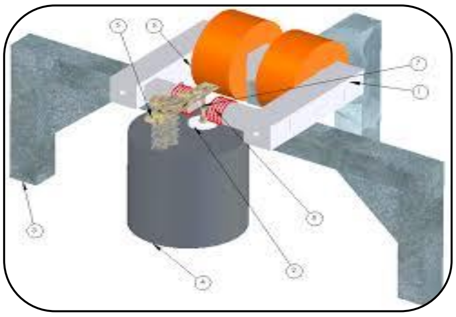
REVIEW OF RESEARCH
ISSN: 2249-894X
IMPACT FACTOR : 5.7631(UIF)
VOLUME - 10 | ISSUE - 12 | SEPTEMBER - 2021

MEASUREMENT OF MAGNETOELECTRIC COEFFICIENTS USING LABORATORY SCALE INSTRUMENTATION SETUP

M. M. Sutar[1] and A. T. Birajdar[2]
[1]Department of Physics, Smt.Meenalben Mehta College, Panchgani, Dist. Satara(MS), India.
[2]Department of Chemistry, Shikshanmaharshi Dr. Bapuji Salunkhe College, Miraj, Dist. Sangli(MS), India.

ABSTRACT

The literature available on Measuring techniques for studying the magnetoelectric (ME) effects are too limited. In this work, I report the setup which is an improved version of the one published in the Journal of Instrumentation society, India for studying the ME effect in ME–composites. The efforts towards design, development, calibration and standardization of the setup are detailed in the paper. To confirm the correctness and accuracy of the setup, measurements of α and β are carried out on substituted $CoFe_2O_4$-$BaTiO_3$ ferrite-ferroelectric composites prepared using similar sintering conditions, where the earlier reports on measurement of α and β are available.



KEYWORDS: *Measuring techniques , calibration and standardization.*

INTRODUCTION

The magnetoelectric (ME) effects are one of the important property that characterize the ferrite-ferroelectric composite materials used as used for Modulation of amplitudes, polarizations and phases of optical waves, ME data storage and switching, Optical diodes, Spin wave generation, Amplification, Frequency conversion devices [1] etc. They are also used in high speed power and signal distribution, tunable filters and electromagnetic / radio interference (EMI/RFI) fillers [2]. In addition to this, industries such as aerospace, electronics and others have continuously provided the impetus pushing the development of such new materials into a wide variety of applications.

Further applications include magnetic film sensors (thus complementing Hall sensors and current measurement probes). Since the magnetic field input is required to have two components, a dc bias and an ac probe, either of the two can be detected by providing the other component. The ME composites can thus be used as a magnetic probe for detecting ac or dc fields. The transduction properties of the ME effect can also be employed in ME recording heads and electromagnetic pick-ups [3] To characterize the material for magnetostriction applications, measurement of linear and quadratic magnetoelectric coefficients α and β is one of the primary requirements. Commercially available systems are very expensive and it is prompted that a suitable laboratory scale setup is required to be designed [4].

At microscopic level, magnetoelectric effect is a result of interaction between ferrite phase(magnetic moments) in a crystal lattice with the ferroelectric phase. Within a single system both the electric as well as magnetic orders are inter coupled through one or other form of exchange mechanism [5-7]. The inter coupled magnetic and electric order may lead to the occurrence of polarization because of application of external magnetic field or occurrence of magnetization because of applied electric field i.e.

$P = \chi^E E + \chi^{EM} H$..................1.1
$M = \chi^M H + \chi^{ME} E$..................1.2

Here P is polarization, E is the applied electric field, H is the applied magnetic field and M is the magnetization. χ^E, χ^M, χ^{EM}, χ^{ME} are corresponding susceptibility tensors. In principle, in addition to the electric and magnetic ordering, an elastic order may also remain inter coupled with both these orders. Taken together the resulting systems are called as multiferroics.

The concept of product property as suggested by Van Suchtelen, a suitable combination of magnetostrictive material and piezoelectric material can give rise to magnetoelectric effect. The composites exhibiting magnetoelectric effect are termed as magneto-electric composites. ME effect in such composites is due to the strain induced in the ferrite phase being mechanically coupled to a stress induced in the ferroelectric phase, coupling results in an electric voltage. In other words ME effect is a product of piezomagnetic effect (magnetic-mechanical effect) in magnetostrictive/ferrite phase and the piezoelectric effect (mechanical-electrical effect) in the ferroelectric phase, namely. The ME effect can be written as

ME Effect = (Electric charge/Mechanical stress)*(Mechanical stress/Magnetostriction)

The ME coefficient $\alpha_{ME} = (1/t)*(dV/dH)$ is the most critical indicator for the ME coupling properties in this kind of material, where V is the induced ME voltage, H is the exciting ac magnetic field and t is the thickness across the sample. Practically, dH is produced by a small ac magnetic field superimposed onto DC bias magnetic fields in the same direction, so dV is also an ac signal. Hence the resulting ME output is found to be strongly depends on the coupling coefficient between magnetostrictive and piezoelectric phase. The coupling coefficient is defined as, $k = \lambda(\partial\lambda/\partial H)$, where λ is the linear magnetostriction. Thus, this effect results from the interaction between different properties of the two phases in the composites. It is important to note that neither the ferrite nor the ferroelectric phase on its own exhibits the ME effect, but composites of these two phases exhibit a remarkable magnetoelectric effect [8- 10].

The earlier reports on magnitude of magnetoelectric coefficient (α) for various particulate composites are summarized in the following paragraph. Each system succeeds with two parentheses. The first parenthesis corresponds to the magnitude of α at room temperature expressed in units of mV/Oe-cm and the second parenthesis provides the corresponding reference to the literature.

1)NFO-PZT (88), NFO-BT (80)Jungho Ryu et al. [11], **2)**NCMFO-BT (80) J. Van den Boomgard et al.[12], **3)**NFO- PZT (80) Junyi Zhai et al. [13], **4)**$CuFeCrO_4$-BPT (0.08) K.K. Patankar et al. [14], **5)**NiCoFeO-BPT (0.194) S.L. Kadam et al.[15], **6)**CFO-SBN (24.8) X. M.Chen et al. [16], **7)** NZFO-SBN (26.6) Y. J. Li et al. [17], **8)** CFO-BT (3.4) Giap V. Duong et al. [18], **9)** NiFeMnO – PZT(88) Rashid Adnan islam [19] **10)** MnZnFe-TbDyFe-PZT (3000) (Shuxiang Dong et al. [20], **11)** NiCoFe-BaPbZrTi (0.536) (B.K. Bammannavar et al. [21], **12)** NFO-PLZT (8.9) Abdul Samee Fawzi et al. [22]

The setup is a basic model, which could be expanded to form a PC based magnetoelectric coefficients measurement unit. The setup is calibrated and standardized. As a part of standardization process, setup is employed for the measurement of α and β on $Co_{0.9}Ni_{0.1}Fe_{1.7}Mn_{0.3}O_4$–$Ba_{0.5}Sr_{0.5}Nb_2O_6$(CNBSN) and $Co_{0.9}Ni_{0.1}Fe_{1.7}Mn_{0.3}O_4$ (CNFMO) and BSTx abbreviated as yCNBSTx, Where x= 0.2, 0.25 and 0.3 for y=0.3 and 0.4.

2. Basic Idea and Principle

The setup is an improved version of the published setup in the Journal of Instrumentation society, India 38(4) [23]. The earlier version includes a Wien bridge oscillator with amplidude controll and variation between 0.2 to 2V. The output of Wien bridge oscillator is coupled to a power amplifier plus V to I current convertor circuit. The present circuit modifies the power amplifier stage that accommodates zero cross over distoration and increase current carrying capacity.

2.1 Experimental

The fundamentals of this method are based on the detection of the conversion of magnetostriction effect into the piezoelectric output voltage. The present circuit adds the buffer amplifier to the earlier version. The present setup ensures almost zero higher harmonics output of the base frequency 850Hz. Sometimes lock in amplifier employed in systems where measurement of vector components of the input signal is of prime importance. The lock in amplifier is tuned to pick up only signals at the vibrating frequency of the magnetic field. This eliminates noise from the environment, such as from the overhead lights or hovering spacecraft nearby. In the present setup the power amplifier stage is developed with without cross over distortion and increased current capacity.

Figure 1 shows the schematic block diagram of the single frequency Magnetoelectric Setup. The main blocks in the setup are Electromagnet MM, Helmholtz coil HH, the Wien bridge sine wave generator, Voltage to Current convertor (Class B push-pull power amplifier stage), instrumentation amplifier, Notch filter, Dual power supply and PC interfaceable digital multimeter.

2.1.1 An Electromagnet

An electromagnet with following specifications is used to produce a DC magnetic field up to 10kOe in the working space of the 1.5cm in the pole pieces of diameter 75mm.

Specifications:

Manufacturer	: Scientific Equipment & Services Roorkee, India.
Model	: emu-75
Maximum DC Current	: 3A.
Maximum Field intensity	: 13kOe.

2.1.2 Helmholtz Coil

The main function of Helmholtz coil HH is to generate the ac magnetic field. HH is the set of two insulated copper wire coils of 200 turns each of 24SWG with ID 75mm, OD 100mm and length 16mm is mounted on the protruded pole pieces of the electromagnet. Use of 24SWG coil allows current up to 600mA in the HH. The field strength h at the center of the HH could be calculated using the following relation.

$$h= \{\mu_0 N I c\, a^2 / (a^2+4D^2)^{3/2}\} * 10^4 \text{.....................................} \quad (2)$$

Where 'Ic' is the current in the HH, 'μ_0' is permeability of free space, 'N' is the number of turns on each coil, 'a' is average radius of the Helmholtz coil and D is the distance between the HH coils set. The Helmholtz coil is excited by a sinusoidal signal of 850Hz which is generated into the Wien bridge oscillator circuit.

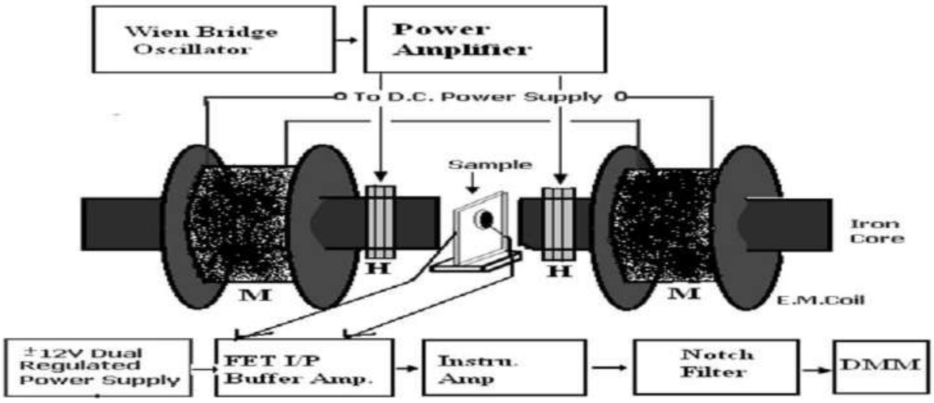


Fig. 1: Block diagram of Instrumentation setup for the ME coefficients.

2.1.3 Wien Bridge Oscillator and Power Amplifier Stage

The Wien bridge oscillator circuit is built using Op-amp ICs741 at 850Hz. The circuit provides good amplitude and frequency stability over the required current range. The power amplifier is combined with a V to I converter with a 10Ω, 10watt resistance. It has been observed that the circuit obeys a linear relation with current Ic.

$$I_c = V_{in} / 10\Omega \qquad (3)$$

For Vin + (Z .Ic) < 10V and Vo > 0.6V

Where, Z = R+jωL. Here R is the resistance and L is the inductance of HH. The amplitude of the oscillator could be varied between 0 to 2V at 850Hz to produce Ic up to 200mA. This feature of improved current capacity is achieved by introducing power transistors in Darlington pairs formed using SL100, SK100 and BD139, BD140 complimentary pairs with IC INA114 in feedback path. Figures 2 and 3 respectively show the Wien Bridge oscillator circuit and modified circuit of Voltage to Current convertor.

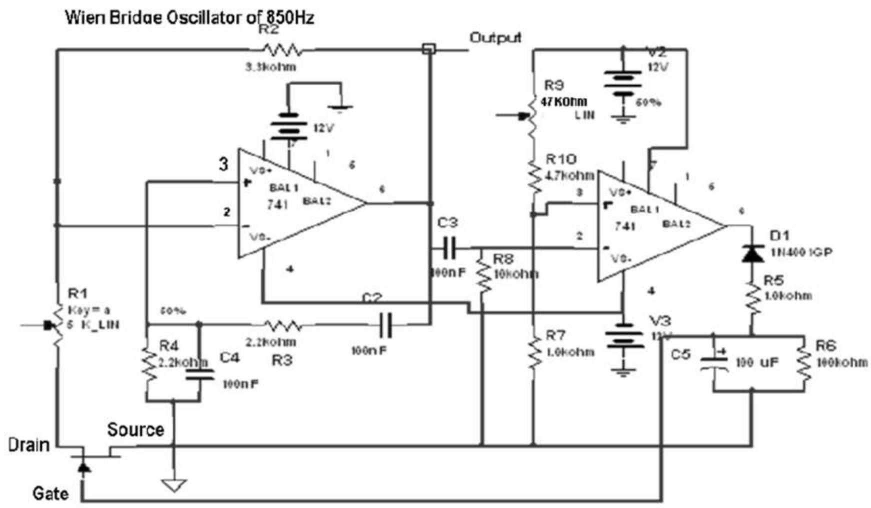


Fig. 2 Circuit diagram of Wien Bridge Oscillator using ICs 741.

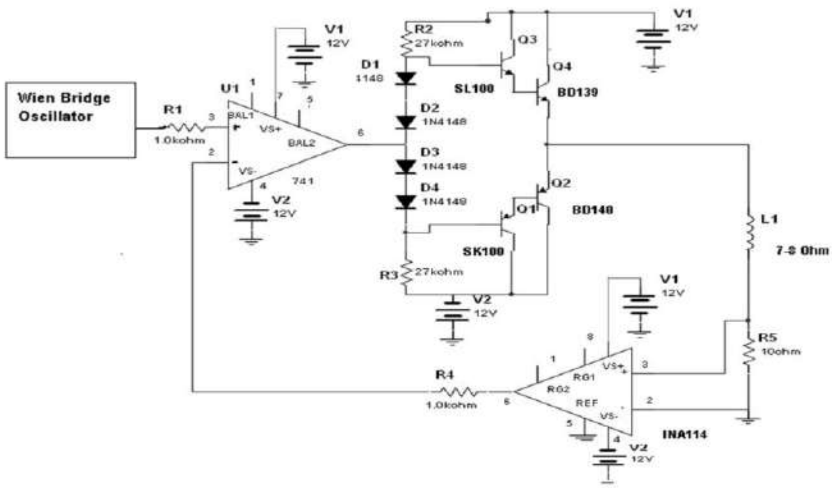


Fig. 3 Modified circuit of Voltage to Current convertor.

2.1.4 High Impedance FET Input Buffer Amplifier Circuit

Figure 4 shows the circuit diagram of FET input buffer amplifier with notch filter. The high impedance FET input buffer amplifier works as a detecting circuit to pick up the ac magnetoelectric voltages. The ME voltage as a single ended output connected through a FET buffer amplifier to an instrumentation amplifier using IC AD620. The buffer stage is a source self-bias amplifier offers very high input impedance of the order of 40MΩ. The output of the instrumentation amplifier is passed through a Notch filter which allows only 850Hz signal, while reject all other side band frequencies. The overall gain is 10 between buffer amplifier and Notch filter output for frequency 850Hz.

2.1.5 An Instrumentation Amplifier

The outputs of the sample are fed to an instrumentation amplifier AD620 with gain adjusted at 10. To receive output only at 850Hz a notch filter has been used with central frequency at 850Hz. The frequency response of an instrumentation amplifier with notch filter is tested and is shown in the figure 5.

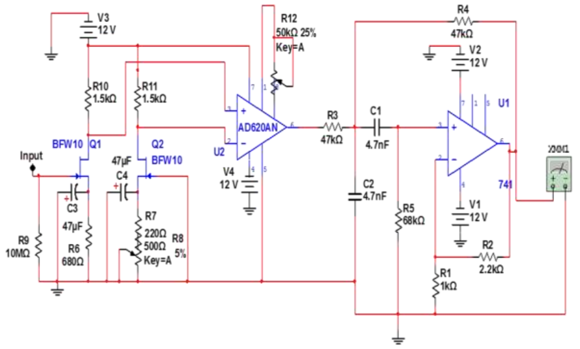
2.1.6 Notch Filter Circuit Design

A notch filter circuit is designed for f_m = 850Hz and Q = 5. The design procedure requires the following equations to be solved to calculate R_1, R_2, R_3, R_4, R_5 and C_1, C_2 etc.

$C_1 = C_2 = C$, $R_5 = 2R_4$.

Mid frequency, $f_m = 1/2\pi RC$ or $R = 1/2\pi f_m C$, $R_3 = R_4$, where f_m is the mid frequency.
Selecting the available values of C (C=4n7F), Inner gain $G = 1+R_2/R_1$

The R_1, R_2, R_3, R_4 and R_5 are calculated and used in the Notch filter (narrow band pass) circuit to have a band pass frequency 850Hz. The dual power supply unit employed for this setup is shown in figure 6.



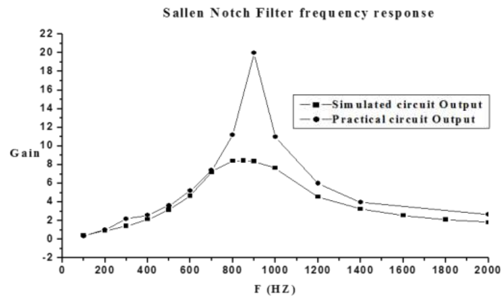


Fig. 4 Circuit diagram of FET input buffer amplifier with notch filter.
Fig.5 Frequency response curve for notch filter circuit

2.2 Measurement Procedure

In a setup the sample whose ME voltage is to be determine is put using a perplex sample holder into a Helmholtz coil, in the middle of two pole pieces of the electromagnet (MM). The signal produced by the sample acts as an input to the FET amplifier by a special sleeve wire. Then the magnetoelectric signal is sampled by the PC interfaceble digital multimeter. Figure 7 shows the Photograph of Single frequency Magnetoelectric (ME) setup, while figure 8 shows the PCB layout.

Determination of α

- Use polled ME sample.
- Set gain of instrumentation Amplifier at 850Hz to 10.
- Measure voltage across 10Ω series resistance to the Helmholtz Coil (HH), and therefore measure equivalent current in HH coil.
- Set current in HH between 20mA to 100mA rms and measure output of instrumentation amplifier V_0 rms.
- Determine slope of V_0 verses I i.e. $\Delta V_0/I$.
- Determine $\Delta V_0/\Delta I$.
- Determine sample thickness (t).
- Determine α = slope/10 * t.

Determination of β

The DC magnetic field is produced by the electromagnet (MM) which is excited by external 5A DC power supply. For measurement of β an AC field with single frequency of 850Hz and amplitude of the order of 50 Oe superimposed onto a DC bias field up to 10kOe.

- Set I in Helmholtz Coil =50mA.
- Vary I_{dc} therefore H_{dc} and measure V_0 rms of I_{dc} A.

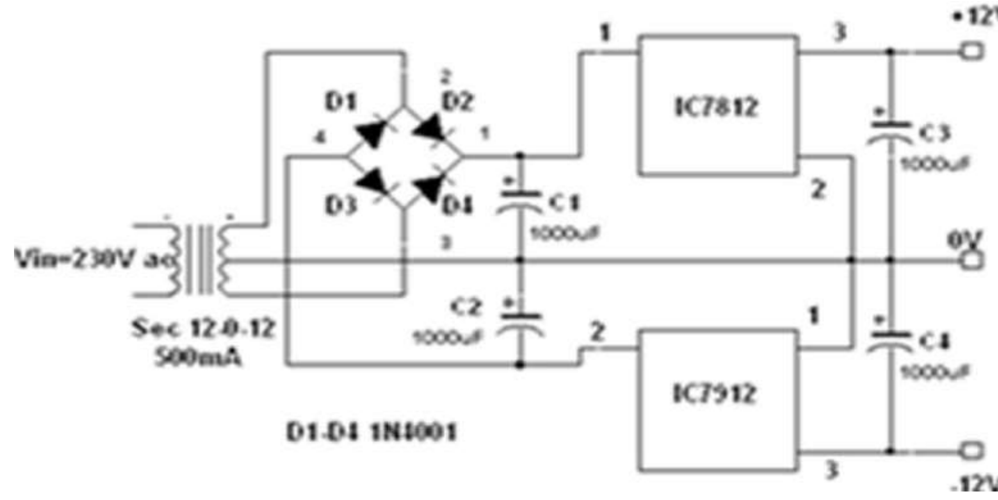


Fig. 6 Dual Power Supply Circuit Using Ic Regulators 7812 And 7912.

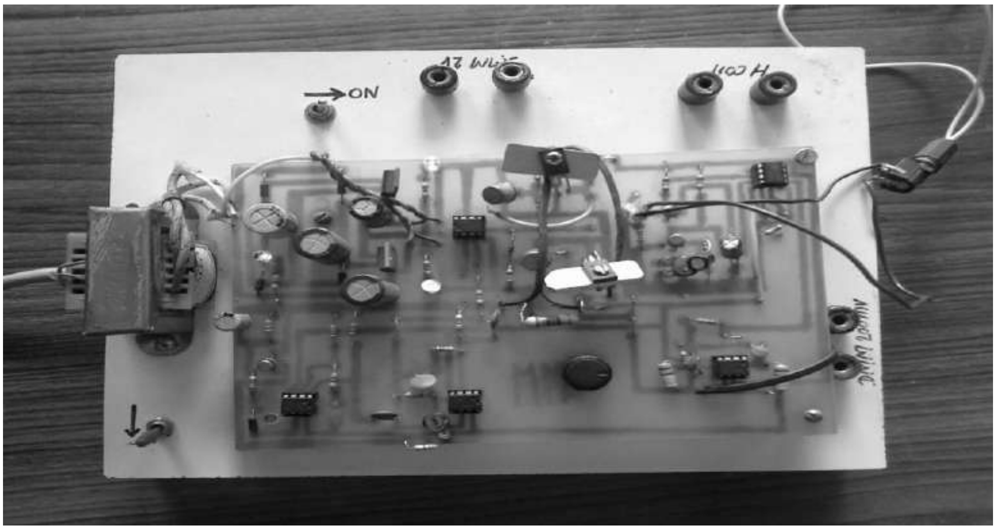


Fig.7 Photograph of Single Frequency Magnetoelectric (ME) setup.

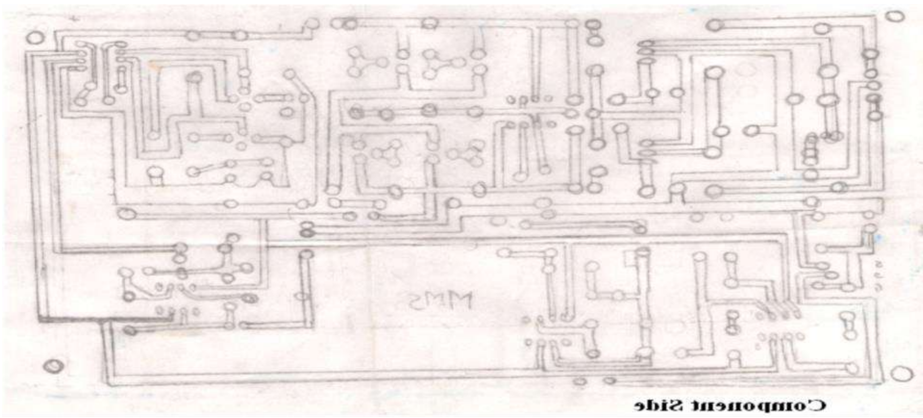


Fig. 8 Actual PCB layout for ME setup.

3 Measurement of Magnetoelectric Coefficients on CNBSN and CNBST composites

The table 1(a) and (b) shows the variation of dynamic ME coefficients α and β respectively for CNBSN and CNBST composites. Here α represents linear, while β represents quadratic ME coefficient defined by the relations as below.

$\alpha = dE/dH = (\Delta V_0)/G*t*(\Delta h)$ and
$\beta = (\Delta V_0)/2*d*h*(\Delta H)$

Where ΔV_0 is the r.m.s output voltage developed across the sample in mV, G is the gain of the amplifier, t is the effective thickness of the sample, h is the r.m.s. value of the AC field at frequency 850Hz and H is the imposed DC magnetic field. Fig. 9(a) and (b) shows the variation of α with y for the CNBSN and yCNBSTx composites sintered at Ts= 1200ºC. From fig. 9(a) and fig. (10) it could be seen that α passes through a maximum in the vicinity of y=0.4. Further from Table 1(b), it is observed that α is maximum for CNBST0.25 and y=0.4. Here the change in β is insignificant for x=0.25 and x=0.3 and y=0.3 and 0.4.

From the basic theory of ME effect in composites α and β are proportional to y(1-y)/ ε, where y is the percentage of the magnetic phase in the composites. Further the α is proportional to piezoelectric coefficient d, magnetostriction coefficient λ, magneto-mechanical coupling coefficient k_m and inversely proportional to ε. And thus the observations in fig.(9) and (10) are in confirmation with the basic theory of magnetoelectric effect. The magnitudes of β are also shown in table-1. It is observed that this contribution is substantially low. The magnitude of β is linearly proportional to the variation of λ with H and inversely to the variation of ε with H.

TABLE 1

y	α (mV/cm-Oe)	β (10^{-3}mV/cm-Oe^2)
0.3	1.4024	$1.55*10^{-4}$
0.4	3.7867	$2.23*10^{-4}$
0.5	3.3931	$1.57*10^{-4}$
0.6	1.8629	$1.14*10^{-4}$

(A)

Composite	α (mV/cm-Oe)		β (10^{-3}mV/cm-Oe^2)	
	y=0.3	y=0.4	y=0.3	y=0.4
CNBST0.2	4.99	5.04	0.44	0.45
CNBST0.25	5.57	5.80	0.43	0.43
CNBST0.3	2.74	3.46	0.12	0.20

(B)

(A) VALUES OF A AND B FOR CNBSN COMPOSITES WITH VARYING Y.

(b) Values of α and β for CNBST composites with varying y.

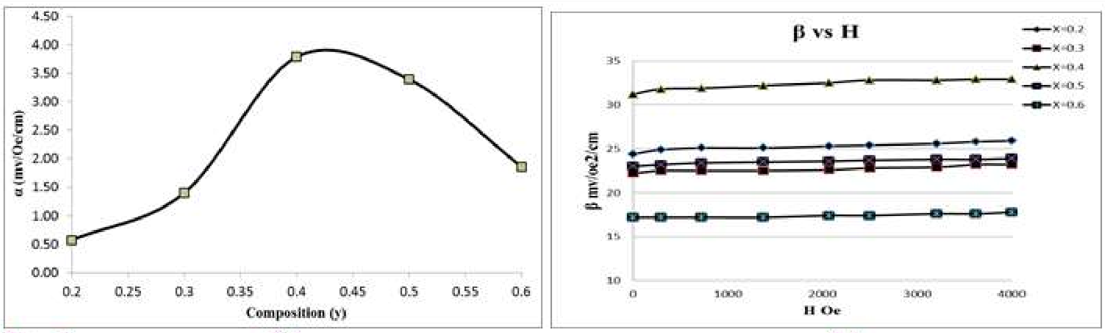


Fig. 9 (a) (b)
(a) Variation of α with y for the CNBSN composites.
(b) Variation of β with H for the CNBSN composites.

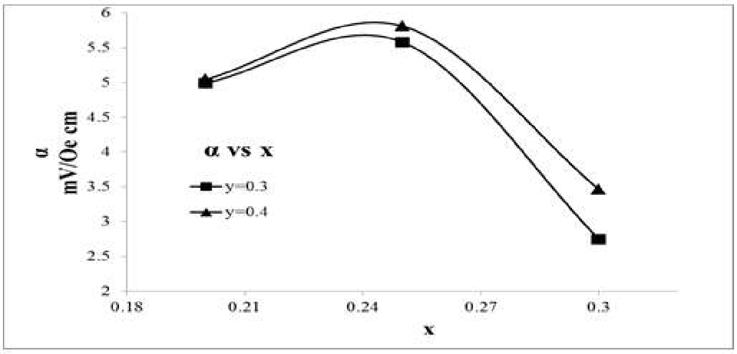


Fig. 10 Variation of α with x for the CNBST composites.

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