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To study of Giant Magneto impedance of some iron rich soft ferromagnetic materials

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Abstract

To study of Giant Magneto impedance of some iron rich soft ferromagnetic materials of $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ (sample-1), $Fe_{81}B_{12}Mo_7$ (sample-2), $Fe_{80}B_{12}Mo_7Cu_1$ (sample-3) & $Fe_{82}B_{12}Mo_7Cu_1$ (sample-4). These samples are magnetically soft materials.

1. Introduction

Magnetoimpedance (MI) consists of a change of total impedance of a magnetic conductor (usually ferromagnetic) under application of a static magnetic field H_{dc}. When an ac current, $I = I_0e^{i\omega t}$ of magnitude I_0 and angular frequency ω (= 2πf, with f the ordinary frequency) flows through the material, it generates, by Ampere's Law, a transverse magnetic field inducing some magnetization. At low frequency, the change in the transverse magnetization generates an additional inductive voltage V_L across the conductor: $V = RI + V_L$ where R is the resistance. Hence MI can be written as $Z = R + j\omega\Phi/I$, where the imaginary part is given by the ratio of magnetic flux to ac current and MI field dependence is related to the transverse permeability. When frequency increases the current gets distributed near the surface of the conductor, changing both resistive and inductive components of the total voltage V . The field dependence of MI is dictated by skin depth

$$\delta_s = \frac{c}{\sqrt{2\pi\omega\mu\sigma}}$$

where σ is the conductivity and μ is the permeability. Not only the shape of the conductor and frequency but also transverse magnetization depending on H_{dc} governs the current distribution.

Typically MI increases with frequency, attains a maximum of frequencies for which the skin effect is strong ($\delta_s << a$), a is the characteristic length scale such as wire radius or ribbon thickness and then decreases since permeability becomes insensitive to the field at high enough frequency.

MI effect is ordinarily weak and did not attract much attention in past. Interest in MI was triggered in early 90's when *Panina et al* [1] and Beach *et al* [2] reported very large (Giant) MI effect amorphous ferromagnetic $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ wires with small magnetic field and at relatively low frequencies.

GMI materials share the property of being magnetically soft (easy to magnetize) and are now available as wires (typical diameter of the order of a mm), microwares (typical diameter of the order of a micron), ribbons, magnetically coated metallic wires, thin films and multilayers, albeit, the effect occurs with widely differing magnitude depending on the geometry and the constituent materials.

In order to clearly identify GMI, several observations should be made:

1.1 A very large change (of the order of at least 100% variation) of impedance should occur with external dc magnetic field H_{dc}

The change expressed in % is defined by the largest value of the ratio

$$\%\frac{\Delta Z}{Z} = \frac{Z(H_{dc}) - Z(H_{sat})}{Z(H_{sat})} * 100$$, where $Z(H_{dc})$ is the impedance measured

In the presence of magnetic field H_{dc} and $Z(H_{sat})$ is the impedance measured at the saturation limit when magnetization does not change any longer with the applied field.

1.2 The external dc magnetic field H_{dc} should be of a few Oersteds only.

1.3 The frequency range is on the order of MHz or tens of MHz (excluding any effect based on Ferromagnetic Resonance (FMR) where the frequencies are typically in the GHz range). In many materials this means that the skin depth δ_s (typically microns at these frequencies) is larger than the thickness of the materials (typically a fraction of a micron). When the frequency is in the GHz, δ_s is generally very small with respect to the thickness. It should be stressed that in ordinary metals, the skin depth does not depend on permeability, whereas in

magnetic materials, the behavior of permeability on geometry, temperature, stress, composition and so on, is reflected in the skin depth. In addition, permeability might be changed by post-processing the material after growth with annealing under presence or absence of magnetic field or mechanical stress.

GMI is a *classical phenomenon* that can explained thoroughly on the basis of usual electromagnetic concepts in sharp contrast with GMR effect where resistance is changed by magnetic field. GMR requires Quantum Mechanical concepts based on spin of the carriers and their interactions with the magnetizations of the magnetic material.

Several general conditions must be satisfied by any material in order to show GMI:

1. The material should be magnetically soft. That is, it should be easily magnetized or in other words must have a relatively narrow hysteresis curve implying, in general, small losses in the course of magnetization cycle.

2. The material should have a well defined anisotropy axis. That means there must be direction along which the magnetization of a material lies on the average (easy axis). However the value of anisotropy field should be relatively small (on the order of a few Oersteds). The typical ratio H_k to H_c must be about 20. That insures observation of large magnetoimpedance effects, typically.

3. The coercive field H_c must be small (fraction of an Oersted) and the hysteresis loop thin and narrow. Since H_c and shape of the hysteresis loop change with the angle the magnetic field makes with the easy axis (or Anisotropy axis) of the material, these are taken at the reference point when the field is along easy axis.

4. The ac current $I = I_0 \exp(j\omega t)$, injected in the material, should be perpendicular to the easy axis and the magnetic field it creates H_{ac} should be small with respect to H_k.

5. The material must have small resistivity $(\leq 100 \mu\Omega.cm)$ since it carries the ac current. This is important, since many magnetic materials have large resistivities. Amorphous metals are interesting in that respect since, typically, their resistivities at room temperature are in the $(\leq 100 \mu\Omega.cm)$ range.

6. The material should have a large saturation magnetization M_s in order to boost the interaction with the external magnetic field.

7. The material should have a very small magnetostriction (*MS*). This means, mechanical effects caused by application of magnetic field should be small. Mechanical stress due to *MS* alters the soft properties of the material by acting as an effective anisotropy. This alters the direction of the anisotropy, displacing it from the transverse case and thereby reducing the value of MI. Typical case materials are displayed along with their *MS* coefficient in Table I.

The general theory of the MI effect is widely available in classic textbooks [9] (for a long cylinder) and it has been shown experimentally that a large MI often occurs at frequencies of a few MHz. Changing the dc biasing field Hdc, the maximum |Z| can be as large as a few times the value of Rdc the dc resistance. At low frequency |Z| has a peak around Hdc = 0 and as the frequency increases, the peak moves toward Hdc = ±Hk where Hk is the anisotropy field. Therefore, |Z| as a function of Hdc possesses a single or a double peak as the frequency increases. When the direction of the anisotropy field is well defined the peaks are sharp.

The behavior of |Z| versus Hdc follows very closely the behavior of the real part of the transverse permeability versus Hdc as we will show in later sections on wires and ribbons. Therefore it is very important to develop an understanding for the processes controlling the permeability. Material permeability depends on sample geometry, nature of exciting field, temperature, frequency, stress distribution in the material as well as internal configuration of the magnetization that might be altered by processing or frequency. For instance, some materials should be annealed under the presence of a magnetic field or a mechanical stress in order to favor some direction for the magnetization or to release the stress contained in them. Regarding frequency, when it is large enough (> 1MHz is sufficient in many materials) Domain Wall Displacements (DWD) are considerably reduced by eddy-currents and therefore magnetization varies by rotation or switching as if in a single domain . As a consequence, the rotational motion of the magnetization controls the behaviour of the permeability, through the skin depth.

Considering a as a typical thickness (in the case of films/ribbons) or radius (in the case of wires or microwires), frequencies in the tens of MHz, lead to δs > a for the observation of GMI. This condition depends strongly on geometry. For instance, δs > a in 2D structures like films is satisfied at much higher frequencies (GHz) than in 1D structures like wires. This is simply due to the optimal circular shape of wires that contains in an optimal fashion the flux while, simultaneously, carrying the ac current.

In terms of GMI performance, multilayered films (such as F/M/F where F is a ferromagnet and M is metallic non magnetic material) are preferred with respect to single layered films since they allow to inject the ac electric current in the metallic layer and sense the magnetic flux in neighbouring or sandwiching magnetic layers. These can be in direct contact with the metallic layer or separated from it by an insulator or a semiconductor. Flux closure, that increases GMI, occurs when the width of the film (transverse with respect to the ac current) is large or that the metallic layer is entirely buried in the magnetic structure to trap the flux.

The progress of GMI is driven towards the increase of the largest value of the ratio r(Hdc) and the sensitivity given by the derivative of the ratio with respect to the field . This sensitivity is simply estimated by looking at the behavior of the permeability μ_t versus H_{dc} as the frequency is changed. We ought to have a large variation of μ_t about Hdc = 0. This happens, in general, at low frequencies that is when δs > a. Applications of GMI range from tiny magnetic field detection and sensing (such as magnetic recording heads) to magnetic field shielding (to degauss Cathode Ray Tubes (CRT) monitors). The reason is that GMI materials, being soft, possess large permeabilities that are required in magnetic shielding.

2. Theory

The coil and sample arrangement is shown in Figure 1.

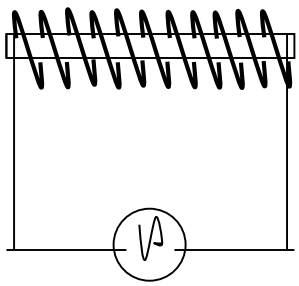


Figure 1

Since the ac current is flowing through the coil, the magnetic field will also be time varying, consequently the susceptibility is a complex number. The inductance of the coil in presence of sample L' is given by

$$L'i = \int B.dS = \mu_0 \int (H + fM)dS$$

Now $$M = \chi H = (\chi' + i\chi'')H$$

By substitution of M in equation (1) and confronting the relation H.dS = L_0i,

$$L' = L_0(1+\chi)$$

Complex Impedance is given by Z = V/I

Z = total impedance of the sample and the coil,

$$Z = R + j\omega L$$

In presence of sample,

$R = R_{sample} + R_{coil}$

$$L = L_0(1+\chi f)$$ L_0 = inductance of coil only.

χ = complex susceptibility, $\chi = \chi' - j\chi''$

χ' = in-phase component.

χ'' = out of phase component.

f = fraction of volume of sample occupied inside the coil.

Hence, we can write

Reactance, $$X = j\omega L = j\omega L_0[1+(\chi' - j\chi'')f]$$

Total Impedance,

$Z = R + j\omega L_0(1+\chi' f) + \omega L_0 \chi'' f$

Thus, $R_{sample} = \omega L_0 \chi'' f$ and $L_{sample} = L_0(1+\chi' f)$

We are interested in estimating the percentage change in **real part** of impedance R_{sample} and **imaginary part** of impedance L_{sample} upon application of dc magnetic field.

From calculations,

$$\frac{L(H)-L(H_{sat})}{L\left(H\rightarrow H_{sat}\right)}=f\frac{\left[\chi'(H)-\chi'(H_{sat})\right]}{\left[1+f\chi'(H\rightarrow H_{sat})\right]}$$

$$\left(\frac{\Delta L}{L}\right)\%=f\chi'(H)$$

since at large fields $\chi'(H\rightarrow H_{sat})$ is small

Similarly, we can write

$$\left(\frac{\Delta R}{R}\right)\%=f\chi''(H)$$

From the above equations it can be seen that inductance changes as a result of change in real component of the complex susceptibility χ' and resistance changes due to imaginary component of complex susceptibility χ''.

3. Phenomenological Models of GMI effect

The research on GMI phenomenological model started in order to understand the experimental data found in metallic glasses. Santos et. Al.[5] has proposed a model of the domain structure and assumed that the metallic glass ribbon has transverse domain structure When an ac current flows through the ribbon, a transverse magnetic field is induced around it. MI effect is observed when an axial dc field comparable to the magnitude of saturation field H_s is applied parallel or perpendicular to the sample. The motion of the magnetic domain walls, which results from combined effect of the external axial field, H_{dc} and transverse ac field H_{ac} created by the ac current, I_{ac}. The increase in the axial field decreases the angle of distribution of the net field.

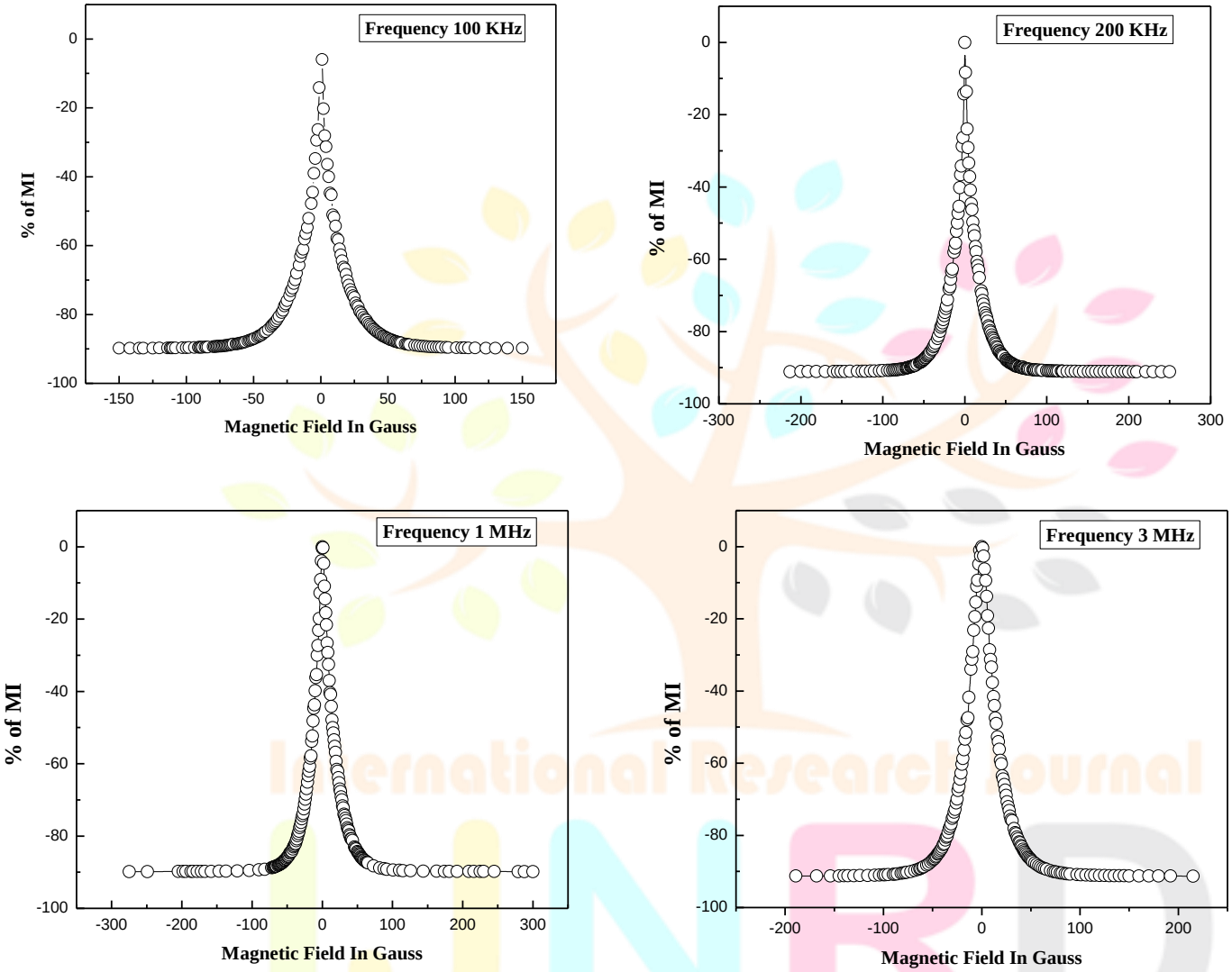
Using the same concept Machado et. al. [1,2] presented a semi-empirical model of Co-rich metallic glass ribbons based on electromagnetic skin depth effect and on the domain wall motion due to magnetic field and ac current, which explained the MI spectra and its frequency and field dependence.

4.1 Results and Discussion

We have discussed the experimental result for sample S0, S1, S2, and metallic sample separately.

MI%,variation with applied D.C. Field

(1) Sample-1 ($Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$)



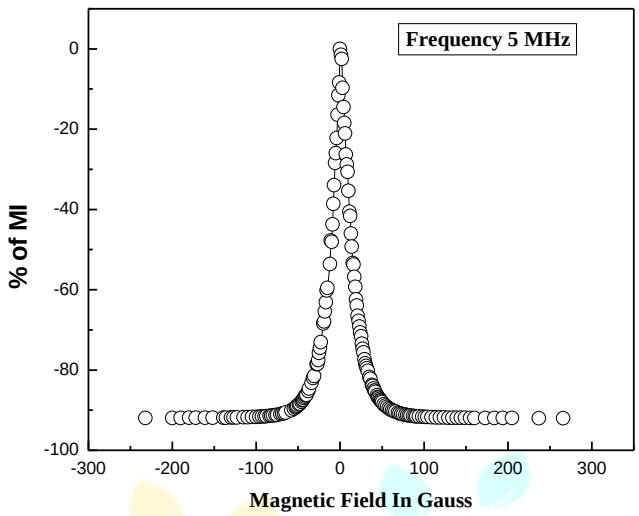
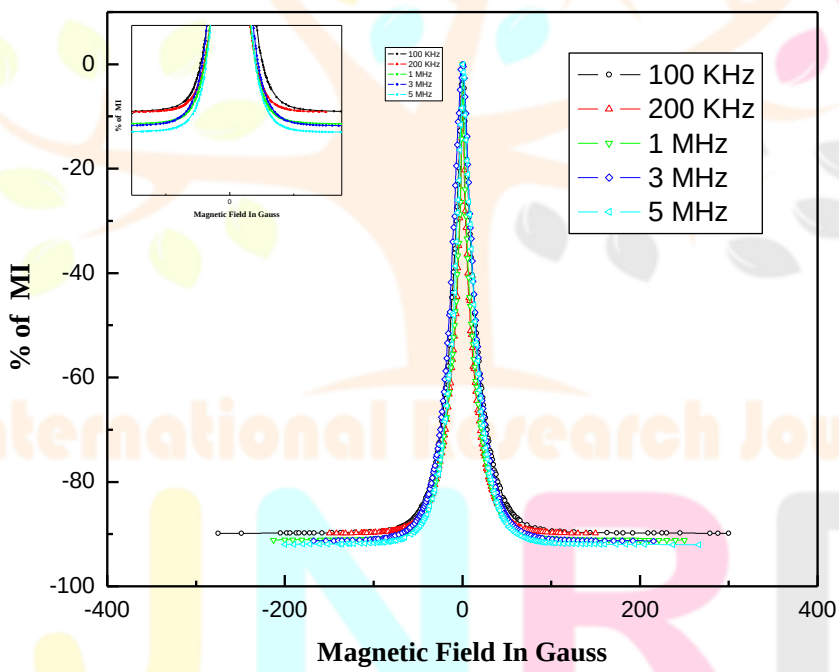


Figure (a). Change of MI% with Parallel Magnetic field for $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ (sample-1)



Figure(b). Change of MI with parallel magnetic field for $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ (sample-1) **at different Frequency**

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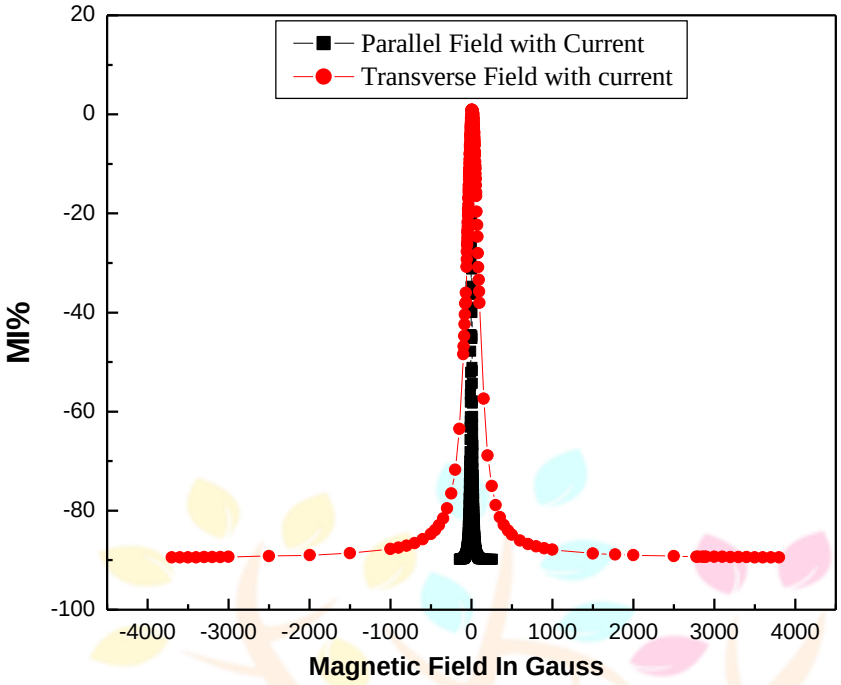
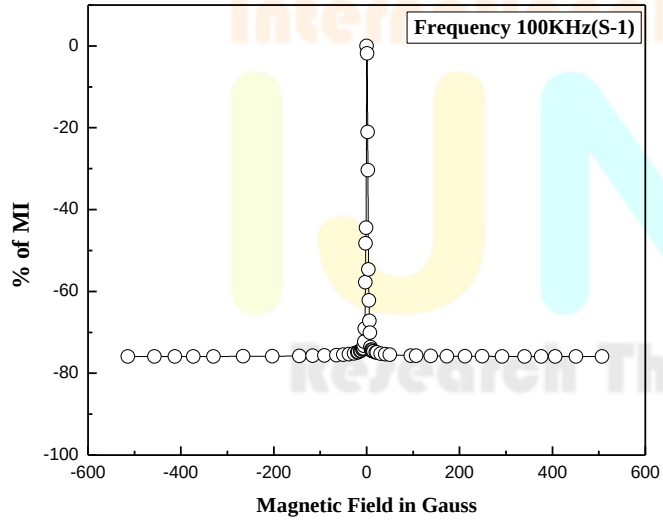
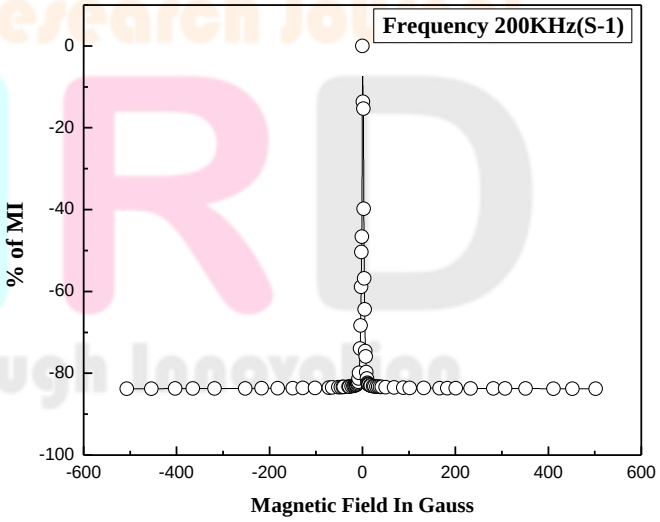
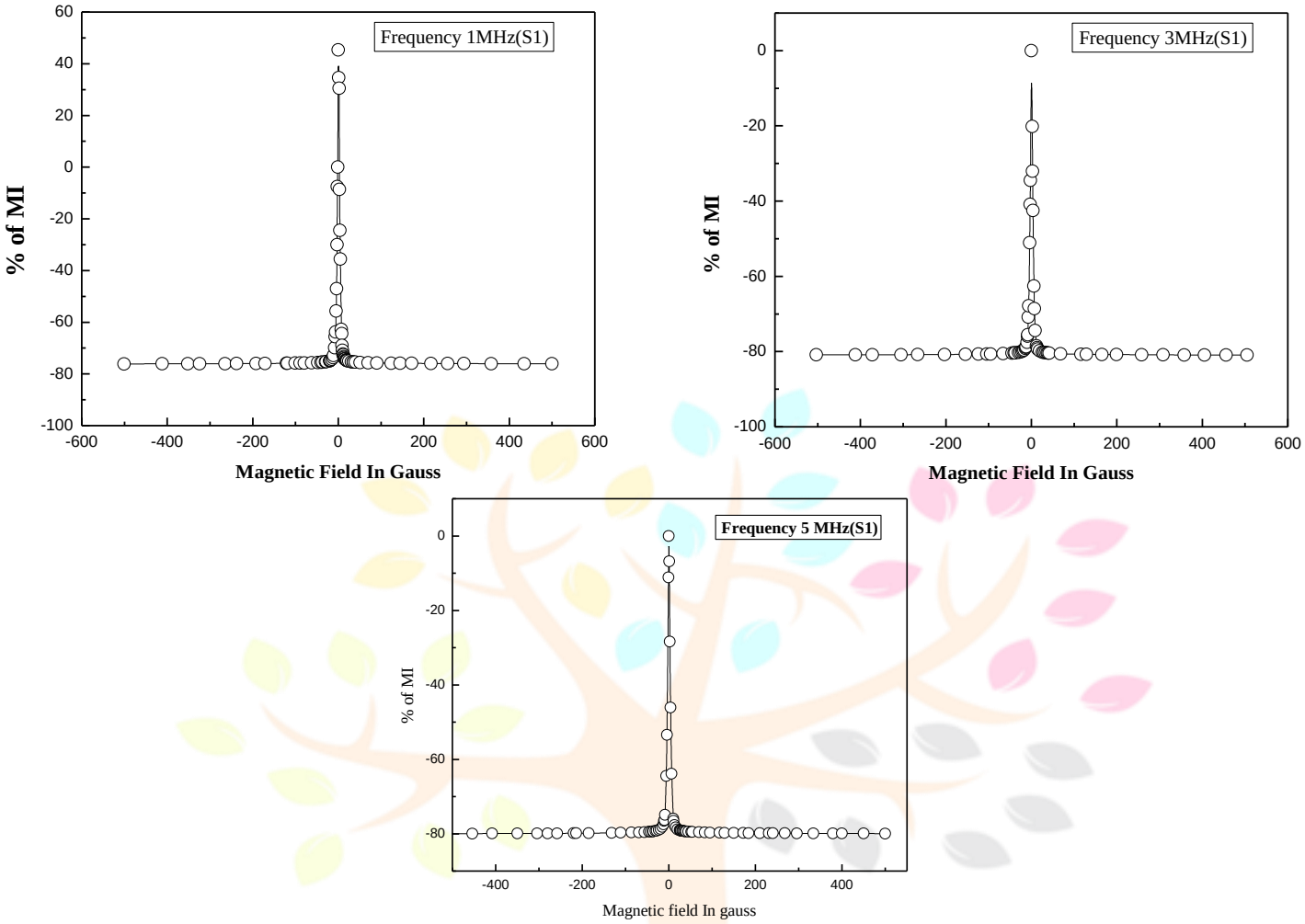


Figure(c). Change of MI at 5MHz with parallel and perpendicular magnetic field for $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ (sample-1)

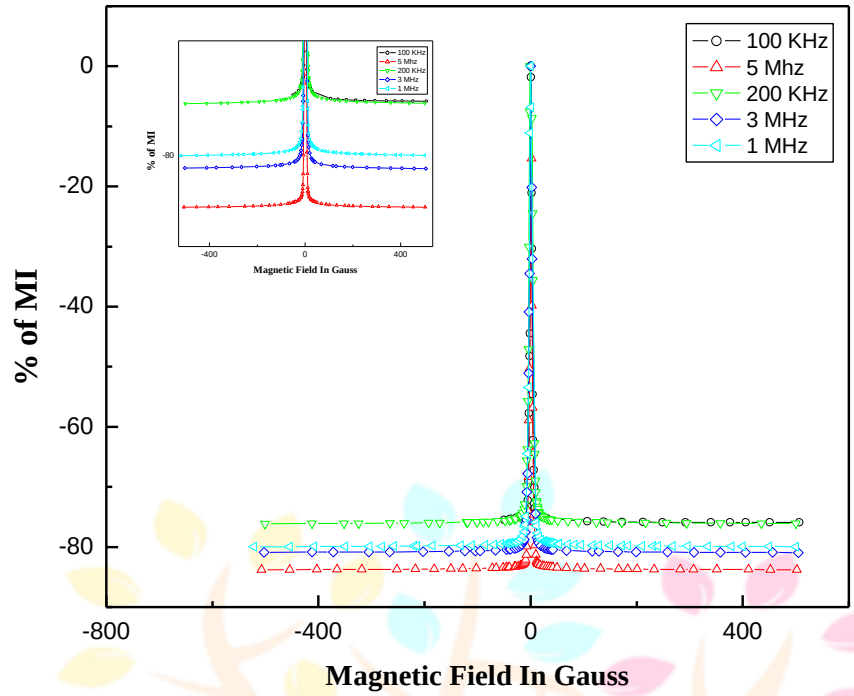
(2).sample-2($Fe_{81}B_{12}Mo_7$)



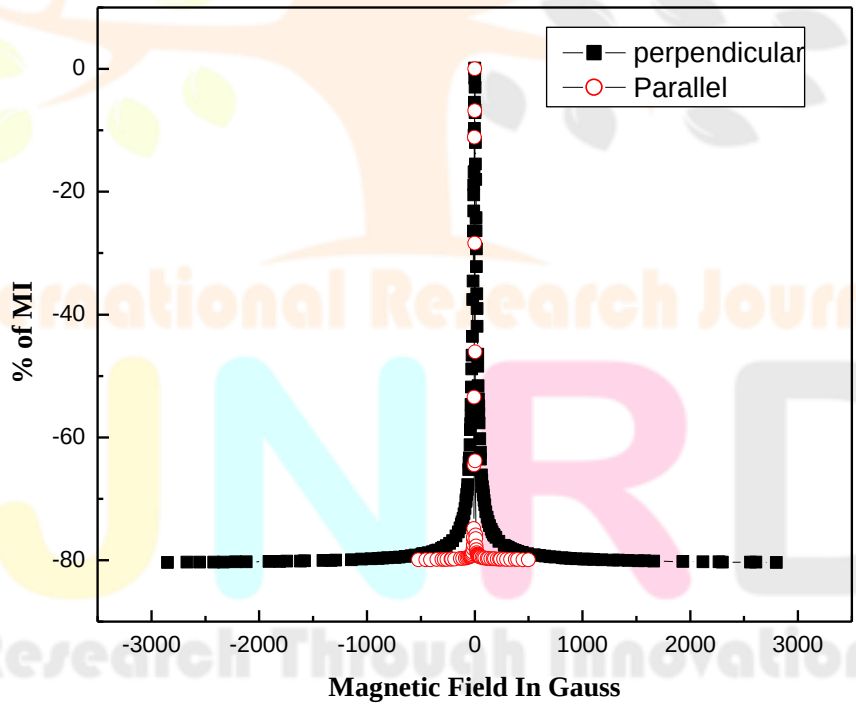




Figure(a). Change of MI with parallel magnetic field for $Fe_{81}B_{12}Mo_7$ (Sample-2)

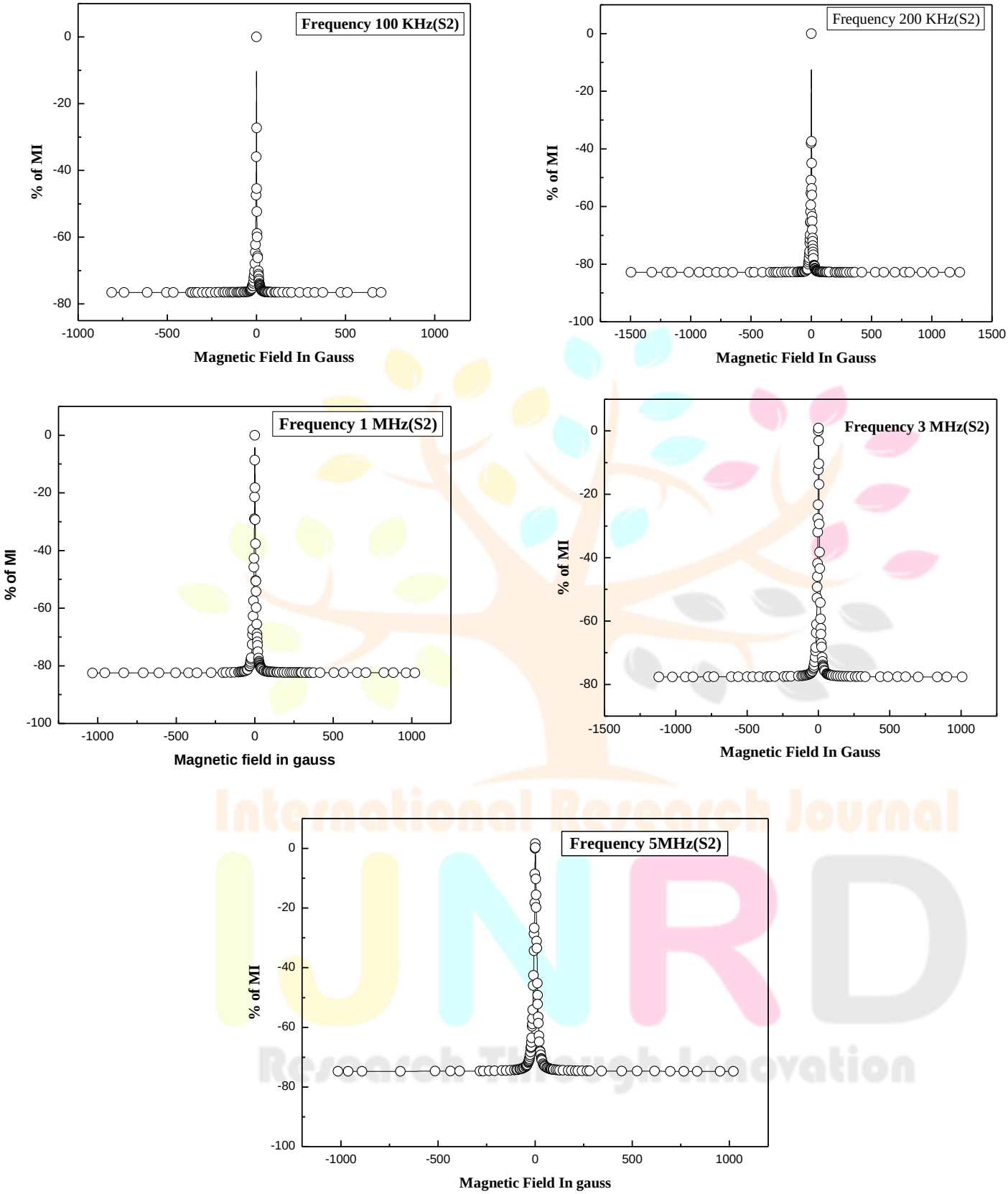


Figure(b). Change of MI with parallel magnetic field for $Fe_{81}B_{12}Mo_7$ (Sample-2) at different Frequency



Figure(c). Change of MI at 5MHz with parallel and perpendicular magnetic field for $Fe_{81}B_{12}Mo_7$ (Sample-2)

(3).sample-3 ($Fe_{80}B_{12}Mo_7Cu_1$)



Figure(a). Change of MI with parallel magnetic field for $Fe_{80}B_{12}Mo_7Cu_1$ (Sample-3)

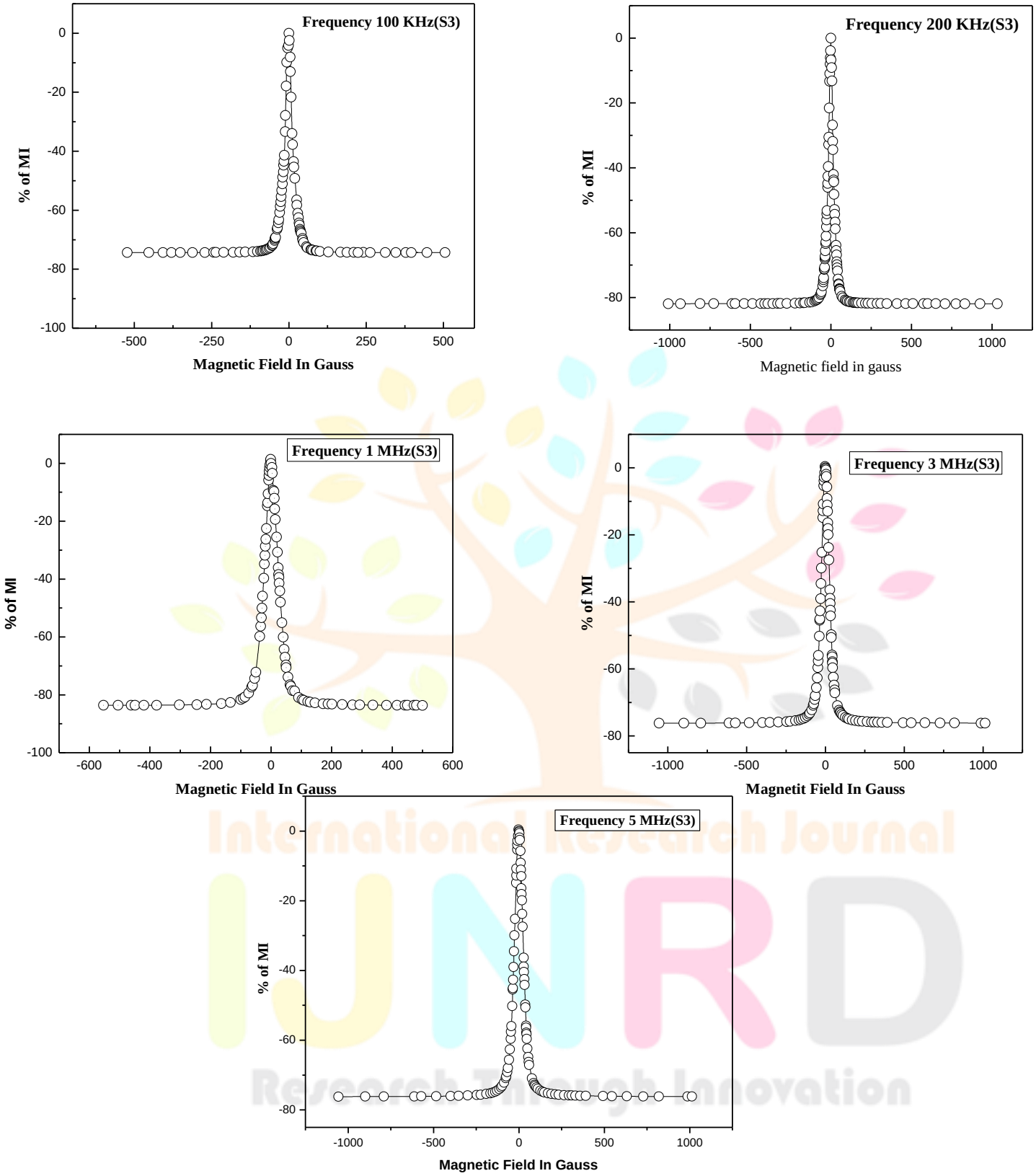
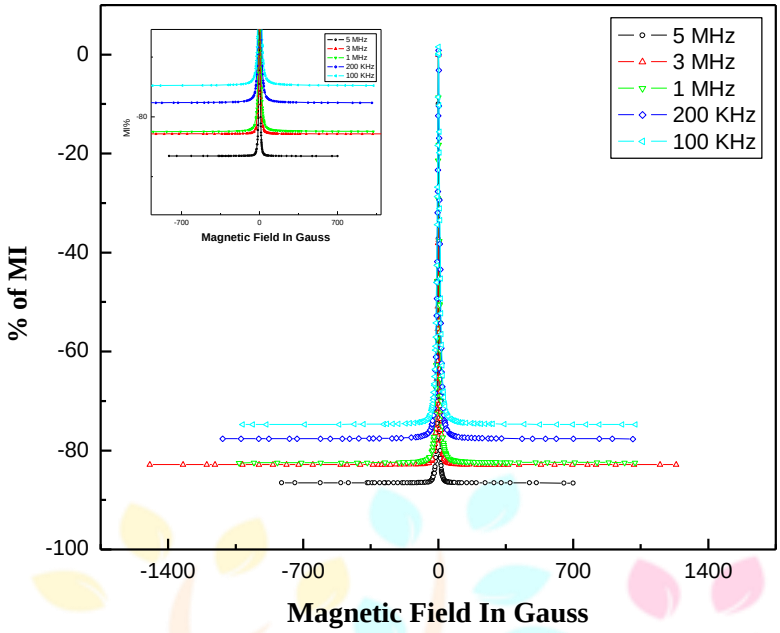


Figure (b). Change of MI% with perpendicular Magnetic field for $Fe_{80}B_{12}Mo_7Cu_1$ (Sample-3)



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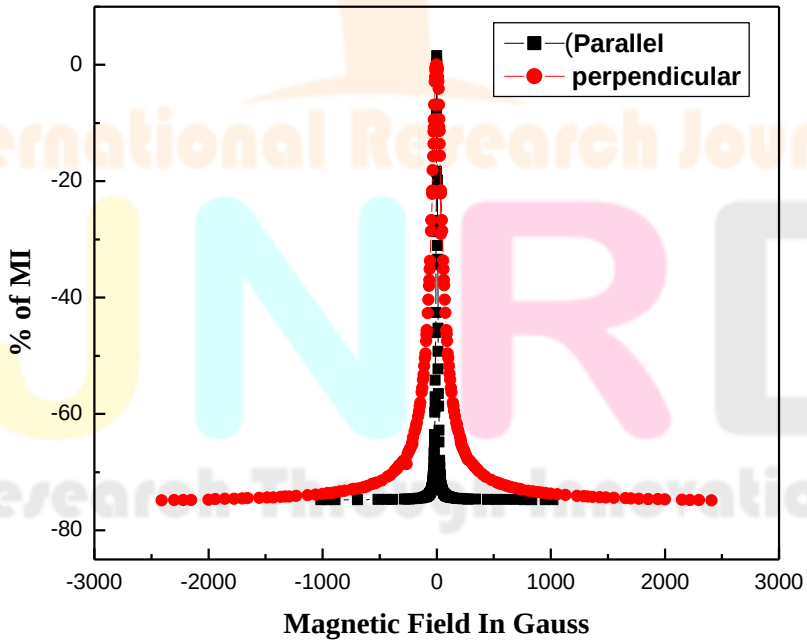
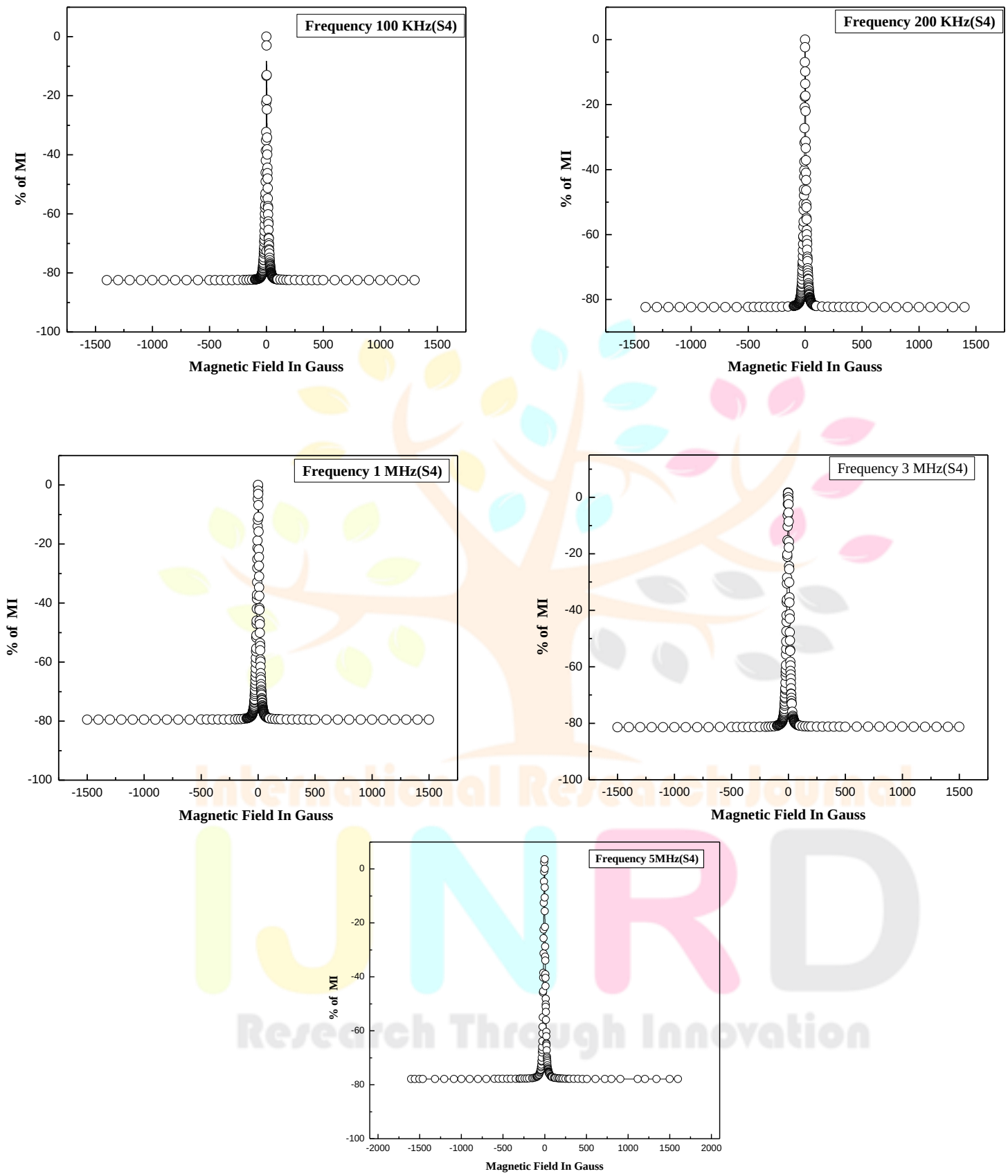
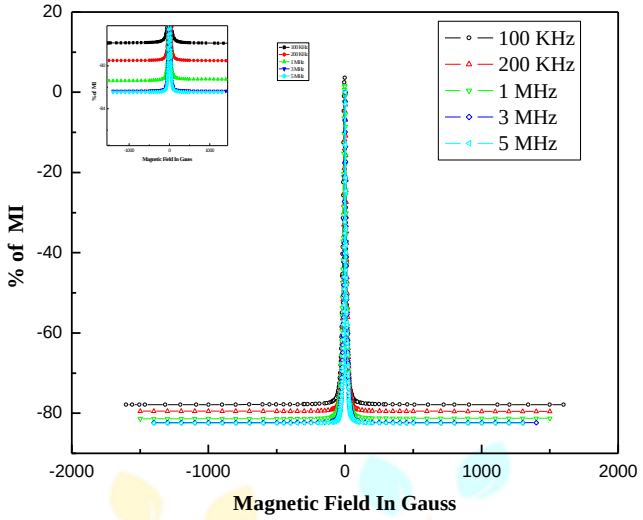
Figure(c). Change of MI with parallel magnetic field for $Fe_{80}B_{12}Mo_7Cu_1$ (Sample-3) at different Frequency



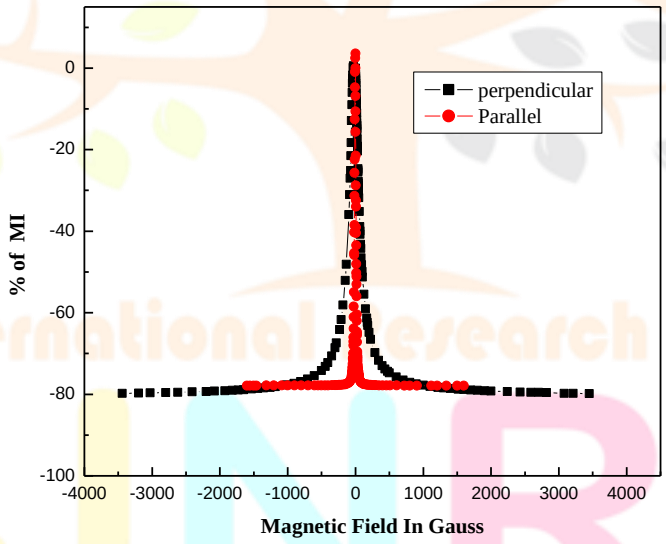
Figure(d). Change of MI at 5MHz with parallel and perpendicular magnetic field for sample-3 ($Fe_{80}B_{12}Mo_7Cu_1$)



Figure(a). Change of MI with parallel magnetic field for $Fe_{82}B_{12}Mo_7Cu_1$ (Sample-4)



Figure(b). Change of MI with parallel magnetic field for (Sample-4) at different Frequency



Figure(c). Change of MI at 5MHz with parallel and perpendicular magnetic field for (Sample-4)

4.2 Discussion

From the above analysis we obtained many interesting features. At a frequency of 5 MHz a large change in MI% (~90%) was observed for the FINEMET sample, within a range of 100 Gauss. But the most striking effect of the change in MI% was observed for the sample1(**$Fe_{81}B_{12}Mo_7$**),sample2(**$Fe_{80}B_{12}Mo_7Cu_1$**) & sample3(**$Fe_{82}B_{12}Mo_7Cu_1$**) Samples.

.At a frequency 5 MHz a change in MI% of ~ 80% was observed within a range of 50 Gauss in sample1,75% of sample2 within the range 70 gauss,76% of sample3 within the range90 gauss&77% of sample4 within the range 90 gauss. Thus this sample could be used as low field GMI sensors. A small change in magnetic field would drastically change the impedance of the material.

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4.3 Conclusion

Interaction between the surface magnetic domains with the applied field was the cause of magneto-impedance properties in amorphous materials. The frequency dependence behavior of the materials was due the variation of the circumferential permeability with skin effect at different frequency of the ac current. GMI property depends on the magnetostriction value of the material. About 90% change in impedance value with application of the field make the amorphous alloy a candidate for giant magneto-impedance material. The natures of variation of GMI materials have established an important position in the hierarchy of magnetic sensor. GMI sensor technology is still at an early stage of its development. Intense research effort in applying GMI materials in the sensor industry is ensuring that the significant technical advance will continue to be made in the foreseeable future.

Owing to the large change in MI and high sensitivity at low fields the amorphous materials could be used as Magnetic sensors. It could easily detect a small change in the magnetic field.

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5.2 Acknowledgement- I want to acknowledge my project guide Dr. Tapan Kumar Nath (Professor IIT- Kharagpur) for introducing me in Condensed matter physics