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Ultra Low Field Sensor Using GMI Effect in NiFe/Cu Wires

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A highly sensitive magnetic sensor using the Giant MagnetoImpedance effect has been developed. The sensor performance is studied and estimated. The sensor circuitry consists of a square wave generator (driving source), a sensing element in a form of composite wire of a 25 μm copper core electrodeposited with a thin layer of soft magnetic material ($Ni_{80}Fe_{20}$), and two amplifier stages for improving the gain, switching mechanism, scaler circuit, an *AC* power source driving the permeability of the magnetic coating layer of the sensing element into a dynamic state, and a signal pickup *LC* circuit formed by a pickup coil and an capacitor. Experimental studies on sensor have been carried out to investigate the key parameters in relation to the sensor sensitivity and resolution. The results showed that for high sensitivity and resolution, the frequency and magnitude of the ac driving current through the sensing element each has an optimum value, the resonance frequency of the signal pickup *LC* circuit should be equal to or twice as the driving frequency on the sensing element, and the anisotropy of the magnetic coating layer of the sensing wire element should be longitudinal.

Keywords : CDMPI sensor, GMI, magnetometer, microwires

1. Introduction

The search for *GMI* in soft magnetic wires and microwires is a topic of interest related to possible applications as tiny field sensors. Magnetic field sensing promises improved sensitivity, better compatibility with electronic systems. At low frequencies (weak skin effect or large skin depth), the first order expansion term of the impedance $Z=R(\omega)+jX(\omega)$ versus frequency is responsible for the voltage field dependence. This term is represented by an inductance, which is proportional to the transverse permeability. When the skin effect is strong, the total impedance including resistance R and reactance X is field dependent through the penetration depth.

The general theory of the *MI* effect in a long cylinder is vast as per the classic textbooks [7] and it has been shown experimentally that a large *MI* often occurs at frequencies of a few MHz. However, changing the dc biasing field H_{dc}, the maximum $|Z|$ can be as large as a few times the value of R_{dc} for amorphous wires. Following Beach *et al.* [8] the behavior of the permeability can be understood on the basis of a simple phenomenal model based on a single relaxation time τ or the magnetization that yields for the permeability:

$$\mu_t(\omega H_{dc})=\mu_t' + j\mu_t'' ;$$

$$\mu_t'=1+\frac{4\pi\chi_o(H_{dc})}{1+\omega^2\tau^2};\quad \mu_t''=\frac{4\pi\chi_o(H_{dc})\varpi\tau}{1+\omega^2\tau^2}$$

The behavior of μ_t' depicted indicates that the strongest variation of μ_t' with H_{dc} happens at low frequencies as required for a sensitive sensor whereas the variation gets totally smeared out at large frequencies.

In case of *GMI* effect in coated tubes such as the electroplated FeNi, FeNiCo, and CoP microwires, Kurlyandskaya *et al.* [9] found a huge enhancement factor approaching 800% at a frequency of 1.5 MHz. This depicts a way of producing largest *GMI* in these systems. Recently sensors based on Magnetic permeability interference (*MPI*) have shown potential in the development of very weak field measurements. For example, the commercially available fluxgate and magnetoimpedance sensors are able to detect magnetic field of 10^{-10} T or even higher resolution [1, 2].

In our module, a novel micro magnetic sensor called the current driven magnetic permeability interference (*CDMPI*) sensor has been developed. The sensor has a sensing element which is composite wire formed by a 25 μm copper core electrodeposited with thin layer of soft magnetic material ($Ni_{80}Fe_{20}$), an ac power source that drives the sensing

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*Corresponding author: Tel: +82-42-821-6632, Fax: +82-42-822-6272, e-mail: cgkim@cnu.ac.kr element with high frequency current, and a signal pick-up circuit consisting of a signal pick-up coil together with a *LC* output circuit.

2. Experiment

The sensor comprises of an *AC* power source, a signal pick-up circuit and the sensing element. The sensing element consists of extremely soft magnetic material such as *Co*-based amorphous, *Fe* based nanocrystalline alloy, or permalloy [3, 5]. The sensor works based on the permeability of the soft magnetic material in the sensing element which is driven into the dynamic state by the high frequency current through it. The permeability of the sensing element at a dynamic state is extremely sensitive to external magnetic field and varies with it. The variation of the permeability in variation with the external field changes the longitudinal magnetic flux in the sensing element. The change of longitudinal magnetic flux induces a signal in the pickup coil. The signal is enhanced by the *LC* resonance circuit. Therefore, the sensitivity and resolution of the sensor depends on three key parameters: 1) the magnetic anisotropy of the sensing element, 2) the magnitude and frequency of the ac driving current, and 3) the *LC* resonance frequency of the signal pickup circuit.

The driving circuit (oscillator) generates the wave form with frequency $2f$. The sensor element is provided with the square wave of f frequency. The current flowing through the sensing element is 10 mA. On the application of external magnetic field, the permeability of the soft magnetic shell changes and it causes the change in the impedance of the shell. Hence some voltage is induced proportionally. This induced voltage is collected by the pick-up coil and is provided with amplification by the amplifier circuit. The signal induced in the sensing element is very low and it is accompanied by the high frequency signal of the waveform generator. In order to obtain the induced signal, the output from the amplifier stage is passed through the band pass filter, phase sensitive detector and low pass filter. At the output of the Integrator circuit, the final *DC* signal is obtained.

3. Results and Discussion

3.1. Magnitude and frequency of the *AC* driving current

The circumferential magnetic field induced by the driving current will magnetize the sensing element to partially or fully saturated state. For different soft ferromagnetic materials, there is an optimum working frequency, at which the permeability of the magnetic material materials can be driven into a most dynamic state. The extent of the magnetization may affect the sensitivity of the *CDMPI* sensor. For each sensing element, there is an optimum frequency, f_{MI} at which, the magnetoimpedance of the sensing element reaches the maximum.

Table 1. Sensor's sensitivity and resolution for sensing elements of different anisotropies.

	Sensitivity	Resolution
Longitudinal anisotropy	958.2 mV/Oe	9.5×10^{-7} T
Circumferential anisotropy	895.5 mV/Oe	2×10^{-7} T

In order to study the effect of the magnitude of the driving current on the sensitivity of the sensor, experiments are conducted at the frequency condition of driving current frequency $f_{DR}=f_{MI}$. The sensitivity of the sensor is obtained by calculating the gradient of the output voltage against the external magnetic field, H_{ext}. The effect of the magnitude of the input voltage, V_I on the sensitivity of the sensor is shown in Fig. 6. It can be seen that the output voltage signal from the sensor not only contains the 1^{st} harmonics of the driving frequency but also higher order harmonics. Further, as V_I was increased, the dominant output voltage signal changes from first harmonics to second harmonics and then to higher order harmonics. The maximum sensitivity for the sensor was attained at V_I =1400 mV, which was in the second harmonic region. This clearly indicates that the sensor is most sensitive when the output voltage signal is at the second harmonic region. The effect of the driving frequency, f_{DR}, on the sensor sensitivity was also examined. The results are shown in Fig. 5. It can be seen that the curve displays a maximum sensitivity occurring at the condition whereby $f_{DR}=f_{MI}$, (f_{MI}=10 MHz) at which the sensing element can be driven to the most dynamic state. The optimum frequency of the driving current is closely related to the properties of the sensing element, and can be determined by obtaining the magneto-impedance of the sensing element when an ac current of a range of driving frequencies was passing through it. The magnitude of the optimum driving current is also closely related to the properties of the sensing element, and the optimum value is determined such that the circumferential magnetic field of the sensing element reaches a saturation level.

3.2. Anisotropy of the sensing element

The anisotropy structure of the sensing element may be varied during the sensing element development [6]. The influence of the anisotropy on the sensitivity and resolution of the sensor was tested. The experiments on the

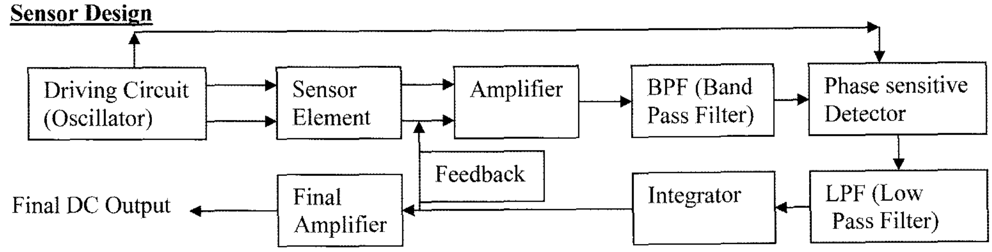

Fig. 1. Block diagram of the sensor.

sensing elements with circumferential and longitudinal anisotropy were carried out using the same testing conditions. The two samples had almost the same maximum magnetoimpedance, *MI* frequency and maximum *MI* ratios. Table 1 shows a comparison between the sensitivity and resolution of the sensor with different anisotropic sensing elements. It can be seen from the Table 1 that the sensing element of longitudinal anisotropy has higher sensitivity and resolution than circumferential one. Using such an anisotropy structure sensing element, a maximum sensitivity of 1850 mV/Oe and a maximum resolution of 2x 10^{-8} T was achieved for the external field ranging from 0 Oe to 1.2 Oe.

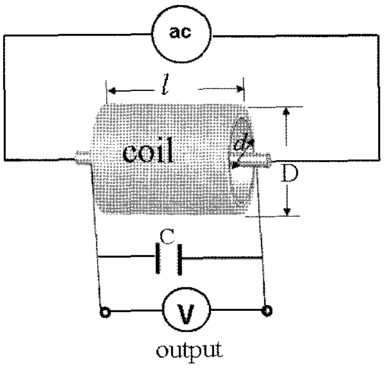

Fig. 2. Sensor Module.

3.3. *LC* resonance frequency

To study the effect of *LC* resonance frequency, f_{LC}, on the sensitivity of the sensor, the capacitance value and the inductance of the pickup coil may be adjusted to f_{LC}. Experiments were carried out using a pickup coil of 100 turns initially and the driving frequency, f_{DR}, and magnitude of input voltage were also kept constant at 10.0 MHz and 8 V, respectively. When the critical frequency met the condition $f_{LC}=f_{DR}$ or $f_{LC}=2f_{DR}$, the output peak-to-peak voltage, V_{pp} was obtained as the maximum variation against the external magnetic field. The result also showed that when a larger capacitance value of the capacitor is used, both the sensitivity and resolution of the sensor deteriorates. When the Current driven magnetic permeability Interference, *CDMPI* sensor was operated at the critical frequency condition whereby the resonance frequency was of the same magnitude as or double that of the driving frequency, it was found that the sensor had the highest sensitivity and resolution. This is due to the occurrence of the magnetic resonance when the driving frequency of the sensing element, f_{DR}, coincides with the resonance frequency of the *LC* circuit, f_{LC}. The effect of the occurrence of this resonance is that it will cause the output peak-to-peak voltage, V_{pp} to be amplified numerous times and these results in the highest sensitivity of the sensor at this critical condition. This is very critical in the *CDMPI* sensor as higher sensitivity of the sensor will result in more precise measurements and higher resolution of the sensor will imply that the sensor will be able to detect weaker magnetic fields.

The value of the capacitor should be determined such that the resonance frequency of the signal pickup circuit is equivalent to the optimum frequency of the driving current, or is twice the magnitude of the optimum frequency of the current driving the sensing element. The sensor output is the voltage induced in the pickup coil when there is a variation in the magnetic field.

3.4. Factors Affecting the Sensitivity of the Sensor

The effect of the coil's length, *l* (shown in Fig. 2) on the sensor's sensitivity is studied. The coil having shorter length (6 mm) shows better sensitivity at ±0.5 Oe external magnetic field. Longer the length of the coil, lower is the sensitivity.

The effect of the diameter, *d* (shown in Fig. 2) of the pick-up coil on the sensitivity also has been studied. Sensing element in a smaller coil of diameter with 1.5 mm has greater sensitivity.

Fig. 3 shows the dependence of sensitivity on the diameter of the pick-up coil wire. An 80 μm pick-up coil is made, tested with the sensing element in it at 1.34 MHz for optimum sensitivity. For a pick-up coil diameter of 200 μm, the sensitivity is decreased by 50%. It's evident from the graph.

Fig. 4 shows the dependence of sensitivity on the number

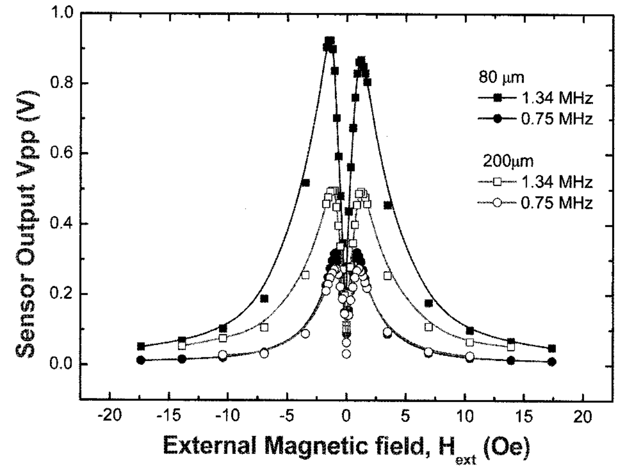

Fig. 3. Sensitivity as a function of diameter of the pick-up coil wire.

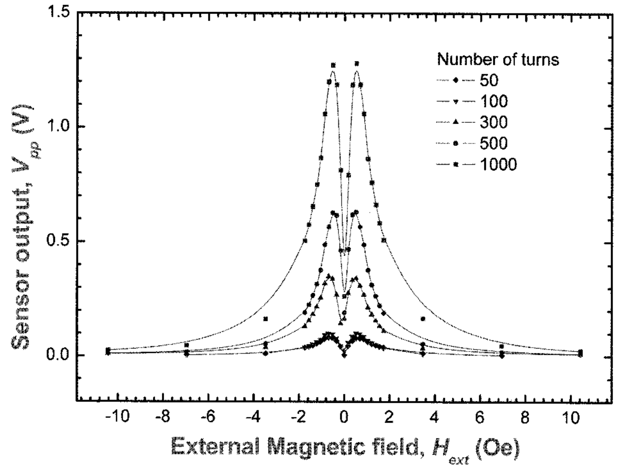

Fig. 4. The effect of number of turns of the pick-up coil on sensitivity.

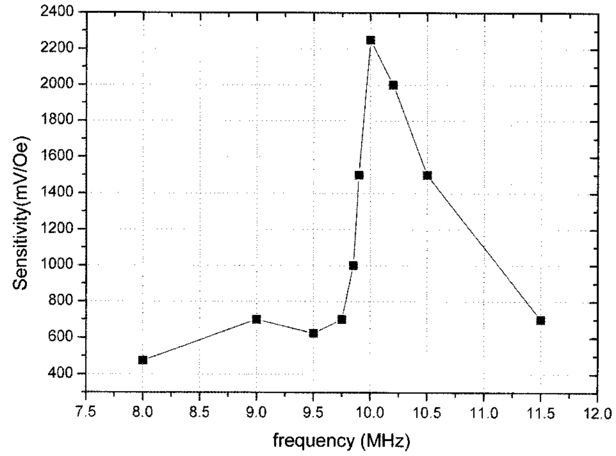

Fig. 5. Sensitivity varying against frequency of the driving current.

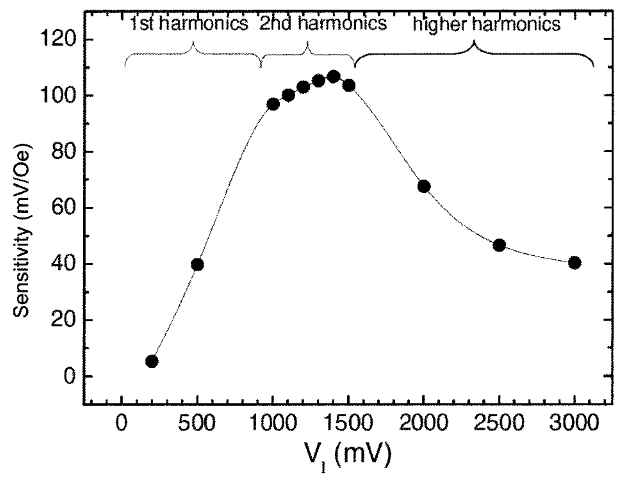

Fig. 6. Frequency spectrum of the sensor, sensitivity varying against magnitude of the driving voltage.

of turns of the pick-up coil. Sensitivity for different number of turns is examined. The sensitivity is directly proportional to the number of turns of the pick-up coil, counter proportional to the length of pick-up coil. It is found that optimum sensitivity is obtained for 1000 turns.

The sensor output in variation with the diameter of the sensing wire by the ac current for I=10 mA is studied. Several experiments are conducted for different diameters of the wires at 10 μm, 16 μm, 23 μm and 30 μm. The optimum sensitivity of 1400 mV is obtained for a wire if diameter is16 μm. The optimum *AC* frequencies used for driving the wires of diameters 7, 10, 16, 23 and 30 μm were 650 KHz, 625 KHz, 520 KHz, 340 KHz, and 320 KHz respectively.

4. Conclusions

A Current driven magnetic permeability interference (*CDMPI*) sensor has been developed. The sensor comprises a sensing element, an ac power source having a high frequency current passing through the sensing element, and a signal pickup *LC* circuit. The effects of the sensor parameters on sensor sensitivity and resolution have been investigated. The results showed that for high sensitivity and resolution, the frequency and magnitude of the ac driving current through the sensing element each has an optimum value, the resonance frequency of the signal pickup *LC* circuit should be equal to or twice as the driving frequency on the sensing element, and the anisotropy of the magnetic coating layer of the sensing wire element should be longitudinal. Using a composite wire of 25 μm copper core electrodeposited with a thin layer of soft magnetic material ($Ni_{80}Fe_{20}$) as the sensing element for the sensor, a maximum sensitivity of 1850 mV/Oe and a maximum resolution of 2.0×10^{-8} T was achieved at the magnetic field ranging from 0 Oe to 1.2 Oe.

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