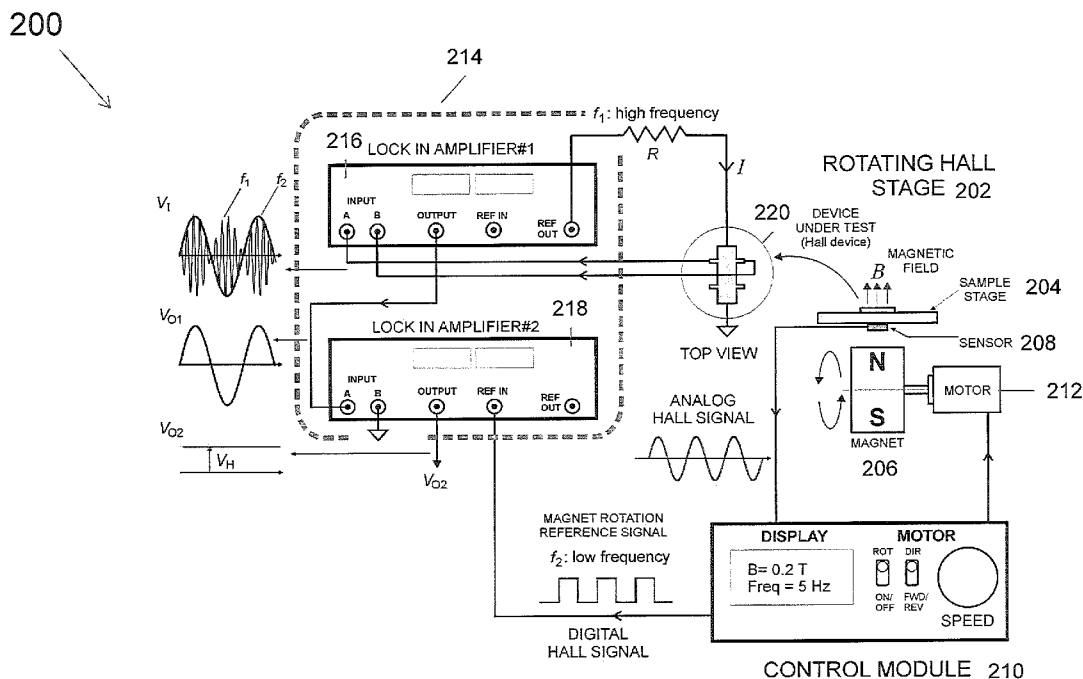




US 20140028305A1

(19) **United States**(12) **Patent Application Publication**
Gokmen et al.(10) **Pub. No.: US 2014/0028305 A1**(43) **Pub. Date: Jan. 30, 2014**(54) **HALL MEASUREMENT SYSTEM WITH
ROTARY MAGNET**(52) **U.S. CL.**
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(US)(57) **ABSTRACT**(73) Assignee: **INTERNATIONAL BUSINESS
MACHINES CORPORATION**,
Armonk, NY (US)(21) Appl. No.: **13/560,404**(22) Filed: **Jul. 27, 2012****Publication Classification**(51) **Int. Cl.**
G01R 33/07 (2006.01)

One or more embodiments are directed to a motor configured to rotate at least one magnet at a first frequency, a sensor configured to generate a reference signal of the at least one magnet's rotation, and a lock-in detection system configured to receive the reference signal, supply an excitation current at a second frequency to a device under test, measure a voltage from the device under test and demodulate the second frequency, and demodulate the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.



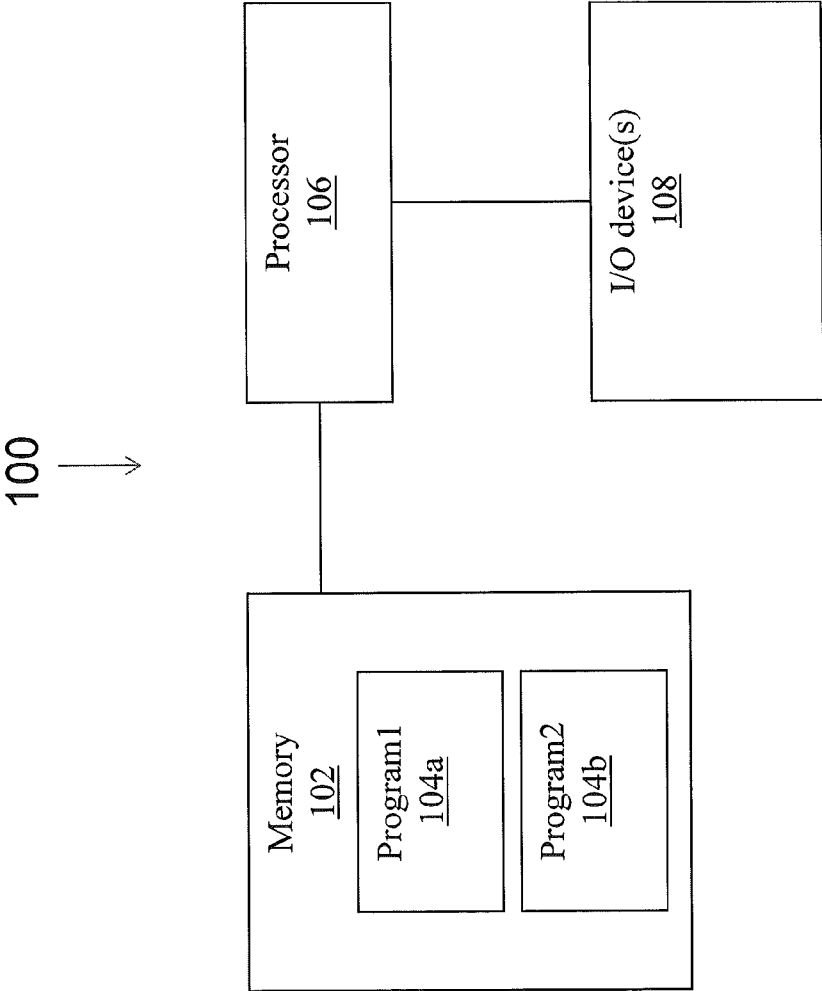


FIG. 1

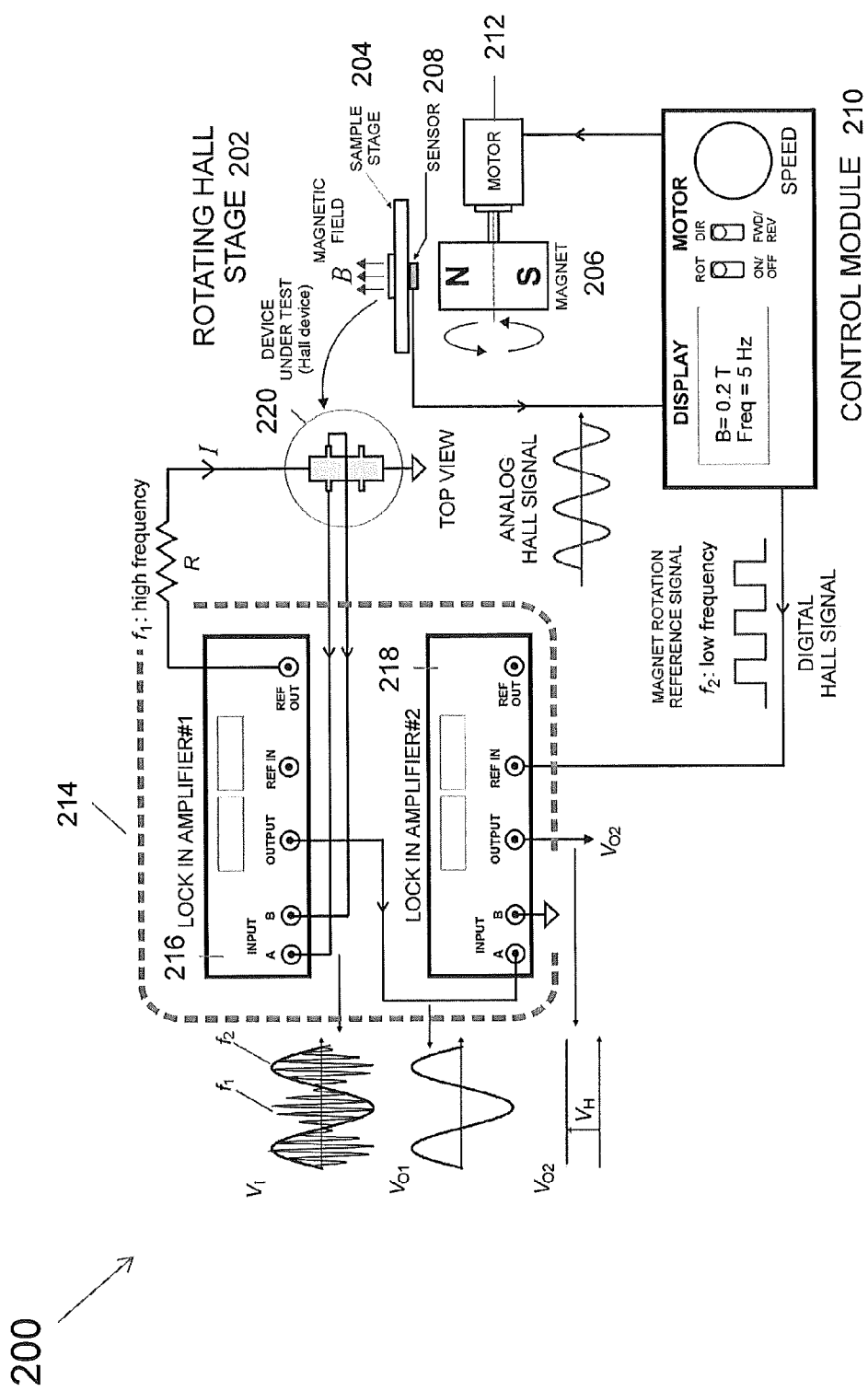


FIG. 2

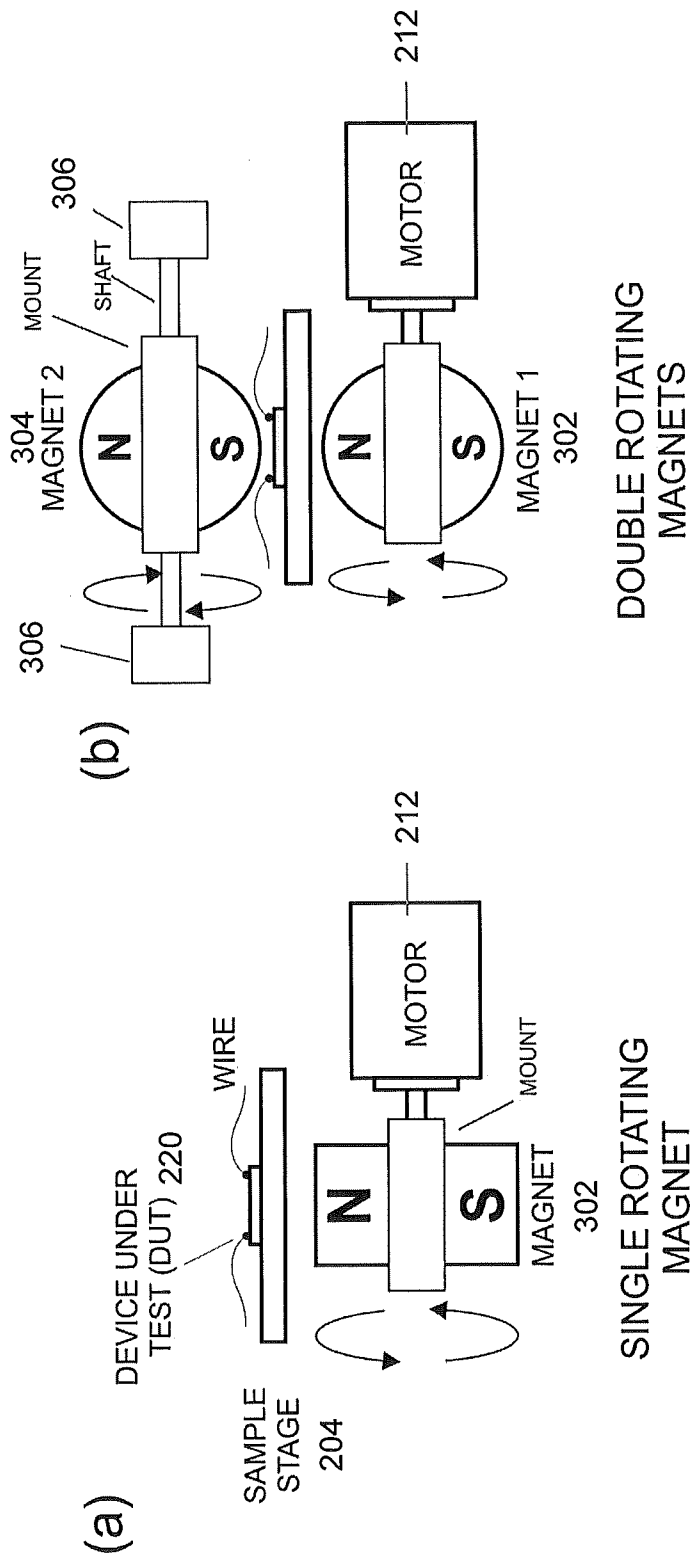


FIG. 3

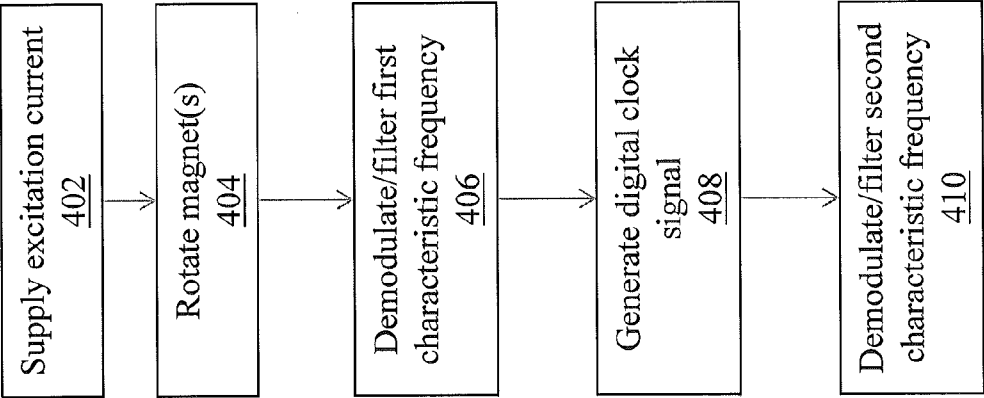


FIG. 4

HALL MEASUREMENT SYSTEM WITH ROTARY MAGNET

FIELD OF INVENTION

[0001] The present disclosure relates generally to measurement techniques, and more specifically, to a Hall measurement system with a rotary magnet.

DESCRIPTION OF RELATED ART

[0002] Hall measurement is a characterization technique that may be used in a variety of applications, such as semiconductor and solid state device research. Hall measurement enables measurement of a free carrier density, which may yield carrier mobility when considered together with a resistivity measurement. The so-called Hall effect occurs when a current is passed through a material with an applied perpendicular magnetic field, such that a Hall voltage V_H is generated, as provided in equation #1 as follows:

$$V_H = BI/nde \quad \text{Eq. \#1}$$

[0003] In equation #1 above, B is the magnetic field, I is the electric current, n is the free carrier density, d is the material thickness, and e is the charge of an electron.

[0004] A figure of merit in the Hall measurement is the Hall angle ϕ , whose tangent is defined as the ratio between the Hall or transverse resistance (R_{xy}) and the longitudinal resistance (R_{xx}). The tangent of this Hall angle, in the case of a square sample, may be given by equation #2 as follows:

$$\tan \phi = R_{xy}/R_{xx} = B\mu \quad \text{Eq. \#2}$$

[0005] In equation #2 above, μ is the mobility of the majority carrier.

[0006] A good or quality Hall measurement requires a sufficiently large Hall angle or $\tan \phi$ on the order of unity. Based on equation #2, a problem may arise when a sample has poor mobility (e.g., $\mu < 1 \text{ cm}^2/\text{Vs}$) or the magnetic field that is available is limited (e.g., $B < 0.1 \text{ Tesla}$). Furthermore, based on equation #1, samples with a very high carrier density n may also cause a small Hall voltage V_H . Some measurement environments, such as low temperature measurement, dictate the use of a very small excitation current I, thus resulting in a small Hall voltage V_H . In such situations, a DC magnetic field Hall measurement may yield a small Hall voltage V_H buried within a large DC voltage offset due to sample geometrical asymmetry. The asymmetry may cause a mixing of the Hall or transverse resistance (R_{xy}) and the longitudinal resistance (R_{xx}).

BRIEF SUMMARY

[0007] According to one or more embodiments of the present disclosure, a system comprises a motor configured to rotate at least one magnet at a first frequency, a sensor configured to generate a reference signal of the at least one magnet's rotation, and a lock-in detection system configured to receive the reference signal, supply an excitation current at a second frequency to a device under test, measure a voltage from the device under test and demodulate the second frequency, and demodulate the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.

[0008] According to one or more embodiments of the present disclosure, an apparatus comprises at least one processor, and memory having instructions stored thereon that,

when executed by the at least one processor, cause the apparatus to receive a reference signal associated with at least one permanent magnet's rotation at a first frequency, supply an excitation current at a second frequency to a device under test, cause a voltage from the device under test to be measured, demodulate the second frequency from the measured voltage, and demodulate the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.

[0009] According to one or more embodiments of the present disclosure, a system comprises a control module configured to control a speed and direction of a motor coupled to a magnet, a sample stage configured to apply a magnetic field associated with the magnet to a device under test and obtain an analog Hall signal, and a lock-in detection system configured to obtain a DC Hall voltage from the analog Hall signal based at least in part on a demodulation or filtration of frequency characteristics associated with an excitation current and the applied magnetic field.

[0010] According to one or more embodiments of the present disclosure, a method comprises generating a reference signal associated with at least one magnet's rotation at a first frequency, supplying an excitation current at a second frequency to a device under test, causing a voltage from the device under test to be measured, demodulating the second frequency from the measured voltage, and demodulating the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.

[0011] Additional features and advantages are realized through the techniques of the present disclosure. Other embodiments and aspects of the disclosure are described in detail herein. For a better understanding of the disclosure with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0012] The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features and advantages of the disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0013] FIG. 1 is a schematic block diagram illustrating an exemplary computing system in accordance with one or more aspects of this disclosure.

[0014] FIG. 2 is a schematic block diagram illustrating an exemplary system architecture in accordance with one or more aspects of this disclosure.

[0015] FIG. 3 is a diagram illustrating exemplary rotatable magnet configurations in accordance with one or more aspects of this disclosure.

[0016] FIG. 4 is a flow diagram illustrating an exemplary method in accordance with one or more aspects of this disclosure.

DETAILED DESCRIPTION

[0017] In accordance with various aspects of the disclosure, a highly sensitive Hall effect measurement system employing a rotary magnet system and a super lock-in detection scheme is described. A Hall measurement may be conducted using one or more small permanent magnets, potentially reducing a

setup footprint. In contrast, a similar traditional Hall measurement may employ a bulky electromagnetic coil system requiring a large power supply and a water cooling system. Embodiments of the disclosure may measure materials with a very small Hall signal due to very high doping density or very poor mobility and can be implemented in a very tight or limited space, such as inside a cryostat.

[0018] It is noted that various connections are set forth between elements in the following description and in the drawings (the contents of which are included in this disclosure by way of reference). It is noted that these connections in general and, unless specified otherwise, may be direct or indirect and that this specification is not intended to be limiting in this respect. In this regard, a coupling of entities may refer to either a direct or an indirect connection.

[0019] Referring to FIG. 1, an exemplary computing system 100 is shown. The system 100 is shown as including a memory 102. The memory 102 may store executable instructions. The executable instructions may be stored or organized in any manner and at any level of abstraction, such as in connection with one or more processes, routines, methods, etc. As an example, at least a portion of the instructions are shown in FIG. 1 as being associated with a first program 104a and a second program 104b.

[0020] The instructions stored in the memory 102 may be executed by one or more processors, such as a processor 106. The processor 106 may be coupled to one or more input/output (I/O) devices 108. In some embodiments, the I/O device(s) 108 may include one or more of a keyboard, a touchscreen, a display screen, a microphone, a speaker, a mouse, a button, a remote control, a joystick, a printer, etc. The I/O device(s) 108 may be configured to provide an interface to allow a user to interact with the system 100.

[0021] The system 100 is illustrative. In some embodiments, one or more of the entities may be optional. In some embodiments, additional entities not shown may be included. For example, in some embodiments the system 100 may be associated with one or more networks, which may be communicatively coupled to one another via one or more switches, routers, or the like. In some embodiments, the entities may be arranged or organized in a manner different from what is shown in FIG. 1. One or more of the entities shown in FIG. 1 may be associated with one or more of the devices or entities described herein.

[0022] FIG. 2 illustrates a system architecture 200 that may be used to illustrate a rotary Hall measurement system. In some embodiments, the architecture 200 may be operative in connection with one or more devices or entities, such as the devices and entities described above in connection with the system 100 of FIG. 1.

[0023] The architecture 200 may include a rotating Hall stage 202. The rotating Hall stage 202 may include a sample stage 204, a magnet 206, and a sensor 208 (e.g., a Hall sensor or an optical sensor).

[0024] The architecture 200 may include a control module 210. The control module 210 may be configured to control the speed and/or direction of one or more motors, such as a motor 212. The control module 210 may be configured to provide a magnetic field (B) and/or rotation frequency read-out. The control module 210 may be configured to produce or generate a digital Hall or clock signal from an analog Hall signal.

[0025] The architecture 200 may include a lock-in detection system 214. The lock-in detection system 214 may include one or more lock-in amplifiers, such as amplifiers 216 and 218.

[0026] The architecture 200 may utilize a “super lock-in” detection scheme to enable detection of a very small Hall voltage, potentially removing a DC offset in the process. A principle of operation of the architecture 200 is described below.

[0027] The amplifier 216 may supply via a reference output an AC excitation current (I) to a device under test 220. The excitation current may take the form of a sinusoid, such as $I = I_0 \cos \omega_1 t$, where I_0 may be the amplitude of the excitation current I and $\omega_1 = 2\pi f_1$. f_1 may be a relatively high frequency (e.g., approximately 100 Hz or higher). The application of the excitation current I and magnetic field B may generate an AC Hall voltage. The current I can be produced from the voltage reference output (REF OUT) of the lock in amplifier and a shunt resistor R.

[0028] Concurrent with the application of the excitation current I to the device under test 220, the magnet 206 may be made to rotate at a frequency f_2 . f_2 may be a relatively low frequency, such as approximately 1 Hz to 10 Hz. The rotation of the magnet 206 may cause an oscillation in the Hall voltage following equation #1, as provided in equation #3 as follows:

$$V_I \sim (I_0 \cos \omega_1 t) \times (B_0 \cos \omega_2 t) \quad \text{Eq. \#3}$$

[0029] The symbol ‘~’ means “proportional to”, $\omega_2 = 2\pi f_2$ and B_0 represents the magnitude or amplitude of the magnetic field associated with the magnet 206. The signal V_I may be provided to the ‘A’ and ‘B’ inputs of the amplifier 216. The signal V_I may include two frequency components corresponding to frequencies f_1 and f_2 .

[0030] The amplifier 216 may operate at a time constant τ_1 such that the amplifier 216 may demodulate the frequency f_1 . In other words, the amplifier 216 may filter out the frequency f_1 and pass through the frequency f_2 with respect to the input signal V_I . Following the filtration performed by the amplifier 216, the output of the amplifier 216 may correspond to a signal V_{O1} of the form given by equation #4 as follows:

$$V_{O1} \sim I_0 B_0 \cos \omega_2 t \quad \text{Eq. \#4}$$

[0031] The signal V_{O1} may be provided from the output of the amplifier 216 and may be provided to an input (e.g., the ‘A’ input) of the amplifier 218. A second input (e.g., the ‘B’ input) of the amplifier 218 may be coupled to a reference, such as ground.

[0032] The sensor 208 may be placed underneath the magnet 206 and may be associated with the sample stage 204. The sensor 208 may generate or produce an analog Hall signal, which may be provided to the control module 210. The control module 210 may generate a digital clock signal with a frequency f_2 based on the analog Hall signal. The clock signal may be provided to a reference input of the amplifier 218.

[0033] The amplifier 218 may lock-in to f_2 using a large time constant τ_2 to demodulate frequency f_2 or filter off the oscillation associated with signal V_{O1} . The output of the amplifier, denoted as a signal V_{O2} , may take the form given by equation #5 as follows:

$$V_{O2} \sim V_H \sim I_0 \times B_0 \quad \text{Eq. \#5}$$

[0034] Thus, as provided in equation #5, the Hall voltage may be proportional to the product of the magnitude of the excitation current and the magnitude of the magnetic field.

[0035] In some embodiments, the lock-in detection system 214 may include one or more computers and/or voltmeters. For example, in some embodiments, one or more both of the amplifiers 216 and 218 might not be used. The computers and/or voltmeters may be configured to perform software lock-in detection. Such replacement may be particularly effective with respect to the amplifier 218, because the frequency f_2 may be relatively small and the signal associated with f_2 may be captured by the voltmeter and the computer.

[0036] FIG. 3 illustrates exemplary configurations in connection with the magnet 206. In the first configuration labeled (a) in FIG. 3, a single magnet 302 (which may correspond to the magnet 206 in some embodiments) may be mounted to the motor 212. The magnet 302 may be a cylindrical magnet. A cylindrical magnet may provide a relatively uniform magnetic field, at the potential expense of having to observe a minimum clearance between the cylindrical magnet and the sample stage 204. The magnet 302 may be a spherical magnet. A spherical magnet may allow the magnet 302 to get closer to the sample, albeit at the potential expense of degraded uniformity relative to a cylindrical magnet.

[0037] In the second configuration (labeled (b)) in FIG. 3, a second magnet 304 may be used in addition to the magnet 302. Two magnets (e.g., magnets 302 and 304) may be used in the second configuration to increase the strength of the magnetic field on the sample relative to the first configuration. One or both of the magnets 302 and 304 may be a spherical magnet. As before, the magnet 302 may be mounted to the motor 212 such that the magnet 302 may rotate based on a drive supplied by the motor 212. The magnet 304 may be mounted on bearings and rotate (e.g., freely rotate) following the magnet 302. The second configuration may provide a magnetic field that may be more uniformly oriented in a vertical direction relative to the first configuration.

[0038] In some embodiments, the motor 212 may include a DC motor or a stepper motor. The magnets 206, 302, and/or 304 may be of any shape, such as primarily cylindrical or spherical.

[0039] FIG. 4 is a flow diagram illustrating an exemplary method in accordance with one or more aspects of this disclosure. The method may be operative in connection with one or more devices, entities, systems, or architectures, such as those described herein. In some embodiments, the method may be used to calculate a Hall voltage associated with a sample or device under test (e.g., the device under test 220).

[0040] In block 402, an excitation current may be supplied to the device under test. The excitation current may generate a voltage, such as an AC Hall voltage with a first characteristic frequency.

[0041] In block 404, one or more magnets may be rotated, generating a magnetic field at a second characteristic frequency. The magnet(s) may be rotated responsive to being driven by a motor. The speed of the motor may be controlled via a control module.

[0042] In block 406, the first characteristic frequency may be demodulated or filtered from a signal comprising the first and second characteristic frequencies. As such, a first output signal may be obtained only containing the second characteristic frequency.

[0043] In block 408, a digital clock signal may be generated based on an analog signal (e.g., an analog Hall signal). The digital clock signal may serve as a reference signal. The digital clock signal may have, or be associated with, the second characteristic frequency.

[0044] In block 410, the first output signal of block 406 may be demodulated or filtered, potentially based on the digital clock signal, such that the second characteristic frequency may be demodulated. A second output signal may be obtained that is indicative of a DC Hall voltage. The second output signal may be proportional to the product of the amplitude of the excitation current and the amplitude of the magnetic field. The second output signal and/or the DC Hall voltage may be output to one or more devices or in one or more formats. For example, the output may take the form of an analog or digital signal, a text message, an email, a voice message, a displayed graphic, etc.

[0045] It will be appreciated that the events of the method of FIG. 4 are illustrative in nature. In some embodiments, one or more of the operations or events (or a portion thereof) may be optional. In some embodiments, one or more additional operations not shown may be included. In some embodiments, the operations may execute in an order or sequence different from what is shown in FIG. 4. For example, the excitation current of block 402 may be applied concurrently with the rotation of the magnet(s) of block 404.

[0046] Embodiments of the disclosure are directed to a high sensitivity Hall measurement system employing a rotary (or AC) Hall setup that provides for a detection of a very small Hall voltage. Such an AC Hall system may remove any DC offset due to any geometrical asymmetry in the Hall sample or background magnetic field.

[0047] In some embodiments, a “super lock-in” configuration may be provided with two lock-in-amplifiers (LIA) run in tandem. A first LIA may be configured to provide a current excitation to the sample at a high frequency (e.g., $f_1 > 100$ Hz) and demodulate it. A second LIA may be configured to detect a Hall voltage oscillation due to one or more rotating magnets operative at a low frequency (e.g., f_2 approximately 1-10 Hz). In some embodiments, rotating permanent magnet(s) may be used.

[0048] In some embodiments, an AC magnetic field may be generated by one or more permanent magnetics, as opposed to electromagnetic coils. In some embodiments, one or more neodymium iron boron (NIB) magnets may be used. The magnetic field produced by a NIB permanent magnet is typically much higher than the magnetic field produced by an electromagnetic coil of the same size. In other words, for the same amount of magnetic field the space required is much smaller using an NIB permanent magnet relative to an electromagnetic coil. For example, the magnetic field produced near the surface of an NIB permanent magnet (2.5 cm×2.5 cm×2.5 cm in size) may be approximately 0.5 Tesla (or 5000 Gauss). If using a standard electromagnetic coil in Helmholtz configuration (two coils sandwiching the sample) the coil setup required to obtain the same strength magnetic field is typically very big, e.g., about 50 cm×50 cm×50 cm.

[0049] In addition to space savings, use of a permanent magnet does not require a large power supply, water cooling system and large frame assembly. Operating an electromagnetic coil in AC mode requires a different and more expensive power supply, while a permanent magnet can be rotated using a simple motor.

[0050] In some embodiments, various functions or acts may take place at a given location and/or in connection with the operation of one or more apparatuses or systems. In some embodiments, a portion of a given function or act may be

performed at a first device or location, and the remainder of the function or act may be performed at one or more additional devices or locations.

[0051] As will be appreciated by one skilled in the art, aspects of this disclosure may be embodied as a system, method or computer program product. Accordingly, aspects of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” or “system.” Furthermore, aspects of the disclosure may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon.

[0052] Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific example (a non-exhaustive list) of the computer readable storage medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

[0053] A computer readable signal medium may include a propagated data signal with computer readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A computer readable signal medium may be any computer readable medium that is not a computer readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

[0054] Program code embodied on a computer readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0055] Computer program code for carrying out operations for aspects of the present disclosure may be written in any combination of one or more programming language, including an object oriented programming language such as Matlab, Java, Smalltalk, C++ or the like and conventional procedural programming language, such as the “C” programming language or similar programming languages. The program code may execute entirely on the user’s computer, partly on the user’s computer, as a stand-alone software package, partly on the user’s computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user’s computer through any type of network, including a local area

network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0056] Embodiments of the disclosure may be tied to particular machines. For example, in some embodiments a Hall voltage (e.g., a DC Hall voltage) may be obtained from a device under test. The Hall voltage may be obtained based on filtering out frequency components associated with an applied excitation current and magnetic field. One or more amplifiers, computers, magnets, and/or control modules may be used to generate the excitation current and magnetic field and to perform the filtration.

[0057] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, element components, and/or groups thereof.

[0058] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present disclosure has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the disclosure. The embodiments were chosen and described in order to best explain the principles of the disclosure and the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

[0059] The diagrams depicted herein are illustrative. There may be many variations to the diagram or the steps (or operations) described therein without departing from the spirit of the disclosure. For instance, the steps may be performed in a differing order or steps may be added, deleted or modified. All of these variations are considered a part of the disclosure.

[0060] It will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow.

What is claimed is:

1. A system comprising:

a motor configured to rotate at least one magnet at a first frequency;

a sensor configured to generate a reference signal of the at least one magnet’s rotation; and

a lock-in detection system configured to:

receive the reference signal,

supply an excitation current at a second frequency to a device under test,

measure a voltage from the device under test and demodulate the second frequency, and

demodulate the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.

2. The system of claim 1, further comprising:
a control module configured to control a speed of the motor.
3. The system of claim 1, wherein the reference signal comprises a digital signal, the system further comprising:
a control module configured to read a Hall signal associated with the at least one magnet's rotation and generate the digital signal based on the read Hall signal.
4. The system of claim 1, wherein the motor comprises a stepper motor.
5. The system of claim 1, wherein the motor comprises a DC motor.
6. The system of claim 1, wherein the sensor comprises at least one of a Hall sensor and an optical sensor.
7. The system of claim 1, wherein the first frequency is less than the second frequency.
8. The system of claim 1, wherein the lock-in detection system comprises an amplifier configured to supply the excitation current to the device under test and measure the voltage from the device under test and demodulate the second frequency.
9. The system of claim 8, wherein the lock-in detection system comprises a second amplifier configured to demodulate the first frequency from the measured voltage using the reference signal to obtain the Hall voltage associated with the device under test.
10. The system of claim 8, wherein the lock-in detection system comprises a computer configured to demodulate the first frequency from the measured voltage using the reference signal to obtain the Hall voltage associated with the device under test.
11. The system of claim 1, wherein the at least one magnet comprises at least a first magnet and a second magnet, and wherein the first magnet is configured to be rotated by a drive supplied by the motor, and wherein the second magnet is configured to rotate on bearings following the rotation of the first magnet.
12. The system of claim 1, wherein the at least one magnet comprises a permanent magnet.
13. The system of claim 1, wherein the at least one magnet comprises a neodymium iron boron (NIB) magnet.
14. An apparatus comprising:
at least one processor; and
memory having instructions stored thereon that, when executed by the at least one processor, cause the apparatus to:
receive a reference signal associated with at least one permanent magnet's rotation at a first frequency,
supply an excitation current at a second frequency to a device under test, cause a voltage from the device under test to be measured,
demodulate the second frequency from the measured voltage, and
demodulate the first frequency from the measured voltage using the reference signal to obtain a Hall voltage associated with the device under test.
15. The apparatus of claim 14, wherein the instructions, when executed by the at least one processor, cause the apparatus to:
receive the reference signal as a digital clock signal at the first frequency.
16. The apparatus of claim 14, wherein the instructions, when executed by the at least one processor, cause the apparatus to:
obtain the Hall voltage as a signal that is proportional to a product of an amplitude of the excitation current and an amplitude of a magnetic field associated with the at least one permanent magnet.
17. The apparatus of claim 14, further comprising:
a voltmeter configured to measure the voltage from the device under test.
18. A system comprising:
a control module configured to control a speed and direction of a motor coupled to a magnet;
a sample stage configured to apply a magnetic field associated with the magnet to a device under test and obtain an analog Hall signal; and
a lock-in detection system configured to obtain a DC Hall voltage from the analog Hall signal based at least in part on a demodulation or filtration of frequency characteristics associated with an excitation current and the applied magnetic field.
19. The system of claim 18, wherein the lock-in detection system is further configured to obtain the DC Hall voltage from the analog Hall signal based at least in part on a digital signal representation of the analog Hall signal generated by the control module.
20. The system of claim 18, wherein the lock-in detection system is configured to generate and provide the excitation current to the device under test.

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