RADIO FREQUENCY TRANSMISSION IN BAND PASS FILTERS CIRCUITS FOR PERFORMING CONTACTLESS CONDUCTIVITY MEASUREMENTS IN HIGH MAGNETIC FIELDS

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ABSTRACT: *In this work we propose a new method to perform contactless conductivity to study many phenomena in material science in high magnetic fields and low temperatures. The new method works by transmitting radio frequency (rf) signals through a simple band-pass circuit with the sample of interest coupled to the circuit's inductance part. The new method is aiming to avoid some of the drawbacks associated with the use of a recent rf transmission method that uses different circuit design. Some of these drawbacks are stemming from the responsive nature of the used circuit to rf signals (i.e., absorption of a specific range of frequencies when band stop circuit is used). The new proposed method is expected to have a better resolution and is expected to be more user friendly due to its simplicity when compared to other methods. More important aspect of the new design is the robustness to the extreme electrical and mechanical conditions experienced by the measuring circuit during the application of high magnetic fields. In order to prove the concept of operation of this new method and its capabilities, a presumed sample that shows the Shubnikov-de Haas effect is investigated.*

Keywords: Contactless Conductivity; rf circuit; rf transmission; Shubnikov-de Haas effect; Band pass filter; Response Function

1. INTRODUCTION

Radio frequency (rf) methods are proven to be very sensitive and very powerful methods when studying materials in very high magnetic fields and at low temperatures [1-5]. Because of the high sensitivity and highe resolution (up to 10^{-8}) rf methods are used to study interesting and sometime hard to observe phenomena like the Shubnikov–de Haas (SdH) effect, superconductivity and magnetic transitions [6-8]. In the SdH effect, the resistivity of a metallic sample would oscillate as the applied magnetic field is varied at low temperatures solely due to quantum effects [9]. Measuring the SdH effect in metallic samples provide valuable information about the geometry of the Fermi surface in the K-space, its dimensionality and the effective masses of the electrons [10]. Recently, rf methods have been used in many studies aimed to measure the SdH effect in Cuprates hoping to unlock the secret of high temperature superconductivity in such materials [2, 6, 11]. So far, the Tunnel Diode Oscillator (TDO) method and the Proximity Detector Oscillator (PDO) method are the main methods that have been used to perform such measurements. In both methods, the sample of interest is inserted in the inductor of a self-resonating LC circuit where the resonance frequency of the circuit is changing as a function of the sample's resistivity [4, 12, 13,]. When these methods are used in high pulse magnetic fields the measuring circuit parameters need to be protected from the effect of induced voltages in their circuitry during the pulse [14]. The PDO method has more robust parameters than the TDO method making it used widely to study SdH effect in the leading pulse magnetic facilities around the world [8, 13]. However, the use of TDO and the PDO methods to perform contactless conductivity needs to be done by a researcher with special skills in rf circuits. Adding to this, the data obtained by these two methods (TDO and PDO) needs an extra effort to interpret and analyze which makes these methods less attractive to be used regardless of their advantages. As a part of the effort to avoid some of the issues associated to the use of the known rf methods and to make them more user friendly, in 2012 a new method was proposed by Altarawneh to perform contactless conductivity on the topological insulator (Bi_2Si_3) through an rf transmission setup in a simple LC circuit [15]. In that method, the measurement was performed by monitoring the amplitude of a constant frequency rf signal that's sent to a band stop circuit with a sample inserted in the inductor. The used band stop circuit passes all frequencies except those very close or equal to the resonance frequency of the circuit. When a sample is inserted in the inductor of the band stop circuit the value of the absorbed frequency in the circuit depends on the resistivity of the sample that varies with magnetic field and temperature. The transmission setup through the band stop circuit was used firstly because of the simple design of the circuit which makes it less vulnerable to induced voltages in the circuit during the application of pulse magnetic field. However, using a band stop circuit has some drawbacks that stem from the nature of the frequency response of the band stop circuit. Particularly, the amplitude of the recovered signal at the circuit's output is very small since the sent frequency is close to the absorbed frequency value in the circuit. Having the amplitude of the recovered signal small and close to the noise floor will lead to a poor resolution measurement. Moreover, having small amplitude at the output requires more electronics (e.g., amplifiers, mixers and filters) to increase the amplitude to the value at which the measurement become possible. Because of these drawbacks it is crucial to introduce another circuit design with a different frequency response so that instead of having the frequency of interest absorbed in the circuit it will be passed through the circuit. The well-known band pass circuits can be modified to fit our needs and to eliminate the main drawbacks associated to the circuit design in Ref. [15]. Especially drawbacks related to the small amplitude of the rf signal at the output of the measuring circuit.

In this paper after this introduction, the theory of operation of the new circuit design will be presented and a description of the new method, experimental setup for dc magnetic field and

1962 ISSN 1013-5316;CODEN: SINTE 8 Sci.Int.(Lahore),28(2),1961-1966 ,2016

for pulse magnet field will be introduced. Also, we will discuss a simulation of the circuit performance when used for studying the SdH effect for a presumed metallic sample. At the end of this paper, we will present a conclusion in which the advantages of this method will be reviewed.

2. Theory of operation:

In general, band pass circuits can be built in many designs and can have complex circuitry. However, in this work, the design in the following figure (Fig.1) is chosen because of its simplicity [16].

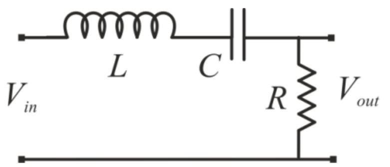

Fig.1: The circuit diagram of a band pass filter circuit, where *L* is the inductance of the coil, *C* is the capacitance, *R* is the resistance, V_{in} and V_{out} are the amplitude of the input and the output of rf signals.

The amplitudes ratio of the rf signals between the output signal and the input signal can be studied by investigating the response function $H(\omega)$ which is given for the circuit in Fig.1 as [16]:

$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{R}{R+j\omega L+1/(j\omega C)} \quad (1)$$

Where $\omega=2\pi f$ and f is the frequency in units of Hz. Eq.1 can be written as the magnitude of $H(f)$ as:

$$|H(f)|=\frac{R}{\left(R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2\right)^{\frac{1}{2}}} \quad (2)$$

The frequency at which the value of $2\pi fL-1/2\pi fC$ is equal to zero is called the resonance frequency which is equal to $f_0=1/(2\pi\sqrt{LC})$ [16]. The magnitude of the response function $H(f)$ for the resonance frequency (f_0) is equal to 1. In this case the signal at this frequency suffers neither reflection nor absorption and it is transmitted as it is to the output with the same amplitude. Other frequencies that are not equal or not close to f_0 in value will not pass to the output of the circuit. When a metallic sample is inserted in the inductor of the circuit the volume at which the rf field is allowed to go thorough inside the coil is reduced by the volume of the sample. At the surface of the sample the rf field penetrates to a depth inside the sample depending on the conductivity (resistivity) of the sample and the frequency of rf field. This depth (δ) is called the skin depth and it is given by the relation:

$$\delta=\sqrt{\frac{\rho}{\pi f\mu}} \quad (3)$$

Where ρ is the resistivity of the sample; μ is the magnetic permeability of the sample and f is the rf field frequency. The reduction of the coil effective volume at which the rf field is allowed to penetrate causes the inductance of the coil to be reduced severely (depending on the volume of the sample and its resistivity) [17]. The resonance frequency of the circuit $f_0=1/(2\pi\sqrt{LC})$ will increase dramatically due to the large reduction of the inductance after inserting the sample ($f_0=1/(2\pi\sqrt{L_sC})$). Fig.2 shows an example of the response function as a function of frequency for an empty coil and for a coil loaded with a presumed sample. Assuming the coil (inductor) in the circuit is a solenoidal coil which its inductance can be given as $L_0=\mu_0 n^2 V_c$. Where n is the number of turns per unit length and V_c is the volume of the coil. Based on the volume the rf field is allowed to go through, the inductance of the coil after inserting the sample (L_s) can be written as:

$$L_s=\mu_0 n^2\left(V_c+V_s\left(\frac{2}{r_s}\sqrt{\frac{\rho}{\mu f\pi}}-1\right)\right) \quad (4)$$

Where V_s is the volume of the sample and r_s is the radius of the sample. From the equation above (Eq.4),

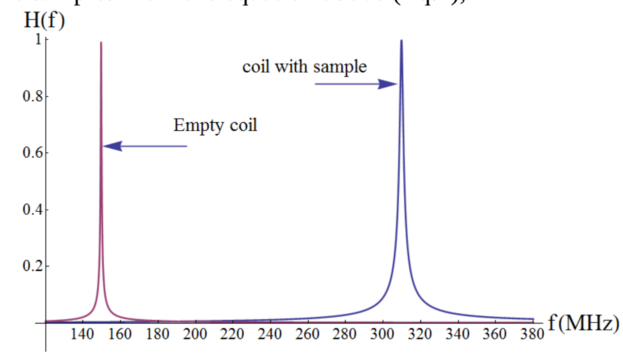

Fig.2: The band pass circuit reponce function $H(f)$ magnitude as a function of frequency for an empty coil and for loaded coil. The values in Eq.2 and Eq.4 were chosen as: $R=0.6\Omega$, $C=5.0$pF, $=1\times10^{-9}\Omega.m$, $r_{coil}=0.75mm$, $r_s=0.70mm$ and $n=$ 20,000 turns $/m$.

when the resistivity of the sample increases or decreases the inductance of the coil will increase or decrease too respectively. The change in the inductance has a direct proportionality to the resonance frequency of the circuit. By monitoring the resonance frequency of the circuit, the resistivity of the sample can be monitored and studied as a function of other variables like temperature or magnetic field.

3. Proposed application in dc magnetic field:

The proposed circuit design in Fig.1 can be used with a Network Analyzer for studying contactless conductivity in a dc magnetic field with high precision. A typical Network Analyzer sends N number of frequencies from port (A) in a chosen range around the resonance frequency of the circuit and recovers them on another port (B) and compares their amplitudes [18]. The resonance frequency then, can be determined as the point where the response function magnitude equals to 1. In dc magnetic field experiments, the applied magnetic field on the sample can be changed gradually. In this case, the Network Analyzer has enough time to find an exact value for the resonance frequency of the circuit that can be used to find the conductivity of the sample. Fig.3 shows the schematic diagram of the experimental setup for measuring the contactless conductivity when the magnetic field is applied. In which the resonance frequency and the transmitted power (at resonance) are measured and collected by a computer along with magnetic field and temperature. A thermometer can be installed close to the sample to measure the sample's temperature. Moreover, a LabVIEW software (National Instruments) can be built to record the resonance frequency of the circuit as collected by the Network Analyzer with magnetic field and temperature in a suitable data file. The advantage of this new approach is that the sensitivity of the measurement is very high since the resonance frequency measured depends on the measurement coil only (not depends on the transmission line and measurement coil as in TDO or PDO methods).

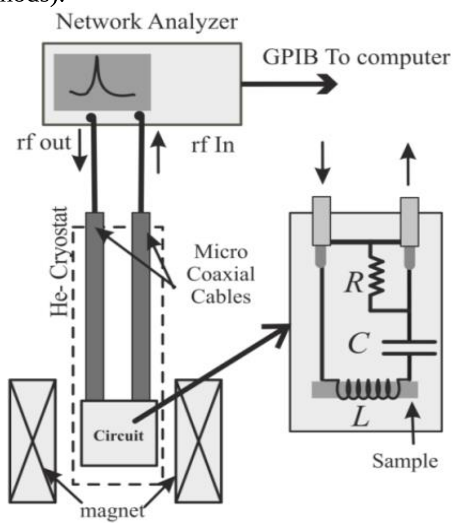

Fig.3: The schematic diagram of the proposed setup for radio frequency transmission through the band pass circuit in dc field magnets and at liquid Helium temperatures.

4. Proposed application in pulse magnetic field:

In pulse magnetic field, the magnetic field applied on the sample is generated by discharging an electric energy stored in a capacitor bank into a well-designed magnet coil to produce a pulse of magnetic field in a time window of (~100 ms or smaller). Due to the relatively long time needed by instruments (~10 ms for a Network Analyzer) to find the resonance frequency of the circuit in Fig.1, another procedure needs to be established to detect changes in the resonance frequency indirectly. In this proposed work, the procedure used in Ref. [15] for a band stop circuit design which has an opposite frequency response can be followed with the new circuit design. In this procedure an rf signal with a fixed amplitude (V_{in}) and fixed frequency (f) that is close to the resonance frequency would be fed to the input of the circuit. The amplitude of the recovered signal at the circuit output (V_{out}) will depend on the frequency difference between the sent frequency (f) and the circuit's resonance frequency (f_0). For example, if the sent frequency is equal to the resonance frequency the signal's amplitude at the output is equal to the amplitude at the input. As the sent frequency (f) into the circuit is increased higher than the resonance frequency (f_0) or decreased lower than the resonance frequency the amplitude (V_{out}) will decrease in both cases. When the resonance frequency of the circuit is changing due to a change in the sample's conductivity, the amplitude of the rf signal flowing in the circuit will change depending on the sample conductivity. Basically, the changes in conductivity can be observed by tracking the changes of the rf amplitude (V_{out}) at the circuit output. The change in the conductivity of a sample could be stimulated by change in temperature or magnetic field. In this case the change in the output amplitude can be recorded as a function of magnetic field and temperature. The following figure (Fig.4) represents the schematic diagram of the proposed experimental setup of rf transmission through the new circuit design.

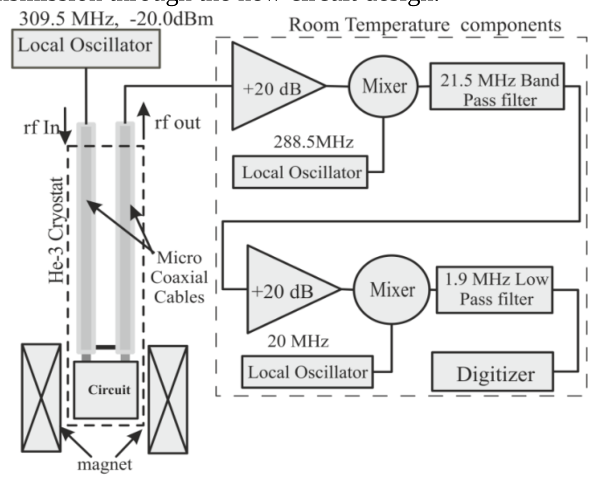

Fig.4: The schematic diagram of the experimental setup for radio frequency signal transmission through the band pass circuit in pulsed magnet and at liquid He4 temperature.

In this work, based on the values we have picked for the circuit elements and for the sample conductivity and geometry, the resonance frequency of the circuit with the sample loaded to the measurement coil is found to be around $309.650\ MHz$. As demonstrated in Fig.4, an rf signal with a frequency of $f = 309.5\ MHz$ would be sent to the circuit at low temperature with an amplitude of (63.2 mV or -20.0 dBm or smaller) and recovered at the output port at the top of probe.

Then the output signal would be amplified, mixed with a smaller frequency and then filtered out twice to get a low enough frequency that can be digitized by a computer card. After going through the steps of amplifying, mixing and filtering the signal will have a clean sinusoidal waveform that can be easily treated mathematically. The final data file would include the magnetic field in units of tesla along with the waveform in units of volts. Simple LabVIEW software can be built to calculate the amplitude and frequency of the waveform as a function of magnetic field [15].

The procedure of processing the output rf signal by amplifying, mixing and filtering and the use of the LabVIEW software is well established for the TDO and PDO setup. With the current circuit design only one stage of amplifying, mixing and filtering would be enough since the output signal in this design would be so clean and has less noise due to the self-filtering nature of the circuit.

5. RESULTS AND DISCUSSIONS (SIMULATION):

To demonstrate the potential application of the new circuit design we use a presumed conductive sample with a cylindrical shape that shows SdH effect as in Fig.5a. The presumed quantum oscillations in resistivity are simulated to

be in the same order and shape ($\sim 10^{-9}\ \Omega.m$) observed in high temperature superconductors (HTS) and other similar systems [19, 20]. Performing a simple simulation using a computational software program (Mathematic), the new proposed circuit described in the previous sections with the same suggested values for the circuit's elements and for the sample's geometry and conductivity we found the following.
Firstly, the operating frequency (f) that is sent to the circuit must be in a region in the spectrum $(H \text{ vs } f)$ where the response is linear over a short range of frequency. Choosing a region with a linear response is important to get the correct shape of the original quantum oscillations without any deformation. For example, using an operating frequency (f) equals to the resonance frequency will not be useful due the non-linearity in the spectrum $(H \text{ vs } f)$. Secondly, the operating frequency (f) must be in a region in the spectrum where (dH/df) is as large as possible to get the highest possible sensitivity. Such regions can be seen clearly in Fig.5-b for frequencies larger and smaller than the resonance frequency where the amplitude of detected oscillations is larger as the magnetic field is increased. The insets c) and d) in Fig.5 show the magnitude of the response function (proportional to quantum oscillations) at the output of the circuit for chosen frequencies less and larger than the resonance frequency $(f_0 \approx 309.65\ MHz)$ respectively. For values less than (f_0) in Fig.5-c we can see the amplitude of oscillations is largest at $f = 309.50\ \ MHz$ and as the frequency is decreased away from the resonance frequency the amplitude is decreasing as for $f = 308.00\ MHz$.

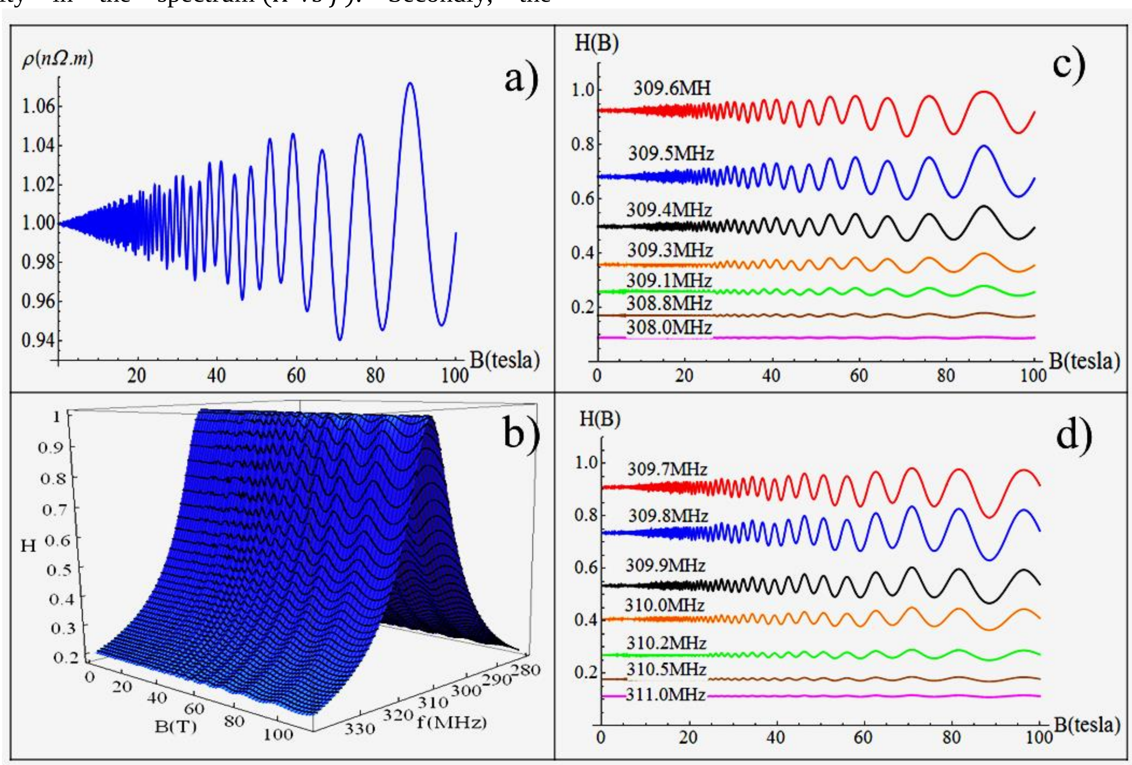

Fig.5: a) A simulation of quantum oscillations in resistivity for (HTS) or similar materials. b) The band pass circuit response function *H* as a function of magnetic field and frequency when a conductive sample showing the SdH effect due to the application of magnetic field. d) and c) the quantum oscillations in the response function magnitude as a function of magnetic field for frequencies less and higher than the resonance frequency respectively.

On the other side of the spectrum for $f > f_0$ as in Fig.5-d, we can see the same behavior where the oscillations amplitude is largest at $f = 309.80\ MHz$ and is decreasing until it becomes very small at $f = 311.00$ MHz. However, the oscillations are out of phase in both sides (as for $f = 309.50\ MHz$ and $309.80 MHz$). In order to get the correct physical behavior of resistivity (as in Fig.5-a) without any kind of mathematical manipulation one must chose the operating frequency to be less than the resonance frequency.

6. CONCLUSION:

For this new method, we can conclude the following: the new modification for the passive band pass circuitry enables the circuit to serve as a probe for measuring conductivity in high magnetic fields. When compared with other methods, the new method has high enough sensitivity to detect quantum oscillations (SdH effect) in dc and in pulse magnetic fields. The new method can eliminate noise better than previous designs since the used circuit allows the operating frequency only to pass. More important, the new method is better than the previous transmission method because the amplitude of the frequency used is much larger than noise floor and introduces less heating for the sample. The new circuit design is more user friendly method when compared to other methods and can provide absolute values for physical quantities with less mathematical manipulation.

7. ACKNOWLEDGEMENTS:

This work is done as a part of the project titled: Development of Radio Frequency Probes for Studying Carbon Nanotubes Based Materials. The author would like to thank the Deanship of Scientific Research at Mutah University for their support and for funding this project.

8. REFERENCES:

[1] B. J. Ramshaw, S. E. Sebastian, R. D. McDonald, James Day, B. S. Tan, Z. Zhu, J. B. Betts, R. Liang, D. A. Bonn, W. N. Hardy, N. Harrison, Science , **348** , 6232 pp. 317-320. (2015).

[2] S. E. Sebastian, N. Harrison, F. F. Balakirev, M. M. Altarawneh, P. A. Goddard, R. Liang, D. A. Bonn, W. N. Hardy, G. G. Lonzarich. Nature, **511**, 61-64. (2014).

[3] E. D. Mun, M. M. Altarawneh, C. H. Mielke, V. S. Zapf, R. Hu, S. L. Budko, and P. C. Canfield, Phys. Rev. B **83**, 100514 (2011).

[4] M. M. Altarawneh, K. Collar, and C. H. Mielke, Determination of anisotropic Hc2 up to 60 T in $Ba_{0.55}K_{0.45}Fe_2As_2$ single crystals. *Phy. Rev.* B, **78**, 220505 (R), (2008).

[5] E. D. Bauer, M. M. Altarawneh, P. H. Tobash, K. Gofryk, J. N. Mitchell, R. D. McDonald, C. H. Mielke, F. Ronning, J. C. Griveau, E. Colineau, R. Eloirdi, R. Caciuffo, B. L. Scott, O. Janka, S. M. Kauzlarich, and J. D. Thompson. J. Phys.: Condens. Matter, **24**, 052206 (2012).

[6] E. A. Yelland, J. Singleton, C. H. Mielke, N. Harrison, F. F. Balakirev, B. Dabrowski, and J. R. Cooper, Phys. Rev. Lett. **100**, 047003 (2008).

[7] M. M. Altarawneh, N. Harrison, R. D. McDonald, F. F. Balakirev, C. H. Mielke, P. H. Tobash, J.-X. Zhu, J. D. Thompson, F. Ronning and E. D. Bauer. *Phy. Rev.* B, **83**, 081103(R), (2010).

[8] S. Ghannadzadeh, M. Coak, I. Franke, P. A. Goddard, J. Singleton and J. L. Manson Rev. Sci. Instrum. **82**, 113902 (2011);

[9] N. W. Ashcroft and N. D. Mermin. Solid State Physics, 1976.

[10] Band Theory and Electronic Properties of Solids, John Singleton 1st Edition.(2001)

[11] S. E. Sebastian, N. Harrison, M.M. Altarawneh, R. Liang, D. A. Bonn W.N. Hardy, G.G. Lonzarich. Nature Communications **2**, 1468 (2011).

[12] C. T. Van Degrift, Rev. Sci. Instrum. **45**, 1171 (1974).

[13] M. M. Altarawneh, C. H. Mielke, and J. S. Brooks. *Rev. Sci. Instrum*, 80, 066104, (2009).

[14] T. Coffey, Z. Bayindir, J. F. DeCarolis, M. Bennet, G. Esper, and C. C.Agosta, *Rev. Sci. Instrum.* **71**, 4600 (2000).

[15] M. M. Altarawneh. *Rev. Sci. Instrum.* **83**, 9, 096102 (2012)

[16] Principles and Applications of Electrical Engineering, Giorgio Rizzoni, McGraw-Hill 5th edition, 2007.

[17] E. Ohmichi,E.Komatsu and T.Osada. *Rev. Sci. Instrum.*, **75**:2094, 2004.

[18] Network Analyzer Basics, Keysight Technologies, Published in USA, July 31, 2014.

[19] G. Grissonnanche, F. Laliberté, S. Dufour-Beauséjour, M. Matusiak, S. Badoux, F. F. Tafti, B. Michon1, A. Riopel, O. Cyr-Choinière, J. C. Baglo, B. J. Ramshaw, R. Liang, D. A. Bonn, W. N. Hardy, S. Krämer, D. LeBoeuf, D. Graf, N. Doiron-Leyraud and L. Taillefer. Arxiv 2015.

[20] S. E. Sebastian, N. Harrison, R. Liang, D. A. Bonn, W. N. Hardy, C. H. Mielke, and G. G. Lonzarich. Phys. Rev. Lett. **108**, 196403 (2012).