Weak AC Magnetic field Measurement by MTJ Sensor Using Lock-in Amplification Technique

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Magnetic tunneling junction (MTJs) is a commonly used magnetics sensor in industry. In this report, we studied the lowest limit of AC magnetic field that MgO-based MTJs sensor can be directly measured using amplification technique. Eventually, we were able to push the measurement limit down to $109pT$ RMS magnetic field in $1kHz$ frequency. In the future, we are going to investigate the lowest limit of magnetic field under different frequencies and hopefully can reproduce the noise spectrum of MTJs using direct measurement.

I. INTRODUCTION

Magnetic tunneling junctions (MTJs) consists of three layers: two ferromagnetic layers sandwiches a tunnel barrier [1]. The bottom layers is called the pinned layer where the magnetization is fixed, while the top layer is free layer where the spins are free to rotate under external magnetic field. When the magnetization vectors of the two ferromagnetic layers are parallel, the resistance $R_{\uparrow\uparrow}$ of the MTJ is the lowest. On the other hand, when they are antiparallel, the resistance $R_{\uparrow\downarrow}$ are the highest. The magnetoresistance (MR) defined in Eq.[1] shows the relative resistance change under an external magnetic field.

$$MR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} \tag{1}$$

For an ideal sensor, the field sensitivity S is given by Eq.[2]:

$$S = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\downarrow} + R_{\uparrow\uparrow}} \times \frac{1}{B_{sat}} = \frac{1}{2}\frac{MR}{B_{sat}} \tag{2}$$

where B_{sat} is the magnetic saturated field for the free layer[1]. In order to increase sensitivity, the key is to reduce the saturated magnetic field and obtain the largest possible of MR. Note that the MR used here is defined differently from Eq.[1]

To measure the magnetoresistance property of the MTJs sensor, a probe station is used to measure the transfer curve of the sensor. The probe station shown in FIG.1 consists of two pairs of electromagnets positioning in both x and y direction so that it can generate magnetic field in all angles. The sensor is placed in the middle metal plate connected with the probes to measure its resistance. The transfer curve shows the resistance of the MTJs sensor over a long range of external magnetic field (FIG.2). Note that in the sensing part there is error due to the hysteresis.

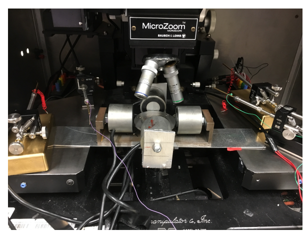

FIG. 1. The probe station.

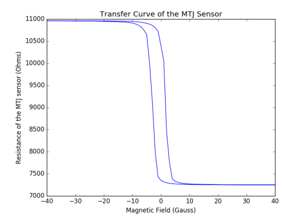

FIG. 2. The transfer curve of a typical MTJs sensor.

For a typical MTJ system, there are four types of noise that limit the measurement, including Johnson noise, shot noise, flicker noise, random telegraph noise [2]. Johnson noise is the electronic white noise generated by the random motion of charge carriers inside a conducting media. The noise power can be described by Eq.[3].

$$S_{Johnson} = 4k_BTR \tag{3}$$

where T is the temperature and R is the resistance across the MTJs.

The shot noise is another type of white noise that comes from the corpuscular nature of electron transport. The power spectral is given by Eq.[4].

$$S_{shot} = 2eIR^2 \tag{4}$$

where e is the electron charge, I is the average DC current, and R is the resistance across the MTJs.

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The flicker noise ($1/f$ noise) is an important noise source at low frequency. It is a frequency dependent noise proportional to inverse of the frequency. The power spectrum of the electronic $1/f$ noise can be modeled with the Hooge parameter, defined as Eq.[5]

$$\alpha = AfS/V^2 \tag{5}$$

, where A is the junction area, f is the frequency, S is the power spectral of flicker noise, and V is the voltage across the junction. In MTJs, α may decrease with bias voltage of the junction and be reduced by proper annealing process [2].

In this project, we used amplification technique to investigate the lowest measurable limit of AC magnetic field of a MTJ sensor. Lock-in amplification technique can extract the signal with known frequency and phase under a very noisy environment. By direct measurement of the lowest limit of magnetic field in different frequency, hopefully we can reproduce the $1/f$ characteristic power spectrum.

II. METHOD

The experimental setup consists of two circuits, including the coil circuit and the sensor circuit. The MTJ sensor was connected to the sensor circuit and placed beside/inside the electromagnetic coil which generates AC magnetic field. The sensor used is shown in FIG.3, and FIG.4 shows a sensor contains four MTJs in an array with two internal concentrators that use to magnify the magnetic field.

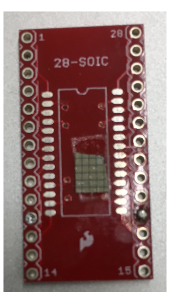


FIG. 3. The MTJ sensors on the chip.

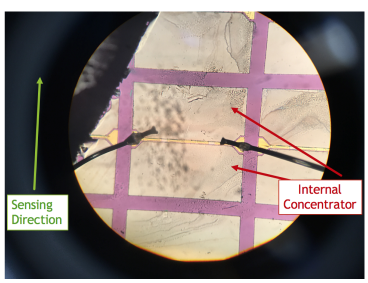


FIG. 4. Image of a MTJs array. The green arrow shows the sensing direction and the red arrows indicate the internal concentrators.

Since the size of a MTJs sensor is very small (about $1mm \times 1mm$ including the internal concentrators), the generated external magnetic field is not necessarily uniform over a long range. Therefore, a small coil was used in the first place for convenience. In order to reduce the saturated magnetic field B_{sat} to obtain higher sensitivity, two secondary concentrators, each $5cm$ long, were then used for further magnifying the magnetic field. The overall size of the sensor (shown in FIG.5) became much larger, hence it requires to apply an uniform magnetic field over the length of the sensor. So, the small coil was replaced by a large coil for generating an uniform magnetic field.

FIG. 5. The MTJs sensor with two secondary concentrators.

For weak AC magnetic field measurement, lock-in amplification technique is used. Lock-in amplification technique can lock the frequency and the phase of the signal by comparing the reference waveform and the signal waveform. It is a powerful tool to eliminate environmental noise such as Earth magnetic field. In the experiment, Signal Recovery 7265 Dual Phase Lock-in Amplifier was used.

A. Coil Circuit

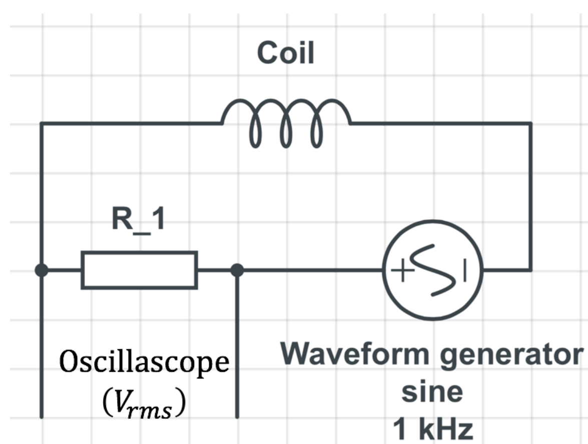


FIG. 6. The coil circuit.

Two electromagnetic coils, one small coil and one large coil, were made to produce AC magnetic field. The calibration is done by LakeShore 450 Gaussmeter. For small coil, the magnetic field was measured a few centimeter away from the coil center, while for the large coil, the magnetic field was measured right at the coil center. The positions where the calibrations were done were marked for placing the sensor. The calibration curves for small coil and large coil are appended in appendix A. The small coil was used in the measurement of MTJ sensor without secondary concentrator, while the large coil was used to produce an uniform magnetic field over a long range for the measurement of MTJ sensor with secondary concentrator. A waveform generator and a resistor are connected in series with the coil as shown in FIG.6. The resistor R_1 is used to control the AC current passing through the circuit. Hence, the magnetic field generated by the coil is given by Eq.[6].

$$B_{rms} = kI_{AC} = k\frac{V_{rms}}{R_1} \tag{6}$$

,where k is the calibration constant for the coil (0.06844 $Gauss/A$ for small coil and 8.677 $Gauss/A$ for large coil), R_1 is the resistance of the resistor, and V_{rms} is the RMS voltage across R_1 measured by an oscillascope DSO-X 2024A.

In order to reduce as much environmental noise as possible, the coils are placed in a metal box so that most of the background magnetic field can be shielded. The experimental setup is shown in FIG.7 and FIG.8.

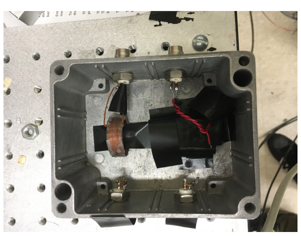


FIG. 7. The metal box containing the small coil.

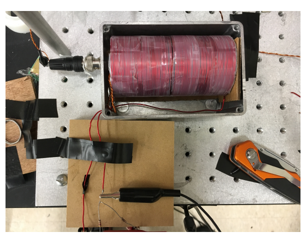


FIG. 8. The metal box containing the large coil.

B. Sensor Circuit

In the sensor circuit, the MTJs sensor is connected with a resistor R_0 and a Keithley 2400 Sourcemeter in series as shown in FIG.9. The Keithley 2400 Sourcemeter is used to output DC voltage bias V_{DC} for the MTJs sensor. Under AC magnetic field, the resistance of the MTJs sensor R_{MTJ} changes sinusoidally with the same frequency as the AC magnetic field, which induces an AC voltage fluctuation across the resistor R_0. A Signal Recovery 7265 Dual Phase Lock-in Amplifier is connected in parallel to the resistor R_0 to measure the AC voltage across R_0. The measured signal ΔV_{LI} is given by Eq.[7].

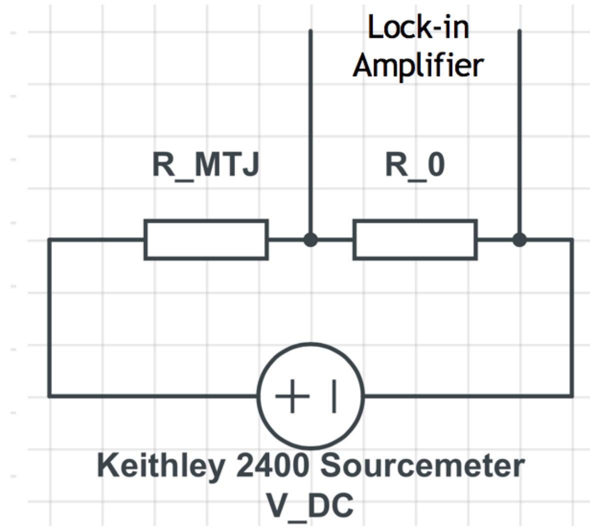


FIG. 9. The MTJ sensor circuit.

$$\begin{aligned} V_{LI} &= V_{DC}\frac{R_0}{R_{MTJ}+R_0} \\ \Delta V_{LI} &= V_{DC}\frac{R_0}{(R_{MTJ}+R_0)^2}\Delta R_{MTJ} \\ &= V_{DC}\frac{R_0 R_{MTJ}}{(R_{MTJ}+R_0)^2}\gamma\Delta B \end{aligned} \tag{7}$$

,where ΔR_{MTJ} is the small resistance change of the MTJs sensor, γ is the sensitivity of the MTJs sensor, and ΔB is the amplitude of the weak AC magnetic field. In order to obtain the highest possible signal ΔV_{LI}, the resistance of R_0 is chosen such the $R_0 \simeq R_{MTJ}$. The resistor R_0 needs to place away from the coil as far as possible to avoid induced voltage directly from the AC magnetic field, so BNC cables were used to extend the distance between the resistor R_0 and the coil to about 1.5 *meter* as shown in FIG.10. All the connection junctions were welded to avoid capturing environmental noise.

For the setup of the Signal Recovery 7265 Dual Phase Lock-in Amplifier, the amplifier contains an internal oscillator which can be used as the AC voltage output of the coil circuit. Since the signal from the ΔR_{MTJ} is directly induced by the AC magnetic field generated by the coil circuit, the signal should have exactly the same frequency as the internal oscillator and the amplifier can hence lock the frequency of the signal. An external waveform generator can also be used in the coil circuit instead of the internal oscillator. The lock-in process can still be easily done by connecting the external waveform generator to the sync. port of the amplifier.

For the phase locking, in my knowledge there is no perfect way to lock the phase of the signal. We assume that if the bias voltage V_{DC} in the sensor circuit is zero,

FIG. 10. The resistor R_0.

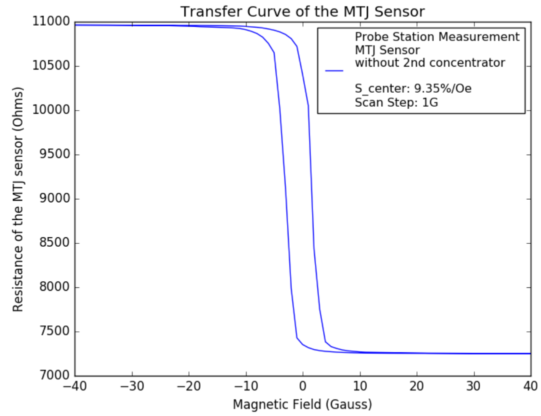


FIG. 11. The probe station measurement of transfer curve of MTJs sensor without 2^{nd} concentrators.

ideally there is no signal coming from the sensor even if the AC magnetic field is present. We also assume that most of the noise comes from the overall inductance of the sensor circuit which induces noise under the presence of the AC magnetic field, hence the induced noise should be anti-phase to the true signal. Therefore, to calibrate the phase of the signal, we first generate the highest possible magnetic field in the coil circuit. Then, turn off the voltage source of the sensor circuit and short the circuit with a wire so that the voltage input V_{DC} is zero. Finally, press the *AUTO PHASE* and then -90 *deg* option of the amplifier to move all the noise to *Y Channel* so that the in phase signal is locked to *X Channel*. After the calibration, the phase of the signal keeps unchanged during the measurement.

The AC gain of the amplifier was set as high as possible without causing overflow in order to obtain maximum gain. The time constant was set to be at least $5s$ in order to obtain a stable reading.

III. RESULT

A. Measurement without 2^{nd} concentrator

Before the weak AC magnetic field measurement, the MTJs sensor underwent the probe station measurement and the transfer curve was obtained as shown in FIG.11. The sensitivity of the sensor is $9.35\%/Oe$.

For the lock-in amplification measurement, a resistor $R_1 = 464.67\Omega$ was connected in series with the small coil in the coil circuit, and the internal oscillator of the Signal Recovery 7265 Dual Phase Lock-in Amplifier was used as the waveform generator. In the sensor circuit, $R_{MTJ} = 7481\Omega$ was obtained from FIG.11 and a resistor $R_0 = 12806.8\Omega$ was used. The bias voltage applying to the sensor circuit chose to $V_{bias} = 1V$. The frequency of the AC voltage output $f = 1000\ Hz$ was chosen in the measurement.

The graph of in phase signal against external magnetic field was plot as shown in FIG.12. The lowest limit of magnetic field measured is 13.39 nT and the sensitivity $= 1.823\%/Oe$ is obtained from the graph.

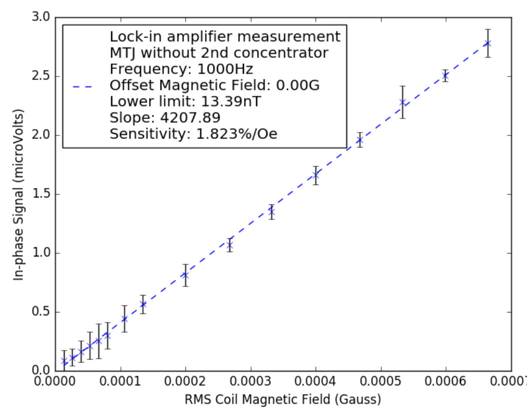


FIG. 12. The plot of in phase signal against external magnetic field.

B. Measurement with 2^{nd} concentrator

To get higher sensitivity, two secondary concentrators were added to the MTJs sensor in this measurement. The transfer curve (shown in FIG.13) obtained from the probe station measurement shows that the B_{sat} is about 10 times smaller then without secondary concentrator, and the obtained sensitivity is $383.02\%/Oe$.

For the lock-in amplification measurement, a resistor $R_1 = 46572.4\Omega$ was connected in series with the small

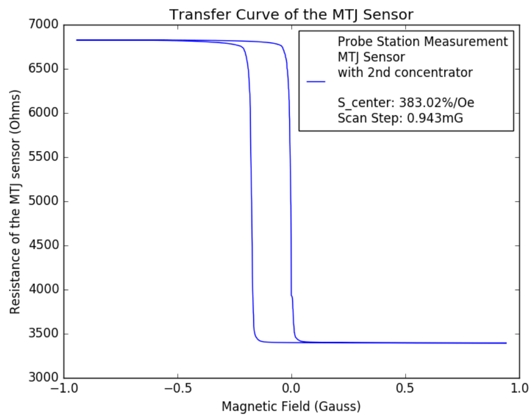


FIG. 13. The probe station measurement of transfer curve of MTJs sensor with 2^{nd} concentrators.

coil in the coil circuit, and the internal oscillator of the Signal Recovery 7265 Dual Phase Lock-in Amplifier was used as the waveform generator. In the sensor circuit, $R_{MTJ} = 7032.2\Omega$ was obtained from FIG.11 and a resistor $R_0 = 3011\Omega$ was used. The bias voltage applying to the sensor circuit chose to $V_{bias} = 0.6V$. The frequency of the AC voltage output $f = 1000\ Hz$ was chosen in the measurement.

The graph of in phase signal against external magnetic field was plot as shown in FIG.14. The lowest limit of magnetic field measured is 5.59 nT and the sensitivity $= 3.273\%/Oe$ is obtained from the graph. The result is clearly better than sensor without secondary concentrator.

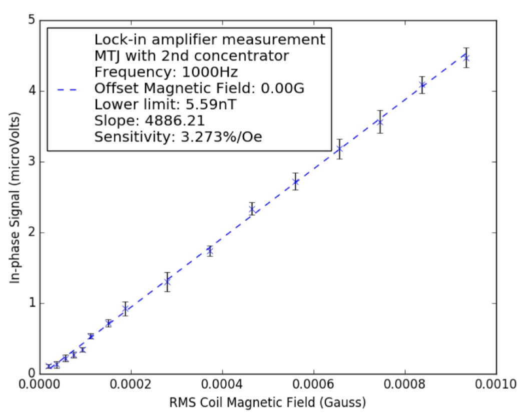


FIG. 14. The plot of in phase signal against external magnetic field.

C. Effect of Offset Magnetic Field on Sensor Sensitivity

In previous measurements, although the lock-in amplification technique successfully measured the lowest limit of magnetic field down to nT scale, the obtained sensitivities were much lower than that in transfer curves from probe station measurement. It suggests that the previous lock-in amplification measurements did not make use of the most sensitive part of the sensor. According to FIG.11 and FIG.13, the slopes of the transfer curve at zero magnetic field are much flatter than the steepest part. In order to obtain maximum sensitivity, an offset DC magnetic field needs to be added.

For MTJs sensor with secondary concentrator, an offset magnetic field $\simeq$ 0.2 *milliGauss* is required according to FIG.13. However, for large coil, we need $\sim 1\mu A$ to generate about $\sim 900pT$ AC magnetic field for measurement but the coil requires $\sim 12mA$ to generate $\sim 0.104mG$ offset magnetic field. That means we need to produce relatively large DC current for offset magnetic field with very low AC current for weak magnetic field, and there is no available device that capable to do that.

Therefore, a new coil circuit is designed by adding a DC voltage source with resistor R_2 parallel to the large coil as shown in FIG.15. Since the measured inductance of the large coil $L = 14.5\mu H$, for the impedance of the coil $\ll R_1, R_2$, $I_{coil} \simeq I_{DC} + I_{AC}$, the current passing through the coil, to the zero order approximation, is equal to the sum of the AC current from the oscillator and the DC current from the voltage sourcemeter. Several tests using oscillascope to measure the resultant voltage across the coil with lower DC to AC ratio shows that the resultant voltage is equal to the sum of AC output and DC output as expected, which means the new circuit design should be good to use. Note that this circuit design definitely is not the best approach to solve the problem.

The parameters $R_1 = 46572.4\Omega$, $R_2 = 130\Omega$, internal oscillator output $V_{AC} = 5V$ were used in the coil circuit, and the sensor circuit for MTJs sensor with secondary concentrator remained unchanged. The in phase signal was measured with different DC bias voltage output V_{DC}. The graph of signal against the bias voltage for magnetic field is shown in FIG.16. The signal reaches maximum under certain offset magnetic field, which indicates that it is possible to make use of the most sensitive part of the MTJs sensor under suitable offset magnetic field.

D. Measurement with 2^{nd} concentrator with best magnetic field offset

In this measurement, there were some changes in both the coil circuit and sensor circuit. In the coil

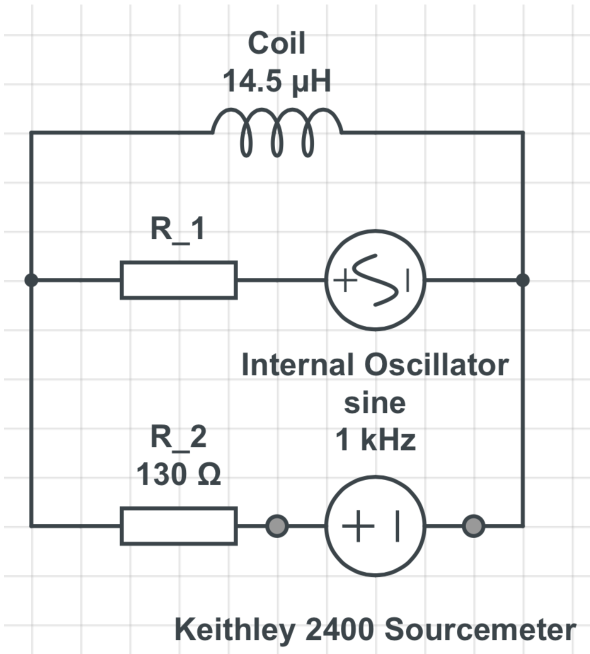


FIG. 15. The coil circuit.

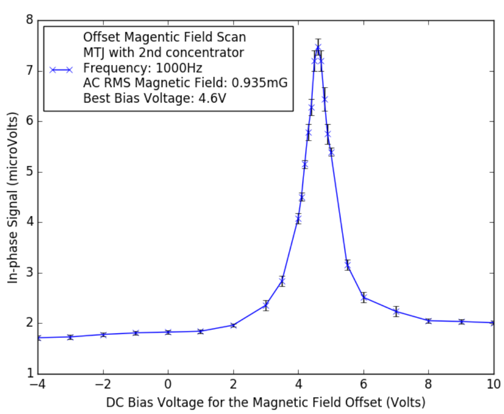


FIG. 16. The graph of signal against the DC bias voltage for magnetic field.

circuit (shown in FIG.17), constant current source was used instead of constant voltage source used in FIG.15. Agilent 33220A waveform generator was used instead of the internal oscillator of the lock-in amplifier. The parameters $R_1 = 150520\Omega$, $R_2 = 130\Omega$, constant current source output $I_{DC} = 12mA$ were used.

In the sensor circuit (shown in FIG.18), the sourcemeter was replaced by a $1.5V$ battery which provides less noise. A resistance substitution box was also connected in series with the battery in order to control the bias voltage applied on the MTJs sensor. The parameters $R_0 = 3011\Omega$, $R_{sub} = 2229.5\Omega$, and constant current source output $I_{DC} = 12mA$ were used. The frequency of

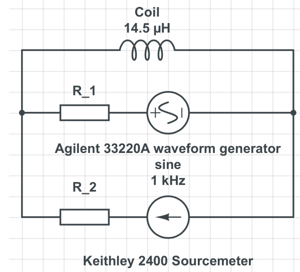


FIG. 17. The coil circuit for offset magnetic field.

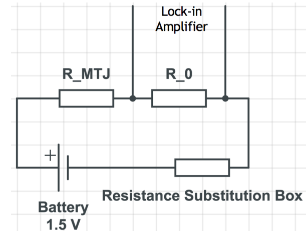


FIG. 18. The sensor circuit with battery.

the AC voltage output $f = 1000\ Hz$ was chosen in the measurement.

The graph of in phase signal against external AC magnetic field was plot as shown in FIG.19. The lowest limit of magnetic field measured is 109 pT and the sensitivity $= 15.387\%/Oe$ is obtained from the graph.

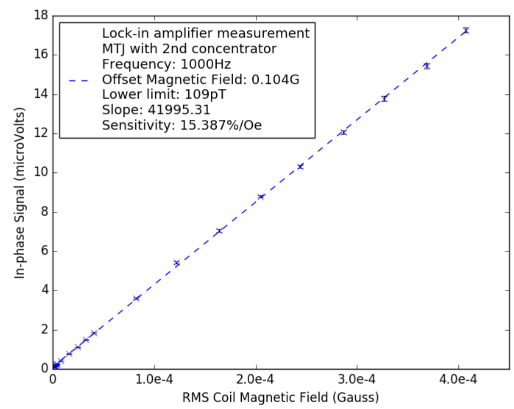


FIG. 19. The plot of in phase signal against external AC magnetic field.

E. Potential Problem

During the measurements, we found two potential problem in MTJs sensor measurement.

The first problem is that the MTJs sensor may have unstable state at the most sensitive region. We carried out two consecutive probe station measurement of MTJs sensor with secondary concentrator as shown in FIG.20. The blue line is the first measurement and the red line is the second measurement. From the transfer curve, the blue line and the red line do not completely overlap in the most sensitive region, which may indicate that the state in the sensing region is not stable.

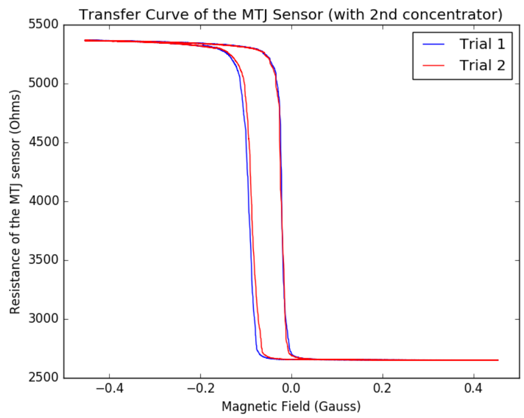


FIG. 20. The transfer curve of two consecutive measurement from probe station.

The second problem is that when the probe station carried out small magnetic domain sweep, the high sensitivity curve appeared only once and could not be reproduced. In the measurement, the probe station was used to scan over a small range of magnetic field (range = $2.266mG$) with step size = $0.2266mG$ for 10 times consecutively. In FIG.21 and FIG.22, after the first scan, the slopes of the curves become much flatter, showing a drop in sensitivity. This may indicate that there exist multiple state in the most sensitive region of MTJs sensor and the high sensitivity region shown in long magnetic domain scan transfer curve cannot be reproduced in weak AC magnetic field measurement.

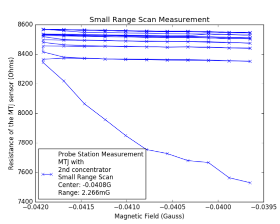


FIG. 21. Small magnetic domain scan from probe station measurement (starting from decreasing magnetic field).

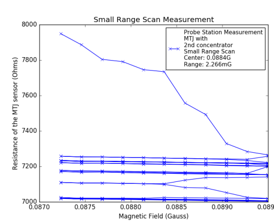


FIG. 22. Small magnetic domain scan from probe station measurement (starting from increasing magnetic field).

However, those potential problems are not yet confirmed because the cores of the electromagnets used in the probe station are made of soft iron which have an error of a few milliGauss due to hysteresis. In order to have a more accurate measurement, electromagnetic coils should be used.

IV. CONCLUSION AND FUTURE WORK

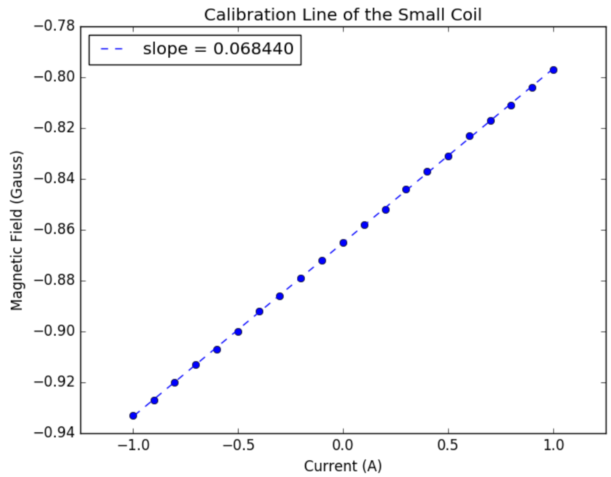
In conclusion, we successfully measure weak AC magnetic field down to 109 pT at $1000Hz$ frequency with the MTJs sensor using amplification technique. In the future, we can continue the measurement at different frequency, identify the source of the $\sim 78nV$ background noise, and use Helmholtz Coil to further investigate the potential problems.

V. ACKNOWLEDGMENTS

I would like to express my special thanks of gratitude to Prof. Gang Xiao for supervising my project as well as Gary and Shu Wang, who taught me various experimental skills and helped me a lot in the project. I would also like to thank the Chinese University of Hong Kong and Prof. Chu for organizing the summer program and providing me an opportunity to learn in Brown University during the summer. Lastly, I would like to thank the financial support from the physics department and Prof. CN Yang's scholarship.

Appendices

A. PLOTS OF CALIBRATION CURVE



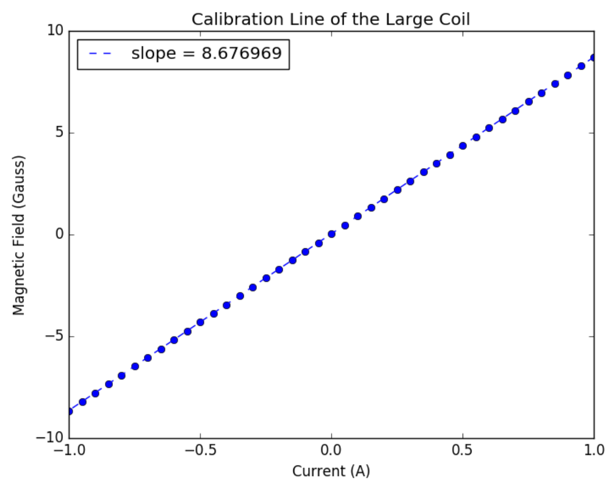


FIG. 23. The calibration curves of small and large electromagnet coil by LakeShore 450 Gaussmeter.

[1] G. Xiao, "Magnetoresistive sensors based on magnetic tunneling junctions - chapter 34 in handbook of spin transport and magnetism (crc press 2011, isbn 9781439803776)," 08 2011.

[2] Z. Wenzhe, "Noise and spin-dependent transport in mgo-based magnetic tunnel junctions," 05 2012.