similarly, $\sigma_1^{e} = \frac{1}{s_{11}^{e}} [\text{k\{A cos (kx) – B Sin(kx)\}} - d_{31}^{e} E_3]$

Applying boundary condition, Stress (σ) = 0 ; at X = $\pm \frac{1}{2}$ to determine the value of A & B.After calculation, We found that the value of B is zero and A depends upon various factors.

$$A = \frac{\eta s_{11}^{m} d_{31}^{e} E_3 + (1-\eta) s_{11}^{e} d_{31}^{m} H_1}{k(\eta s_{11}^{m} + (1-\eta) s_{11}^{e})\ Cos\frac{kl}{2}}$$

$$\therefore \quad \sigma_1^{e} = \frac{1}{s_{11}^{e}} [\text{kA cos (kx)} - d_{31}^{e} E_3]$$

While we have stated that $D_3 = d_{31}^{e}\sigma_1^{e} + \varepsilon_{33}E_3$

$$\Rightarrow D_3 = d_{31}^{e} \ \frac{1}{s_{11}^{e}} [\text{kA cos (kx)} - d_{31}^{e} \text{ E3}] + \varepsilon_{33}E_3$$

Since, Electric current is defined as I = $\frac{dQ}{dt}$ and electric displacement D = $\frac{dQ}{dA}$

Therefore dQ = D.dA = D.w.dx [dA = w.dx]

∴ I = w.$\frac{dD}{dt}$ dx.

In this consideration, we have taken an elementary part 'dx'of the specimen. So, the value of current is only the current flowing through the elementary part. The electric current flowing through whole ferroelectric layer is $I_3 = \int_{-l/2}^{l/2} w \frac{dD_3}{dt} dx$

In term of frequency, $I_3 = \int_{-l/2}^{l\backslash 2} i\omega w \, D_3 \, dx = i\omega w \int_{-l/2}^{l\backslash 2} D_3 \, dx$

On solving this integral , we found the current

$$I_3 = i\omega w \left[\frac{\frac{d^e_{31}}{s^e_{11}}[\eta s^m_{11} d^e_{31} E_3 + (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} - \frac{{d^e_{31}}^2}{s^e_{11}} . E_3 + \varepsilon_{33} E_3 \right]$$

In open circuit, Current between the electrode is zero. $I_3 = 0$

$$\therefore I_3 = i\omega w \left[\frac{\frac{d^e_{31}}{s^e_{11}}[\eta s^m_{11} d^e_{31} E_3 + (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} - \frac{{d^e_{31}}^2}{s^e_{11}} . E_3 + \varepsilon_{33} E_3 \right] = 0$$

$$\Rightarrow \frac{\frac{d^e_{31}}{s^e_{11}}[\eta s^m_{11} d^e_{31} E_3 + (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} - \frac{{d^e_{31}}^2}{s^e_{11}} . E_3 + \varepsilon_{33} E_3] = 0$$

$$\Rightarrow \frac{\frac{d^e_{31}}{s^e_{11}}[\eta s^m_{11} d^e_{31} E_3 + (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} = \left[\frac{{d^e_{31}}^2}{s^e_{11}} . - \varepsilon_{33} \right] E_3$$

$$\Rightarrow \frac{\frac{d^e_{31}}{s^e_{11}} \eta s^m_{11} d^e_{31} E_3}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} + \frac{\frac{d^e_{31}}{s^e_{11}} (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} = \left[\frac{{d^e_{31}}^2}{s^e_{11}} . - \varepsilon_{33} \right] E_3$$

$$\Rightarrow \frac{\frac{d^e_{31}}{s^e_{11}} (1-\eta) s^e_{11} d^m_{11} H_1]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} = - \frac{\frac{d^e_{31}}{s^e_{11}} \eta s^m_{11} d^e_{31} E_3}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} + \left[\frac{{d^e_{31}}^2}{s^e_{11}} . - \varepsilon_{33} \right] E_3$$

$$= - \left[\frac{\frac{d^e_{31}}{s^e_{11}} \eta s^m_{11} d^e_{31}}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} - \frac{{d^e_{31}}^2}{s^e_{11}} . + \varepsilon_{33} \right] E_3$$

Now, the coefficient $\alpha_{me} = dE/dH = E_3 / H_1$

$$\alpha_{me} = - \frac{\frac{\frac{d^e_{31}}{s^e_{11}} (1-\eta) s^e_{11} d^m_{11}]}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}}}{\left[\frac{\frac{d^e_{31}}{s^e_{11}} \eta s^m_{11} d^e_{31}}{k[\eta s^m_{11} + (1-\eta) s^e_{11}]} . \frac{\tan(\frac{kl}{2})}{\frac{kl}{2}} - \frac{{d^e_{31}}^2}{s^e_{11}} . + \varepsilon_{33} \right]}$$

3. **Study of magneto-electric effect in a BT – BHF bilayer (Barium titanate as FE and Barium hexa ferrite as FM)** : Authors have verified the above derived expression for a bilayer in which one layer is Barium titanate (BaTiO3) and another layer is barium hexaferrite($BaFe_{12}O_{19}$). they have studied the properties of BT – BTF bilayer for different thickness of Barium ferrite and different frequency of applied vibration . they have taken a term thickness ratio which is the ratio of thickness of FE and total

thickness of bilayer. In order to get excellent result , thickness ratio (η) of values between 0.1 to 0.7 are used in MATLAB program. .

The numerical values of considered variables for Barium titanate & Barium hexa ferrite is applied to the formula to study the behaviour of BT-BF bilayer in different situations. The typical value of elastic compliances s_{ik} are enlisted in Table 1[20]

Table -1

s_{11}^{E} = 8.55 x 10^{-12} m^2/N	s_{11}^{D} = 8.18 x 10^{-12} m^2/N
s_{33}^{E} = 8.93 x 10^{-12} m^2/N	s_{33}^{D}= 6.76 x 10^{-12} m^2/N
s_{12}^{E} = -2.61 x 10^{-12} m^2/N	s_{12}^{D} = -2.98 x 10^{-12} m^2/N
s_{13}^{E} = -2.85 x 10^{-12} m^2/N	s_{13}^{D} = -1.95x 10^{-12} m^2/N
s_{44}^{E} = 23.3 x 10^{-12} m^2/N	s_{44}^{D} = 18.3x 10^{-12} m^2/N
s_{66}^{E} = 22.3 x 10^{-12} m^2/N	s_{66}^{D} = 22.3 x 10^{-12} $m^2/$

Typical values of elastic compliance(in SI unit) of Barium titanate ($BaTiO_3$)

The piezoelectric constants for Barium titanate is d_{15} =2.70 x 10^{-10} C/N, d_{31} = - .79 x 10^{-10} C/N, d_{33} = 1.91 x 10^{-10} C/N and the relative permittivity of Barium titanate is $\in_{11}^{T}$ = 1436 x 10^{-11} F/m , $\in_{33}^{T}$ = 1680 x 10^{-11} F/m , $\in_{11}^{s}$ = 1123 x 10^{-11} F/m , $\in_{33}^{s}$ = 1256 x 10^{-11} F/m [20]. The density of Barium titanate is 6.08 gm/cc. The ferromagnetic constant of Barium ferrite d_{11}^{m} = 3.2 x 10^4 A/m, elastic compliance s_{11}^{m} = 8.97 x 10^{-11} m^2/N and density = 528 g/cc has been considered to study the ME coefficient of the BT – BF bilayer.In this work , Authors have analysed ME coefficient of bilayer in two basic parameters – dimension of the specimen and frequency.

Authors have studied the variation of ME coefficient with respect to different thickness of Barium titanate specimen in term of thickness ratio at constant frequency through the software MATLAB.. The output is shown in table -2. In this table author compiled valu of ME coefficient at different constant frequency. Each row of the table gives variation of ME coefficient with respect to the thickness ratio of the specimen at a particular frequency. Authors have used the frequency from 500Hz to 1300Hz..

Table-2

η ->	0.1	0.17	0.24	0.31	0.38	0.45	0.52	0.59	0.66
f= 500	6539	4789.6	3637.2	2820.8	2212.2	1740.9	1365.3	1058.8	804
f= 700	6596.2	4820.1	3654.8	2831.4	2218.7	1745.0	1367.7	1060.3	804.8
f= 900	66742	4861.6	3678.6	2845.7	2227.5	1750.4	1371.1	1062.3	806
f= 1100	6774.8	4914.6	3708.9	2863.7	2238.5	1757.2	1375.3	1064.8	807.5
f= 1300	6900.2	4980.0	3745.9	2885.8	2252	1765.5	1380.4	1067.9	809.2

Variation of ME coefficient with thickness ratio at constant frequency

This variation of ME coefficient wrt thickness ratio is plotted using MATLAB software. The plot is shown in figure-2

Figure -2

Variation of ME coefficient with respect to frequency at constant thickness ratio

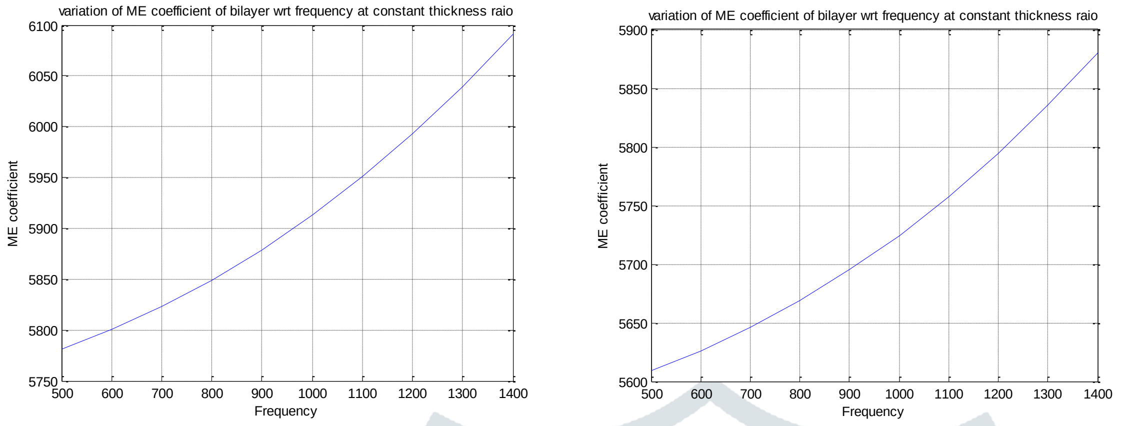

Fig.-2(a) Variation of ME coefficient with respect to frequency at constant η =0.15

Fig.-2(b) Variation of ME coefficient with respect to frequency at constant η = 0.18

The change in ME coefficient with respect to frequency at constant thickness ratio is also studied by authors. The output of the MATLAB program is enlisted in table-3. The variation between ME Coefficient with respect to frequency at different constant thickness ratio is plotted using MATLAB software, the output of the plot is shown in figure-3. From these outputs, It is clear that the value of ME coefficient increases with increase in frequency and decreases with increasing the thickness of the layer of Barium Titanate .

Table-3

F ->	500	600	700	800	900	1000	1200	1300	1400	1500
η =0.12	5953.1	5974.6	6000.4	6030.4	6064.8	6103.8	6147.7	6196.5	6250.6	6310.3
η =0.15	5781.7	5800.5	5822.9	5849	5878.9	5912.8	5950.7	5992.9	6039.5	6090.8
η =0.18	5609.4	5625.9	5645.7	5668.6	5694.8	5724.5	5757.7	5794.6	5835.2	5879.9
η =0.21	5435.8	5450.4	5467.9	5488.2	5511.4	5537.6	5566.9	5599.4	5635.2	5674.4
η =0.24	5260.6	5273.6	5289.2	5307.2	5327.8	5351.1	5377.1	5405.9	5437.6	5472.3
η =0.27	5083.6	5095.3	5109.1	5125.2	5143.6	5164.4	5187.5	5213.2	5241.3	5272.1
η =0.30	4904.7	4915.2	4927.6	4942	4958.4	4977	4997.6	5020.5	5045.6	5073

Variation of ME coefficient with frequency at constant thickness ratio

Since the value of ME coefficient depends upon both factor- frequency & thickness of layers and these factors shows inverse proportionality . so, authors have tried to calculate optimum value of thickness ratio and frequency for which the value of ME coefficient becomes optimum.

Figure -3

Variation of ME coefficient with respect to thickness at constant frequency

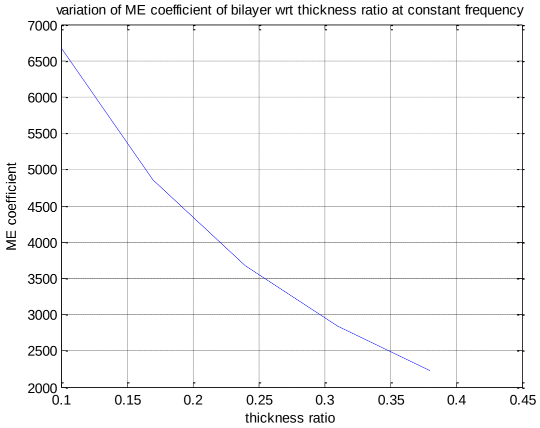

Fig.-3(a) Variation of ME coefficient with respect to frequency at constant η =0.15

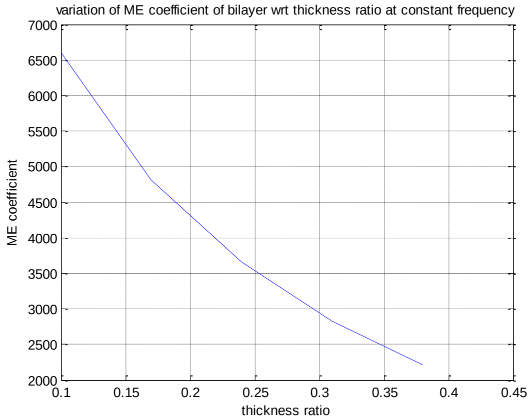

Fig.-3(a) Variation of ME coefficient with respect to frequency at constant η =0.15

4. Conclusion: The behaviour of magneto electric coupling of bilayer bar structure is analysed using the mathematical model based on constitutive equation of piezoelectric effect and magnetostriction in high frequency range. Authors used bilayer of barium titanate ($BaTiO_3$) and Barium hexaferrite(BaFeO) to analyse the developed mathematical model. Authors used frequency range 500Hz -1500 Hz and thickness ratio range 0.1-0.45.

   The graph between ME coefficient (α) and frequency/ thickness ratio shows exponential graph. This output is due to presence of $\frac{tan^{kl}/_{2}}{kl/_{2}}$ in the expression of ME Coefficient in developed mathematical model.

   Graph 2(a) & 2(b) shows that the ME coefficient increses wrt increse in frequency while the graph 2(a) & 2(b) shows that the ME coefficient decreses wrt increse in thickness ratio. The simultaneous study of both the data with the help of MATLAB results the approx. optimum ME coefficient 5935.2 SI unit at frequency 1250 Hz and thickness ratio 0.13.

   These output support and confirm the role and key mechanism of magnetostrictive effect in magneto electric behaviour of the composite . This bilayer may be used to design a transducer .All results suggest that sensing capacity may be improved .

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