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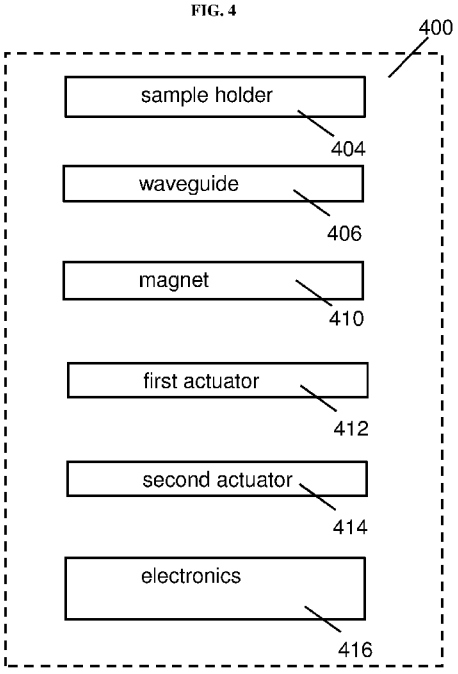
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(54) Title: SYSTEM FOR AND METHOD OF DETERMINING FERROMAGNETIC RESONANCE RESPONSE OF SAMPLE, METHOD OF FORMIMG THE SYSTEM

FIG. 4



(57) Abstract: Various embodiments may relate to a system for determining a ferromagnetic resonance response of a sample. The system may include a sample holder configured to hold the sample. The system may also include a waveguide configured to direct a microwave to within a predetermined distance from the sample. The system may further include a magnet configured to apply a magnetic field to the sample. The system may additionally include a first actuator configured to rotate the sample within a first plane. The system may also include a second actuator configured to rotate the sample within a second plane different from the first plane. The system may further include a detector configured to detect or determine the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

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SYSTEM FOR AND METHOD OF DETERMINING FERROMAGNETIC RESONANCE RESPONSE OF SAMPLE, METHOD OF FORMIMG THE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10201608509W filed October 11, 2016, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to a system for determining a ferromagnetic resonance response of a sample. Various aspects of this disclosure relate to a method of forming a system for determining a ferromagnetic resonance response of a sample. Various aspects of this disclosure relate to a method of determining a ferromagnetic resonance response of a sample.

BACKGROUND

[0003] Applications of ferromagnetic resonance (FMR) may include study of magnetic anisotropy in various materials (which may be important for material development), study of magnetic damping (which may be crucial for magnetic random access memory (MRAM) and other high frequency devices), and fundamental research

[0004] While commercially available cavity-based systems, such as electron paramagnetic resonance (EPR) systems or electron spin resonance (ESR) systems have high signal-to-noise (SNR) ratio and high sensitivity, they can only work at single frequency. As such, they may not be suitable to characterize material over a range of frequencies. In addition, they may not be ideal for damping measurements, as accurate damping-related data would need to be obtained over multiple frequencies.

[0005] On the other hand, broadband ferromagnetic resonance (FMR) based on coplanar waveguides (CPW) may work at multiple frequencies (up to a maximum of about 100 GHz), and may be better suited for damping measurements. However, this technology has only been developed for 10 years and development work is still mainly done in research labs. In response to increasing needs (e.g. labs in Singapore have built more than 5 CPW based FMR systems in the past two years), NanOSc has commercialized the first broadband FMR

instrument at around 2015. FIG. 1A shows a schematic of the commercial system. FIG. 1B shows a circuit related to the commercial system.

SUMMARY

[0006] Various embodiments may relate to a system for determining a ferromagnetic resonance response of a sample. The system may include a sample holder configured to hold the sample. The system may also include a waveguide configured to direct a microwave to within a predetermined distance from the sample. The system may further include a magnet configured to apply a magnetic field to the sample. The system may additionally include a first actuator configured to rotate the sample within a first plane. The system may also include a second actuator configured to rotate the sample within a second plane different from the first plane. The system may further include a detector configured to detect or determine the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

[0007] Various embodiments may relate to a method of forming a system for determining a ferromagnetic resonance response of a sample. The method may include providing a sample holder configured to hold the sample. The method may also include providing a waveguide configured to direct a microwave to within a predetermined distance from the sample. The method may further include providing a magnet configured to apply a magnetic field to the sample. The method may also include providing a first actuator configured to rotate the sample within a first plane. The method may additionally include providing a second actuator configured to rotate the sample within a second plane different from the first plane. The method may also include providing a detector configured to detect the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

[0008] Various embodiments may relate to a method of determining a ferromagnetic resonance response of a sample. The method may include holding the sample using the sample holder. The method may also include directing a microwave to within a predetermined distance from the sample. The method may additionally include applying a magnetic field to the sample to cause magnetization using a magnet. The method may also include rotating the sample with a first plane using the first actuator. The method may further include rotating the sample with a second plane different from the first plane using the second

actuator. The method may additionally include detecting the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1A shows a schematic of the commercial system.

FIG. 1B shows a circuit related to the commercial system.

FIG. 2A illustrates the relative orientations of an applied magnetic field (H) and the equilibrium magnetization (M) of the applied magnetic field. The radio frequency wave has a magnetic component (h_{rf}) perpendicular to the plane formed by H and M in order to generate the ferromagnetic resonance response for various orientations of M.

FIG. 2B illustrates the relative orientations of another applied magnetic field, magnetization and the radio frequency magnetic field component (h_{rf}). The orientation of h_{rf} is perpendicular to H in order to generate the ferromagnetic resonance response for various orientations of M.

FIG. 3A shows that a ferromagnetic resonance response may be generated when an applied magnetic field (H_{dc}) is applied orthogonally to the magnetic field of a radio frequency wave (h_{rf}).

FIG. 3B shows that no ferromagnetic resonance response may be generated when an applied magnetic field (H_{dc}) is applied in parallel to the magnetic field of a radio frequency wave (h_{rf}).

FIG. 3C shows out-of-plane rotation wherein the applied magnetic field (H_{dc}) is applied in a plane different from the plane of the surface of the sample according to various embodiments.

FIG. 3D shows how out-of-plane rotation shown in FIG. 3C may be achieved according to various embodiments.

FIG. 3E shows a conventional arrangement including a waveguide and a sample arranged over the waveguide.

FIG. 4 is a general illustration of a system for determining a ferromagnetic resonance response of a sample according to various embodiments.

FIG. 5A shows one implementation of a system for determining a ferromagnetic resonance response of a sample according to various embodiments.

FIG. 5B shows a photograph of the system shown in FIG. 5A according to various embodiments.

FIG. 5C illustrates the operation of rotating or tilting the sample within the second plane according to various embodiments.

FIG. 5D shows a ferromagnetic resonance (FMR) probe sub-system or arm according to various embodiments.

FIG. 5E shows a magnified view of the probe head according to various embodiments.

FIG. 5F shows (left) the front view of the mounting manipulator and (right) a perspective view of the mounting manipulator according to various embodiments.

FIG. 5G shows illustrates the operation of rotating the sample within the first plane according to various embodiments.

FIG. 6A shows a plot of amplitude of transmission (S_{21} coefficient) (in arbitrary units or a.u.) as a function of magnetic field (in oersteds or Oe) showing the ferromagnetic resonance (FMR) spectrum in different magnetic fields at selected azimuthal angles according to various embodiments.

FIG. 6B shows a polar plot showing the ferromagnetic resonance signal at different azimuthal angles between 0 and 360 degrees (inclusive) according to various embodiments.

FIG. 6C shows a plot of magnetic field (in oersteds or Oe) at resonance as a function of out-of-plane (OP) angle (in degrees) showing the ferromagnetic resonance out-of-plane rotation results at 10 GHz of a sample according to various embodiments.

FIG. 7A is a plot of magnetic field at resonance H_{res} (in kilo-oersteds or kOe) as a function of polar angle θ_H (degrees) showing the ferromagnetic resonance (FMR) peak obtained according to various embodiments fitted to theoretical Smith-Beljers equation.

FIG. 7B is a plot of magnetic field H_{res} (in kilo-oersteds or kOe) / lande g factor as a function of frequency (in gigahertz or GHz) showing the effective saturation magnetization and lande g factor from the fits provided in FIG. 7A according to various embodiments.

FIG. 8A is a plot of magnetic field H_{res} (in oersteds or Oe) as a function of azimuthal angles ϕ_H (in degrees) showing the ferromagnetic resonance field with in plane rotation of a sample at 15 GHz according to various embodiments.

FIG. 8B is a plot of effective magnetization $4\pi M_{eff}$ (in gauss or G) / magnetic field H (in oersteds or Oe) as a function of frequency (in gigahertz or GHz) showing variation of magnetization / magnetic field with frequency according to various embodiments.

FIG. 9A is a plot of resonance linewidth (full width at half maximum, in oersteds or Oe) as a function of azimuthal angle ϕ_H (in degrees) showing magnetic damping measurements of a sample according to various embodiments.

FIG. 9B is a plot of resonance linewidth (in oersteds or Oe) as a function of frequency (in gigahertz or gHz) at various azimuthal angle ϕ_H (in degrees) showing variation of ferromagnetic resonance linewidth with frequency for selected in plane orientations according to various embodiments.

FIG. 9C is a plot of damping α as a function of azimuthal angle ϕ_H (in degrees) based on data shown in FIG. 9B according to various embodiments.

FIG. 10A shows a polar plot showing the in-plane ferromagnetic resonance signal at different azimuthal angles between 0 and 180 degrees (inclusive) of another sample according to various embodiments.

FIG. 10B is a plot of magnetic field H_{res} (in oersteds or Oe) as a function of azimuthal angles ϕ_H (in degrees) showing the ferromagnetic resonance field with in plane rotation of the other sample at 15 GHz according to various embodiments.

FIG. 11 is a plot of resonance linewidth (full width at half maximum, in oersteds or Oe) as a function of frequency (in gigahetz or gHz) showing variation of ferromagnetic resonance linewidth with frequency for selected in plane orientations according to various embodiments.

FIG. 12 illustrates a method of forming a system for determining a ferromagnetic resonance response of a sample according to various embodiments.

FIG. 13 illustrates a method of determining a ferromagnetic resonance response of a sample according to various embodiments.

DETAILED DESCRIPTION

[0010] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical

changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0011] Embodiments described in the context of one of the methods or systems are analogously valid for the other methods or systems. Similarly, embodiments described in the context of a method are analogously valid for a system, and vice versa.

[0012] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0013] The word "over" used with regards to a deposited material formed “over” a side or surface, may be used herein to mean that the deposited material may be formed "directly on", e.g. in direct contact with, the implied side or surface. The word "over" used with regards to a deposited material formed “over” a side or surface, may also be used herein to mean that the deposited material may be formed "indirectly on” the implied side or surface with one or more additional layers being arranged between the implied side or surface and the deposited material. In other words, a first layer “over” a second layer may refer to the first layer directly on the second layer, or that the first layer and the second layer are separated by one or more intervening layers.

[0014] The system as described herein may be operable in various orientations, and thus it should be understood that the terms “top”, “bottom”, etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of the system.

[0015] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0016] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0017] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0018] As highlighted above, there is a commercial system for measuring broadband ferromagnetic resonance (FMR). However, the commercial system is very simple and does not possess angular capabilities.

[0019] Various embodiments may possess angular capabilities. Angular-resolved FMR may allow determination of anisotropy more precisely. Further, angular-resolved FMR may allow determination of damping as a function of magnetization orientation, which may be used for the development of next-generation devices.

[0020] When a ferromagnetic material is magnetized by an external magnetic field, there may be damping as the magnetic moments of the ferromagnetic material line up in parallel to the external magnetic field to reach equilibrium magnetization.

[0021] FIG. 2A illustrates the relative orientations of an applied magnetic field, the equilibrium magnetization and a radio frequency magnetic component (h_{rf}). FIG. 2B illustrates the relative orientations of another applied magnetic field, magnetization and a radio frequency magnetic component (h_{rf}) generated in the presence of a current of the same frequency.

[0022] When a varying force, such as the magnetic field of a radio frequency wave (h_{rf}), is applied perpendicular to the applied magnetic field over the magnetic moment, the magnetic field of the radio frequency wave may make the magnetic moments precess about the equilibrium direction. If the frequency of the force or wave is similar to the precession frequency, a maximum energy absorption by the ferromagnetic material may be observed. In such a situation, ferromagnetic resonance may take place, and the magnetic moments may oscillate in phase.

[0023] Anisotropy and damping may be determined using the tetragonal symmetry method. The magnetization and applied magnetic fields may be related by the following equation:

$$E =$$

$$-MH[cos\theta_H cos\theta_M + sin\theta_H sin\theta_M \cos(\phi_M - \phi_H)] + 2\pi M^2 cos^2\theta_M - \frac{1}{2}MH_{2\perp}cos^2\theta_M -$$

$$\frac{1}{4}MH_{4\perp}cos^4\theta_M - \frac{1}{2}MH_{2\parallel}sin^2\theta_M sin^2(\phi_M - \phi_{2IP}) - \frac{1}{4}MH_{4\parallel}\frac{3+cos4(\phi_M-\phi_{2IP})}{4}sin^4\theta_M$$

In addition,

$$2\pi f = \frac{\gamma}{Msin\theta}\sqrt{E_{\theta\theta}E_{\phi\phi} - {E_{\phi\theta}}^2}$$

where E represents the total energy of the system, f is the RF frequency. θ_m and ϕ_M may be solved numerically. M represents the magnetization and H represents the applied magnetic field. $E_{\theta\theta}$, $E_{\phi\phi}$ and $E_{\phi\theta}$ are second partial derivatives of the total energy. The FMR peak data may be fitted to obtain various anisotropic field. ($H_{2\perp}$ $H_{2\parallel}$, $H_{4\perp}$ and $H_{4\parallel}$, represents the in plane uniaxial anisotropy field, out of plane uniaxial anisotropy field, in plane cubic anisotropy field and out of plane cubic anisotropy field respectively). However, in conventional methods, a large number of curves may be required for fitting. About 1000 curves may be required for one sample. Also, the theory may not be well-developed.

[0024] FIG. 3A shows that a ferromagnetic resonance response may be generated when an applied magnetic field (H_{dc}) is applied orthogonally to the magnetic field of a radio frequency wave (h_{rf}). FIG. 3B shows that no ferromagnetic resonance response may be generated when an applied magnetic field (H_{dc}) is applied in parallel to the magnetic field of a radio frequency wave (h_{rf}). FIGS. 3A-B show that FMR may occur when h_{rf} is orthogonal to H_{dc}, and that some in – plane rotation angles may not be helpful for angular resolved FMR if only one of these two fields is rotated, e.g. rotating the magnetic field while keeping the coplanar waveguide (hence the radio frequency field orientation) fixed.

[0025] FIG. 3C shows out-of-plane rotation wherein the applied magnetic field (H_{dc}) is applied in a plane different from the plane of the surface of the sample according to various embodiments. The rotation illustrated in FIG. 3C may be able to generate FMR, since the applied magnetic field (H_{dc}) is orthogonal to the magnetic field h_{rf}. Accordingly, out-of-plane rotation may be helpful in angular resolved FMR.

[0026] FIG. 3D shows how out-of-plane rotation shown in FIG. 3C may be achieved according to various embodiments. A sample 304 may be rotated or tilted at an angle θ_H using a rotary positioner where the waveguide is mounted. Coils 308 may generate the applied magnetic field H_{dc}. By tilting or rotating the sample holder through an angle of θ_H, the magnetic component of the electromagnetic wave (h_{rf}) may still be perpendicular to the applied magnetic field H_{dc}.

[0027] The sample 304 may be required to be in close proximity to the waveguide 306. In various embodiments, the microwave should be directed to within a predetermined distance from the sample, e.g. < 20 μm or < 10 μm. FIG. 3E shows a conventional arrangement

including a waveguide 306' and a sample 304' arranged over the waveguide 306'. The waveguide 306' may be made by etching away part of the metallic film deposited on top of an insulating substrate . The patterned metallic film may have a center conductor 310, and two ground planes 312. The typical width of the center conductor 310 may be about 100 μm. Importantly, a radio frequency current flowing in the center conductor 310 may generate the rf magnetic field h_{rf}. The center conductor 310 may also serve as a detector to measure the FMR response. Therefore, in a FMR measurement, only the lower surface of the sample (thickness from nanometers up to micrometers) directly on top of the center conductor 310 may contribute to the signal. Only the lower surface of the sample 304' (with thickness from nanometers up to micrometers) directly on top of the center conductor 310 may contribute to the signal. The gap between the center conductor 310 and the lower surface of the sample 304' may be required to be as small as possible. Since the sample width is a few millimeters, an unwanted sample tilting from the waveguide plane may cause a gap between the center conductor 310 and the sample 304' being detected as the sample 304' is no longer parallel to the surface of the waveguide 306'. In some cases, the gap (d) may exceed 20 μm. The manipulator and sample holder according to various embodiments may prevent the tilting of sample from the waveguide surface. In various embodiments, the relative angle between the magnetic field generated by the coil and the sample plane may be varied using the manipulator and/or rotator while keeping the sample and the waveguide surface parallel to each other.

[0028] FIG. 4 is a general illustration of a system 400 for determining a ferromagnetic resonance response of a sample according to various embodiments. The system 400 may include a sample holder 404 configured to hold the sample. The system 400 may also include a waveguide 406 configured to direct a microwave to the sample to within a predetermined distance from the sample. The system 400 may further include a magnet 410 configured to apply a magnetic field to the sample to cause magnetization. The system 400 may additionally include a first actuator 412 configured to rotate the sample within a first plane. The system 400 may also include a second actuator 414 configured to rotate the sample within a second plane different from the first plane. The system may include electronics, e.g. a detector or a detector circuit arrangement, configured to detect the microwave that has interacted with the magnetization of the magnetized sample. The waveguide 406 may be further configured to direct the microwave that has interacted with the magnetization of the

magnetized sample to the electronics to be detected. The electronics may be included on or in the waveguide. The electronics may be further configured to control the system 400.

[0029] In other words, various embodiments may provide a system 400 for determining a ferromagnetic resonance response of a sample by applying a magnetic field and passing a microwave in close proximity from the sample. The sample may undergo angular rotation in two different planes via the first actuator 412 and the second actuator 414.

[0030] The magnet 410 may be an electromagnet such as a pair of Helmholtz coils.

[0031] The first plane may be perpendicular to the second plane. The sample may be a ferromagnetic film and the first plane may be parallel to a film plane, i.e. a plane parallel to the plane of the sample. The first plane may also be parallel to the ground or base of a system. The second plane may be referred to as a vertical plane.

[0032] In various embodiments, the second actuator 414 configured to rotate or tilt the sample (and sample holder 404) within the second plane may include moving from the sample (and sample holder 404) from an initial plane parallel to the ground or base to a plane at an angle to the ground or base, i.e. not parallel to the ground, base or surface. For instance, the sample (and sample holder 404) may be initially parallel to the surface (i.e. taken as an initial reference plane). When the sample (and sample holder 404) is rotated or tilted within the second plane (e.g. using the second actuator), the second plane perpendicular to the ground, the sample or film plane may end up along a plane which is not parallel to the surface (e.g. as illustrated in FIG. 3D). As shown in FIG. 3D, the film plane may be at an angle θ to the initial reference plane or surface.

[0033] FIG. 5A shows one implementation of a system 500 for determining a ferromagnetic resonance response of a sample according to various embodiments. FIG. 5B shows a photograph of the system 500 shown in FIG. 5A according to various embodiments. The system 500 may include a sample holder 504 configured to hold the sample. The system 500 may include a first actuator 512 configured to rotate the sample within a first plane (such as within x-y plane). The system 500 may also include a second actuator 514 configured to rotate the sample within a second plane (e.g. within the y-z plane) different from the first plane. The second plane may be orthogonal to the first plane.

[0034] The system 500 may include a base 518. The second plane may be a vertical plane e.g. the y-z plane, while the first plane may be a horizontal plane, e.g. the x-y plane, parallel

to a main surface of the sample. The system 500 may include a magnet, e.g. an electromagnet 510, configured to apply a magnetic field to the sample to cause magnetization.

[0035] The system 500 may include a frame 522 attached to the base 518. A first end of the frame 522 may be attached to a ferromagnetic resonance (FMR) probe arm 526 via a rotary stage 524. A second end of the frame 522 opposite the first end may be attached to a mounting manipulator 528 via a positioner system 520. The positioner system 520 may be configured to adjust a linear position of the mounting manipulator 528, e.g. along the x axis and/or the y axis within the x-y plane. The system 500 may also include a guide tube 580 coupled to the probe arm 526, and a stand 582 on base 518 for supporting or holding guide tube 580.

[0036] The rotary stage 524 may include the second actuator 514. The rotary stage may be attached to the frame 522. The second actuator 514 may be a rotary positioner.

[0037] FIG. 5C illustrates the operation of rotating or tilting the sample within the second plane according to various embodiments. The probe arm 526 may include a first end mounted or attached to the rotary positioner or second actuator 514. A second end of the probe arm 526 may be configured to hold the sample holder 504. The rotary positioner 514 may be configured to rotate the sample within the second plane, e.g. the y-z plane. The second actuator or rotary positioner 514 may further include a motor (not shown in FIG. 5C). Various embodiments may be able to achieve up to 90° rotation along the second plane, e.g. the vertical y-z plane. The second actuator 514 may be configured to rotate up to 90°.

[0038] FIG. 5D shows a ferromagnetic resonance (FMR) probe sub-system or arm 526 according to various embodiments. The sub-system or arm 526 may also include an adaptor 532 for mounting to a top plate 530 of rotary positioner 514, and a shaft 536 extending from or coupled to the adaptor 532. The sub-system or arm 526 may further include a bulkhead adaptor mounting base 538. The base 538 may be attached to the adaptor 532. The adaptor 532 and the base 538 may form a "L" shape. Microwave connector mounting kit 540 may be mounted on the base 538. The kit 540 may hold bulkhead connectors 542a, 542b. The connector 542a may hold a microwave cable 544a and the connector 542b may hold another microwave cable 544b. The sub-system or arm 526 may include a coplanar waveguide 506 having a first end connected to microwave cable 544a, and a second end connected to microwave cable 544b. The waveguide 506 may be on a planar surface 502 (of the probe head). The waveguide 506 may be configured to direct a microwave to within the

predetermined distance from the sample. The microwave may travel from a source through cable 544a to the waveguide 506. The waveguide 506 may be further configured to direct the microwave that has interacted with the magnetization of the magnetized sample towards or to the detector (via cable 544b).

[0039] The sub-system or arm 526 may also include an adaptor 546 for the FMR probe head. The adaptor 546 may also support the microwave cables 544a, 544b. The sub-system or arm 526 may also include a guide tube adaptor 548. The adaptor 548 may be used to couple a guide tube 580 as shown in FIG. 5A.

[0040] During rotation of the probe arm 526, the torque may be balanced by bearings on the opposite side of the magnet 510.

[0041] Should only out-of-plane rotation measurements be required, only the probe arm (and not the mounting manipulator 528) may be required. The components of the probe arm may be properly secured by screws to reduce noise.

[0042] FIG. 5E shows a magnified view of the probe head according to various embodiments. The probe head may be a part of the probe sub-system or arm 526, and FIG. 5D may correspond to the dashed box shown in FIG. 5D. The probe head may include a housing 550 (which may be made of a suitable material such as copper), an end launch connector 552, and connection ports 554a, 554b. The connection ports 554a, 554b may have first ends connected to cables 544a, 554b respectively, and second ends coupled to the waveguide 506 on planar surface 502 of the housing 550. The cables 554a, 554b may be 2.4 mm radio frequency (RF) cables, and connection ports 554a, 554b may be 2.4 mm connection ports matching the cables 554a, 554b.

[0043] The probe head may further include a clip such as a spring-loaded clip. The clip may include a clip base 556, a spring clip 558 on a first end of the clip base 556, and a biasing spring 560 on a second end of the clip base 556 (opposite the first end). The clip, i.e. the clip base may be pivotally mounted on the housing 550. The biasing spring 560 may be configured to bias the second end of the clip base 556 against the housing 550 (i.e. pushes the second end of base 556 away from the housing 550) so that the spring clip 568 presses the sample holder 504 onto the planar surface 502. The clip may thus be configured to secure the sample holder onto the planar surface 502.The clip may thus reduce the gap between the sample and the waveguide 506, which may in turn increases signal intensity and/or enhance stability. The design shown may allow faster out-of-plane sample mounting, which may be

better suited for practical industry needs compared to conventional designs. The spring clip 568 may be a beryllium copper (BeCu) spring clip, and the spring 560 may be a copper spring.

[0044] FIG. 5F shows (left) the front view of the mounting manipulator 528 and (right) a perspective view of the mounting manipulator 528 according to various embodiments. The mounting manipulator 528 may also be referred to as in-plane rotation sample mounting manipulator. The mounting manipulator 528 may have a first end configured to couple or attach to the sample holder. As shown in FIG. 5A, a second end of the mounting manipulator 528 may be attached or coupled to frame 522. The first actuator 512 (included in the mounting manipulator 528) may include a motor configured to rotate the mounting manipulator 528 so as to rotate the sample within the first plane. The first actuator 512 may be a rotary positioner. The first actuator 512 may be configured to rotate up to 360°.

[0045] The mounting manipulator 528 may further include a spring holder 562 and a housing tube 566 including a set screw lock 564a, screw holes 564b to receive screw lock 564a, and slots 568 for guiding sample loading. The housing tube 566 may also include screw hole 570 for coupling with shaft 572. The shaft 572 includes spring 574 for coupling with the screw hole 570. The mounting manipulator 528 may include a linear positioner configured to extend a length of the elongate mounting manipulator so as to adjust a linear position or height position of the sample, e.g. along the z-axis shown in FIG. 5A. The linear positioner may include the spring holder 562, the housing tube 566 and the shaft 572. An adaptor 576 may couple the mounting manipulator 528 to a positioner system 520. The spring 574 may provide an adjustable force to the sample holder As the linear positioner extends the length of the manipulator, the spring nay exert a greater force against the sample holder. The spring 574 may be a copper (Cu) spring.

[0046] In-plane measurements of FMR in conventional devices may not be possible for all angles. The sample may be required to be taken out, rotated and reloaded in.

[0047] In contrast, the system according to various embodiments may be able to achieve 360° rotation in the first plane. The spring 574 and the slots 568 may allow loading and unloading of the sample to be controlled by the linear positioner in addition to the rotary positioner 512 of the mounting manipulator 528.

[0048] In addition, the spring 574 may apply a force or pressure on the sample holder 504, thus reducing the gap between the sample and the waveguide. The mounting manipulator 528

may be configured to push the sample holder 504 against the waveguide of the probe arm. A standalone sample holder 504 may make changing of samples easier. For in-plane measurements, the sample may not be directly rotated on the probe head as shown in FIG. 5D.

[0049] FIG. 5G shows illustrates the operation of rotating the sample within the first plane according to various embodiments. The mounting manipulator 528 may be configured to mount the sample holder 504 containing the sample, and may raise the sample holder 504 to above the surface 504 of the probe head before rotating the sample holder to the desired angle within the first plane, i.e. x-y plane. The mounting manipulator 528 may be further configured to adjust the height of the sample holder 504 so that it is in contact with the surface 504 during measurement.

[0050] FIG. 6A shows a plot of amplitude of transmission (S_{21} coefficient) (in arbitrary units or a.u.) as a function of magnetic field (in oersteds or Oe) showing the ferromagnetic resonance (FMR) spectrum in different magnetic fields at selected azimuthal angles according to various embodiments. The minima of the curves correspond to the FMR peaks. The curves are shifted along the y-axis for the sake of clarity. The frequency is 10 GHz and the power is 5dBm.

[0051] FIG. 6B shows a polar plot showing the ferromagnetic resonance signal at different azimuthal angles between 0 and 360 degrees (inclusive) according to various embodiments. The circular shapes of different colors indicate that the sample is isotropic in the film plane.

[0052] FIGS. 6A-B relate to results obtained at 10 GHz for a silicon / permalloy (10 nm) / tantalum (5 nm) sample (Si/Py/ Ta) sample.

[0053] The in-plane rotation results show that the system may be capable of determining FMR spectrum of a sample with magnetization along any orientation or angle. As expected, the results show that the FMR peak position determined from the isotropic Py sample may be the same or similar at all angles.

[0054] FIG. 6C shows a plot of magnetic field (in oersteds or Oe) at resonance as a function of out-of-plane (OP) angle (in degrees) showing the ferromagnetic resonance out-of-plane rotation results at 10 GHz of a sample according to various embodiments. The sample in which FIG. 6C is derived from is silicon / permalloy (10 nm) / tantalum (5 nm) (Si/Py/ Ta) sample. FIG. 6C shows that the resonance field for fields parallel to the sample plane (OP = 0°) is lower than for fields perpendicular to the sample plane (OP = 90°). The results show

that the sample has an easy axis along the film plane. As the sample has an easy axis in plane, the rotation of the magnetization towards an out-of-plane direction may require a large external magnetic field. The peak position may be determined by the Smit-Beljers equation.

[0055] FIG. 7A is a plot of magnetic field H_{res} (in kilo-oersteds or kOe) at resonance as a function of polar angle θ_H (degrees) showing the ferromagnetic resonance (FMR) peak obtained according to various embodiments fitted to theoretical Smith-Beljers equation. The equation may be provided by:

$$2\pi f = \gamma\sqrt{(Hcos(\theta_M - \theta_H) - 4\pi M_{eff}cos2\theta_M)(H\cos(\theta_M - \theta_H) - 4\pi M_{eff}cos^2\theta_M)}$$

The experimental data fits well with the theoretical equation at all three frequencies. FIG. 7B is a plot of magnetic field H_{res} (in kilo-oersteds or kOe) / lande g factor as a function of frequency (in gigahertz or GHz) showing the effective saturation magnetization and lande g factor from the fits provided in FIG. 7A according to various embodiments. The value of the variation may be only 1 percent, which may provide evidence of the consistency amongst different frequencies.

[0056] FIG. 8A is a plot of magnetic field H_{res} (in oersteds or Oe) as a function of azimuthal angles ϕ_H (in degrees) showing the ferromagnetic resonance field with in plane rotation of a sample at 15 GHz according to various embodiments. The sample is iron (10 nm) / tantalum (3 nm) (Fe / Ta). The line is based on equations of in plane cubic anisotropy:

$$2\pi f = \gamma\sqrt{UV}$$

$$U = Hcos(\phi_M - \phi_H) + 4\pi M_{eff} + H_{4\|}\frac{3 + cos4(\phi_M - \phi_{4IP})}{4}$$

$$V = Hcos(\phi_M - \phi_H) + H_{4\|}\cos(\phi_M - \phi_{4IP})$$

$H_{4\|}$ the cubic magnetic anisotropy field, and $\phi_{4IP} = 45°$ is the easy axis of the cubic magnetic anisotropy field.

[0057] $H_{4\|}$ of 570 Oe may be determined. Single crystal iron (Fe) films may be used to test the design. The film may have large in plane cubic (4- fold) anisotropy, which may result in changing FMR peak field as a function of in-plane angles at a given frequency.]

[0058] The data may be fitted to theory, which may allow the extraction of cubic magnetic anisotropy energy or effective field ($H_{4\|}$ here). The results obtained with the broadband method may be consistent with previous published results done by cavity based instruments. FIG. 8B is a plot of effective magnetization $4\pi M_{eff}$ (in gauss or G) / magnetic field H (in

oersteds or Oe) as a function of frequency (in gigahertz or GHz) showing variation of magnetization / magnetic field with frequency according to various embodiments. FIGS. 8A – B relate to a silicon / permalloy (10 nm) / tantalum (5 nm) sample.

[0059] FIG. 9A is a plot of resonance linewidth (full width at half maximum, in oersteds or Oe) as a function of azimuthal angle ϕ_H (in degrees) showing magnetic damping measurements of a sample according to various embodiments. The sample in which FIG. 9A relates to is a silicon /Py (10 nm) / Ta (6nm) sample. Py is a very soft magnetic material which is known to show isotropic magnetic property. As expected, the FMR measured linewidth as a function of in-plane angle only varies by about 1 Oe. The variation may be due to sample inhomogeneity. Further, the 1 Oe variation is within the upper limit of the system error bar.

[0060] FIG. 9B is a plot of resonance linewidth (in oersteds or Oe) as a function of frequency (in gigahertz or gHz) at various azimuthal angle ϕ_H (in degrees) showing variation of ferromagnetic resonance linewidth with frequency for selected in plane orientations according to various embodiments. The symbols represent the data points while the lines are the linear fits.

[0061] FIG. 9C is a plot of damping α as a function of azimuthal angle ϕ_H (in degrees) based on data shown in FIG. 9B according to various embodiments. The magnetic damping α may be determined via the following equation:

$$\Delta H = \frac{4\pi\alpha}{\gamma} f + \Delta H_0$$

The damping may be determined to be 0.0086 ± 0.0001. The sample from which FIGS. 9B and 0C are derived from is also the silicon /Py (10 nm) / Ta (6nm) sample. FIG. 9C shows that damping is isotropic for Py.

[0062] In general, the FMR linewidth may be calculated based on sample crystal symmetry and the method as described herein may be applied to any angle.

[0063] An advantage of coplanar waveguide based FMR may be the broadband capability. In other words, the FMR of any frequency within the bandwidth may be determined. Determining the FMR at multiple frequencies at a given magnetization orientation may allow the determination of magnetic damping.

[0064] FIG. 10A shows a polar plot showing the in-plane ferromagnetic resonance signal at different azimuthal angles between 0 and 180 degrees (inclusive) of another sample

according to various embodiments. The sample from which FIG. 10A is derived from is magnesium oxide / iron (10 nm) / tantalum (3 nm) (MgO / Fe / Ta).

[0065] FIG. 10B is a plot of magnetic field H_{res} (in oersteds or Oe) as a function of azimuthal angles ϕ_H (in degrees) showing the ferromagnetic resonance field with in plane rotation of the other sample at 15 GHz according to various embodiments. FIG. 10B is also derived from MgO / Fe / Ta. FIGS. 10A-B show that MgO / Fe / Ta exhibit anisotropy.

[0066] FIG. 11 is a plot of resonance linewidth (full width at half maximum, in oersteds or Oe) as a function of frequency (in gigahetz or gHz) showing variation of ferromagnetic resonance linewidth with frequency for selected in plane orientations according to various embodiments. The sample tested used to derive FIG. 11 is silicon / permalloy (6 nm) / platinum (10 nm) (Si / Py/ Pt). The spin-pumping effect of Py is manifested and damping is 0.0179 ± 0.0001.

[0067] Various embodiments may provide a system for determining a ferromagnetic resonance response of a sample. The system may be an apparatus or an instrument. The system may include a sample holder configured to hold the sample. The system may also include a waveguide configured to direct a microwave to within a predetermined distance from the sample. The system may further include a magnet configured to apply a magnetic field to the sample to cause magnetization. The system may additionally include a first actuator configured to rotate the sample within a first plane. The system may further include a second actuator configured to rotate the sample within a second plane different from the first plane. The system may further include a detector configured to detect the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

[0068] The first plane may be perpendicular to the second plane. For instance, the first plane may be the x-y plane, and the second plane may be the y-z plane.

[0069] The system may also include a base. The system may also include a frame. The frame may be rigidly mounted or attached to the base. The system may further include a rotary stage attached to the frame, the rotary stage including the second actuator.

[0070] The system may further include a probe arm with a first end attached to the second actuator and a second end configured to hold the sample holder. The probe arm may include the waveguide. The probe arm may further include a first microwave cable connected to a first end of the waveguide and a second microwave cable connected to a second end of the

waveguide. The first microwave cable may be configured to direct a microwave from a microwave source to the waveguide. The second microwave cable may be configured to direct the microwave that has interacted with the magnetization of the magnetized sample to the detector. The second actuator may be configured to rotate the probe arm so as to rotate the sample within the second plane.

[0071] The probe arm may also include a housing including a planar surface. The probe arm may further include a clip. The waveguide may be on the planar surface. The clip may be configured to secure the sample holder onto the planar surface.

[0072] The clip may be pivotally mounted on the housing. The clip may include a clip base, a spring clip on a first end of the clip base, and a biasing spring on a second end of the clip base. The biasing spring may be configured to bias the second end of the clip base against the housing so that the spring clip presses the sample holder onto the planar surface.

[0073] The first actuator may be included in a mounting manipulator. The mounting manipulator may further include a linear positioner configured to extend a length of the elongate mounting manipulator so as to adjust a linear position or height position of the sample, e.g. along the z-axis. The first actuator may be configured to rotate the mounting manipulator so as to rotate the sample within the first plane.

[0074] The system may also include a positioner system configured to adjust a linear position of the mounting manipulator, e.g. within or along the x-y plane. The positioner system may be a linear positioner. The mounting manipulator may be configured to push the sample holder against the waveguide.

[0075] The mounting manipulator may be further configured to push the sample holder against the waveguide.

[0076] In various embodiments, determining the ferromagnetic resonance response of the sample may include determining a ferromagnetic resonance of the sample.

[0077] In various embodiments, the microwave may be an extreme high frequency (EHF) wave.

[0078] In various embodiments, the microwave may be of any frequency or range of frequencies from 1 GHz or to 100 GHz. Various embodiments may be suitable to work at any frequency or range of frequencies from 1 GHz to 100 GHz without changing hardware. On the other hand, conventional systems or methods may require tuning hardware when frequency is changed. Cavity-based FMR may require a cavity for detecting signals, and may

either work at only a single frequency or may need to tune the hardware to change the working frequency. In various embodiments, the microwave may be of any value or range of values from 1 GHz to 100 GHz.

[0079] Various embodiments may relate to a system capable of two degrees of rotational freedom broadband FMR. 360 degrees of rotation in the film plane, and up to or more than 90 degrees rotation out of film plane rotation may be achieved. In contrast, other broadband FMR systems, such as fixed angle commercial products, may be only able to measure FMR with rotation along a single plane or field orientation. Other system may not cover all field orientations and output signals may be dependent on angle. The relative angle between applied magnetic field and the magnetization component of the microwave may keep changing due to rotation. The output signal may not be a constant value and may disappear when the applied magnetic field and the magnetization component of the microwave are parallel to each other.

[0080] Various embodiments may be capable of fast and reliable sample mounting.

[0081] Various embodiments may provide a system including an electromagnetic, two motorized linear positioners, two motorized rotary positioners, microwave connectors and cables. One or more of the components included in the system may be standard commercial items. One or more of the components included in the system, including components for achieving angular dependent FMR measurements, may be assembled or built in-house.

[0082] Various embodiments may provide a system for angular resolved broadband FMR. Field rotation in the sample film plane measurement may be achieved by an in-plane spring-loaded sample loading manipulator. Sample loading and un-loading may be motorized by a rotary positioner and a linear positioner at every azimuthal angle. Field rotation from in-the sample plane to perpendicular to the sample plane may be achieved by a motorized rotary positioner. Various embodiments may include a FMR probe, a probe head for housing a co-planar waveguide, and a spring-loaded clip.

[0083] The system may be suitable for measuring magnetic anisotropy and damping, and may be important or essential for industry and research related to magnetic random access memory (MRAM) devices, magnetic sensors and high frequency devices.

[0084] Various embodiments may provide fast and efficient angular-resolved broadband FMR.

[0085] FIG. 12 illustrates a method of forming a system for determining a ferromagnetic resonance response of a sample according to various embodiments. The method may include, in 1202, providing a sample holder configured to hold the sample. The method may also include, in 1204, providing a waveguide configured to direct a microwave to within a predetermined distance from the sample. The method may further include, in 1206, providing a magnet configured to apply a magnetic field to the sample. The method may also include, in 1208, providing a first actuator configured to rotate the sample within a first plane. The method may additionally include, in 1210, providing a second actuator configured to rotate the sample within a second plane different from the first plane. The method may also include, in 1212, providing a detector configured to detect the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

[0086] FIG. 13 illustrates a method of determining a ferromagnetic resonance response of a sample according to various embodiments. The method may include, in 1302, holding the sample using the sample holder. The method may also include, in 1304, directing a microwave to within a predetermined distance from the sample. The method may additionally include, in 1306, applying a magnetic field to the sample to cause magnetization using a magnet. The method may also include, in 1308, rotating the sample with a first plane using the first actuator. The method may further include, in 1310, rotating the sample with a second plane different from the first plane using the second actuator. The method may additionally include, in 1312, detecting the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

[0087] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A system for determining a ferromagnetic resonance response of a sample, the system comprising:

a sample holder configured to hold the sample;

a waveguide configured to direct a microwave to within a predetermined distance from the sample;

a magnet configured to apply a magnetic field to the sample to cause magnetization;

a first actuator configured to rotate the sample within a first plane;

a second actuator configured to rotate the sample within a second plane different from the first plane; and

a detector configured to detect the microwave that has interacted with a magnetization of the magnetized sample , thereby determining the ferromagnetic resonance response of the sample.

2. The system according to claim 1,

wherein the first plane is perpendicular to the second plane.

3. The system according to claim 1, further comprising:

a frame; and

a rotary stage attached to the frame, the rotary stage comprising the second actuator.

4. The system according to claim 3, further comprising:

a probe arm with a first end attached to the second actuator and a second end configured to hold the sample holder.

5. The system according to claim 4,

wherein the probe arm comprises the waveguide.

6. The system according to claim 5,

wherein the probe arm further comprises a first microwave cable connected to a first end of the waveguide and a second microwave cable connected to a second end of the waveguide.

7. The system according to claim 4,

wherein the probe arm comprises:

a housing comprising a planar surface; and

a clip;

wherein the waveguide is on the planar surface; and

wherein the clip is configured to secure the sample holder onto the planar surface.

8. The system according to claim 7,

wherein the clip is pivotally mounted on the housing;

wherein the clip comprises a clip base, a spring clip on a first end of the clip base, and a biasing spring on a second end of the clip base; and

wherein the biasing spring is configured to bias the second end of the clip base against the housing so that the spring clip presses the sample holder onto the planar surface.

9. The system according to claim 1,

wherein the first actuator is comprised in a mounting manipulator.

10. The system according to claim 9,

wherein the mounting manipulator further comprises a linear positioner configured to extend a length of the elongate mounting manipulator so as to adjust a height position of the sample; and

wherein the mounting manipulator further comprises a spring to provide an adjustable force to the sample holder.

11. The system according to claim 9; further comprising:

a positioner system configured to adjust a linear position of the mounting manipulator.

12. The system according to claim 9,

wherein the mounting manipulator is configured to push the sample holder against the waveguide.

13. The system according to claim 1,

wherein determining the ferromagnetic resonance response of the sample comprises determining a ferromagnetic resonance of the sample.

14. The system according to claim 1,

wherein the microwave. is of any value from 1 GHz to 100 GHz.

15. A method of forming a system for determining a ferromagnetic resonance response of a sample, the method comprising:

providing a sample holder configured to hold the sample;

providing a waveguide configured to direct a microwave to within a predetermined distance from the sample;

providing a magnet configured to apply a magnetic field to the sample to cause magnetization;

providing a first actuator configured to rotate the sample within a first plane;

providing a second actuator configured to rotate the sample within a second plane different from the first plane; and

providing a detector configured to detect the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

16. A method of determining a ferromagnetic resonance response of a sample, the method comprising:

holding the sample using the sample holder;

directing a microwave to within a predetermined distance from the sample;

applying a magnetic field to the sample to cause magnetization using a magnet;

rotating the sample with a first plane using the first actuator;

rotating the sample with a second plane different from the first plane using the second actuator; and

detecting the microwave that has interacted with a magnetization of the magnetized sample, thereby determining the ferromagnetic resonance response of the sample.

17. The method according to claim 16,

wherein the first plane is perpendicular to the second plane.

18. The method according to claim 16,

wherein the microwave is an extreme high frequency (EHF) wave.

19. The method according to claim 16,

wherein the microwave is of any value from 1 GHz to 100 GHz.

20. The method according to claim 16,

wherein determining the ferromagnetic resonance response of the sample comprises determining a ferromagnetic resonance of the sample.

FIG. 1A

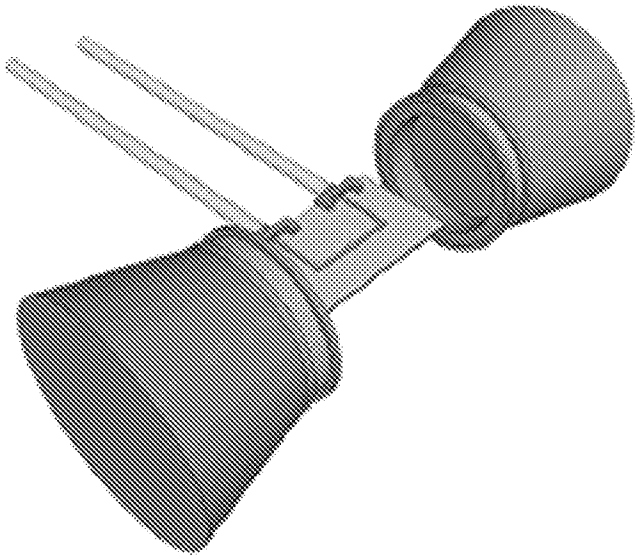


FIG. 1B

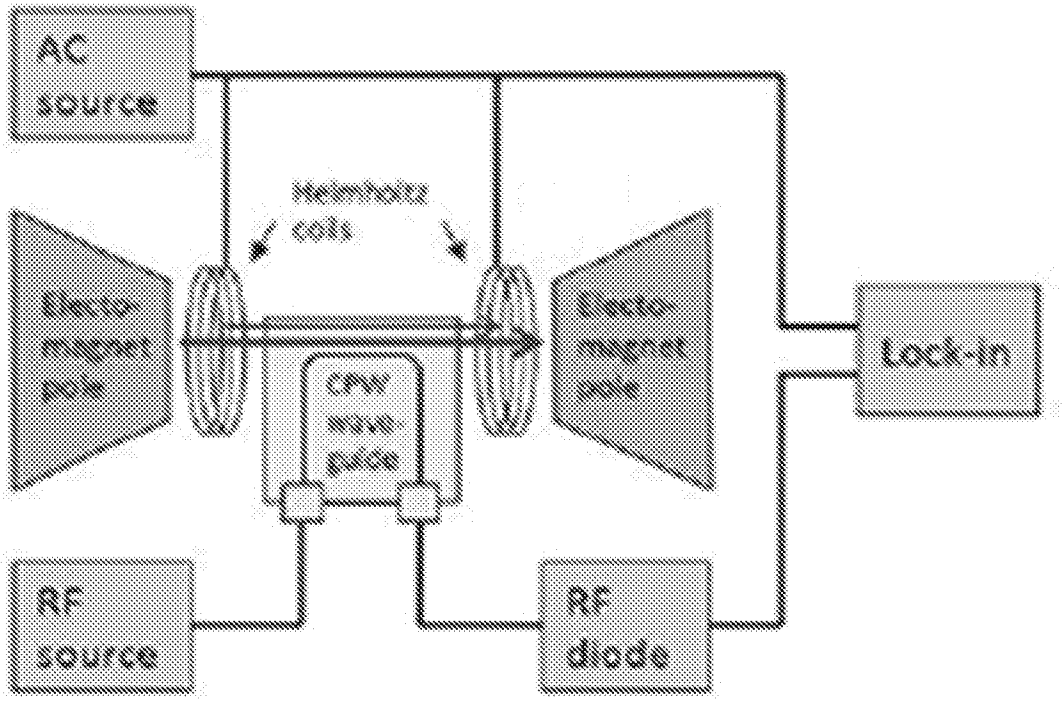

AC source
Helmholtz coils
Electro-magnet pole
Electro-magnet pole
CPW waveguide
Lock-in
RF source
RF diode

FIG. 2A

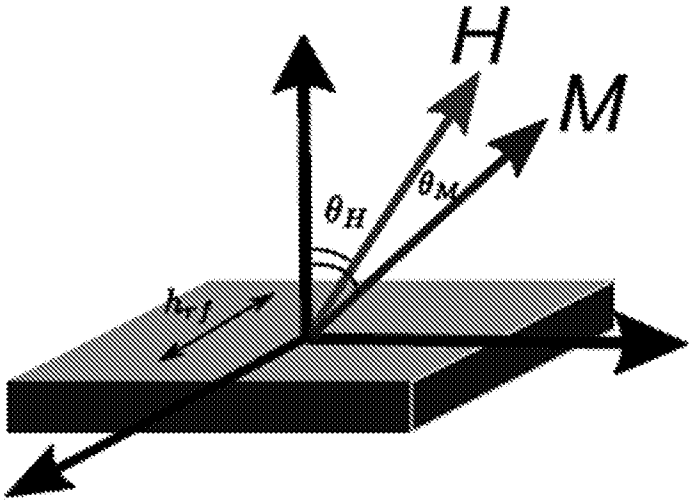


FIG. 2B

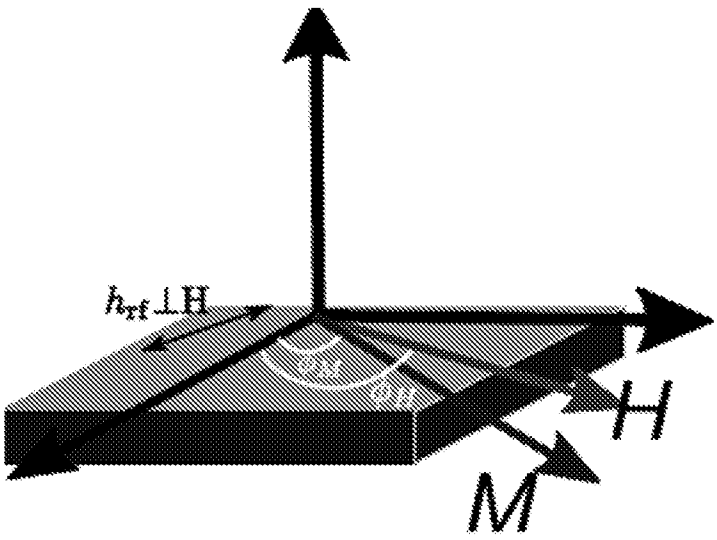


FIG. 3A

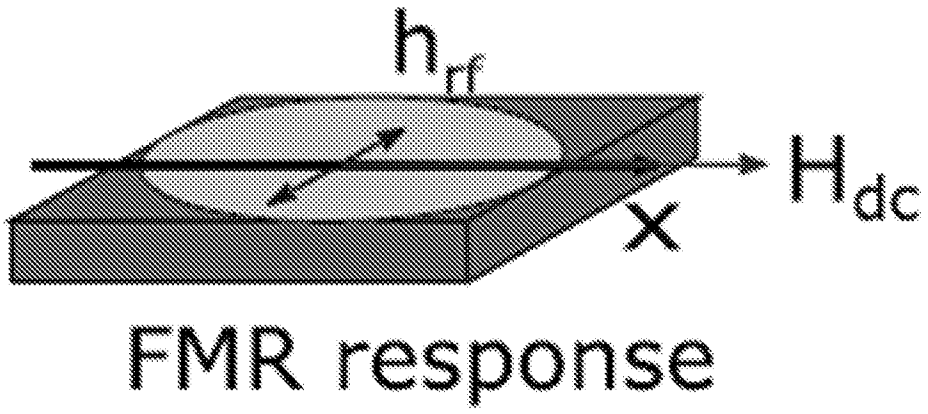


FIG. 3B

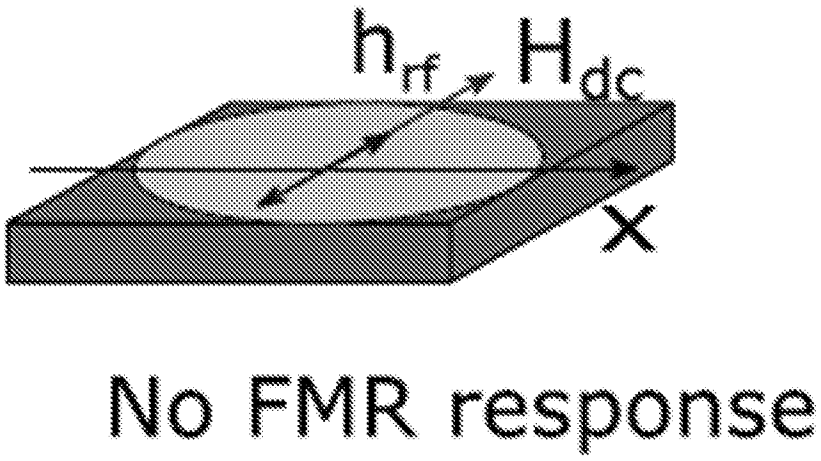


FIG. 3C

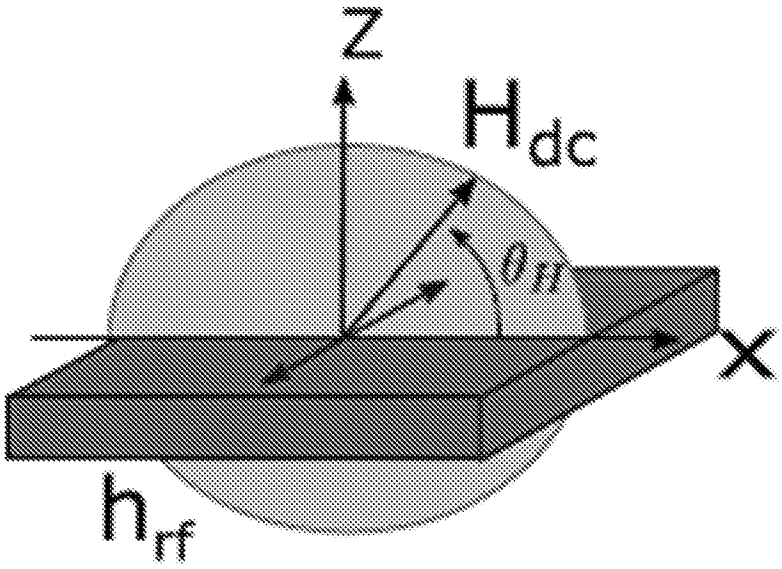


FIG. 3D

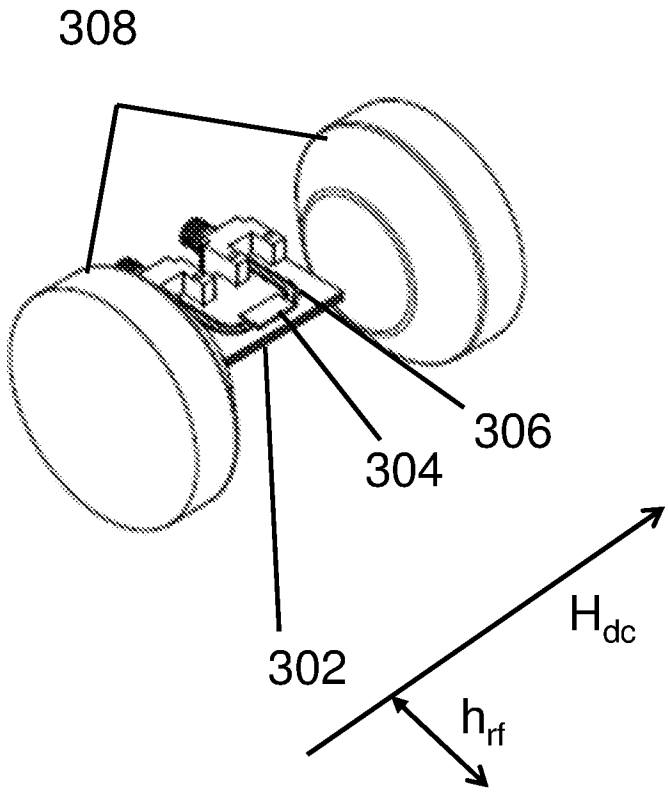


FIG. 3E

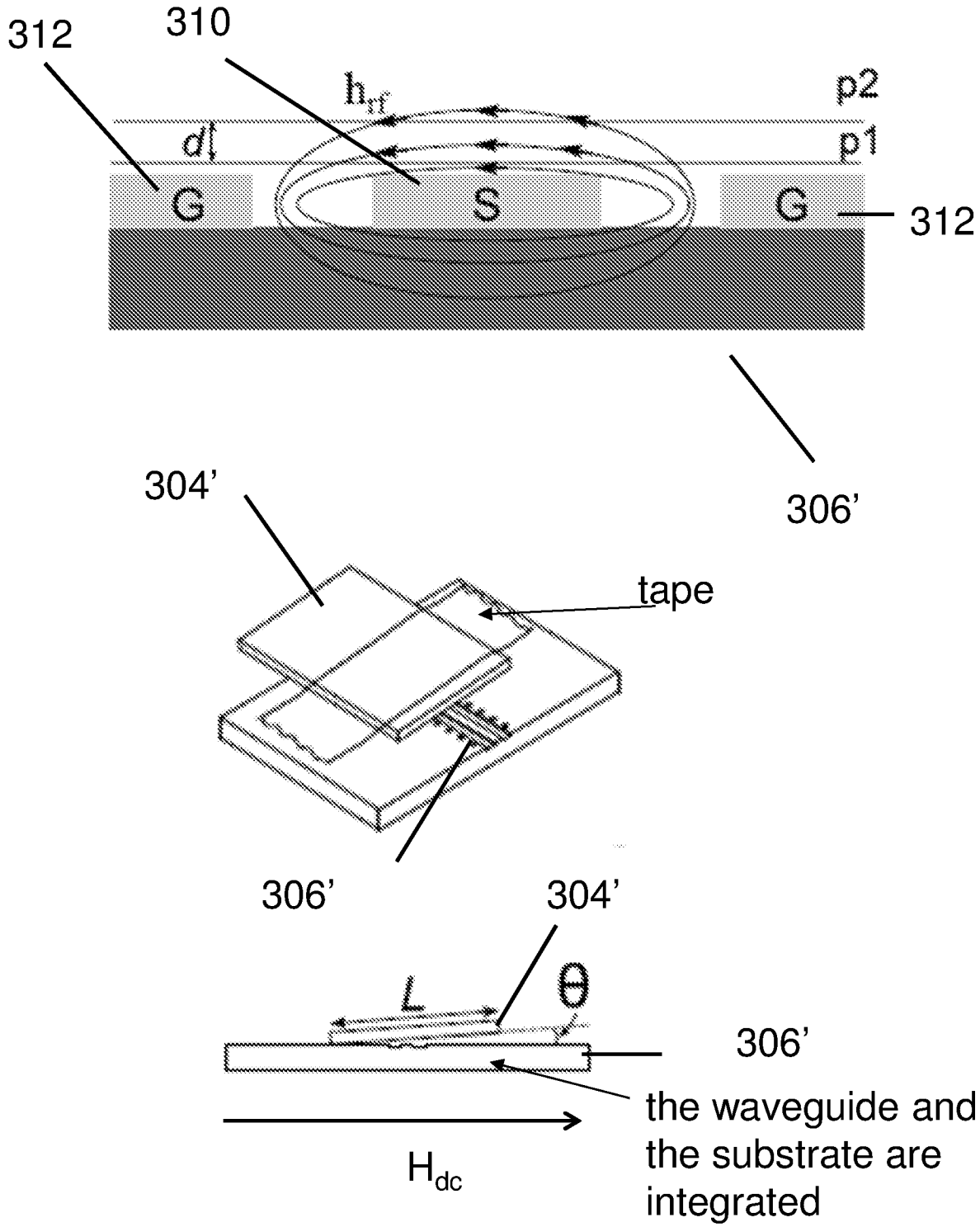

312
310
h_{rf}
p2
d
p1
G
S
G
312
306'
304'
tape
306'
304'
L
θ
306'
the waveguide and the substrate are integrated
H_{dc}

FIG. 4

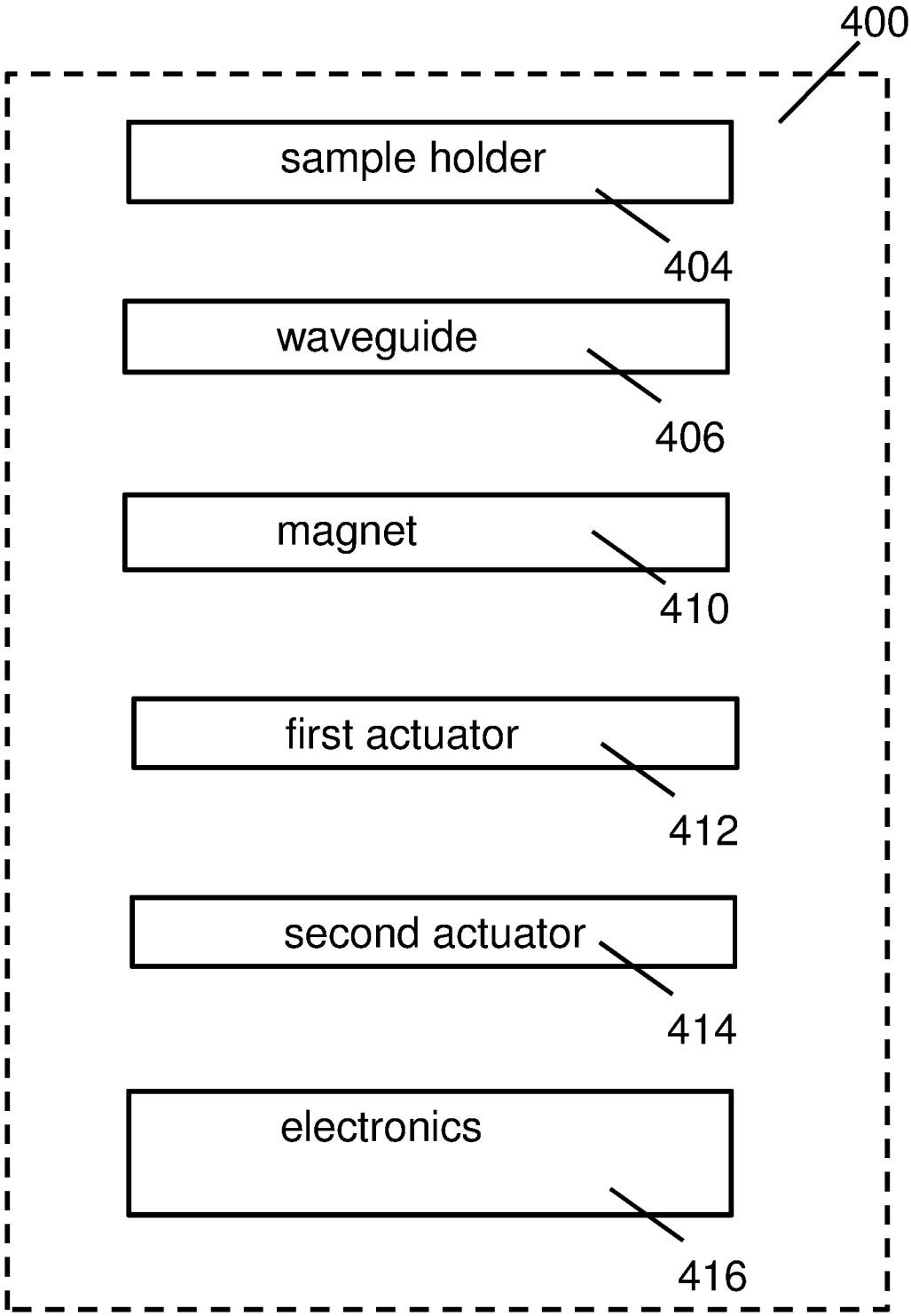

400
sample holder
404
waveguide
406
magnet
410
first actuator
412
second actuator
414
electronics
416

FIG. 5A

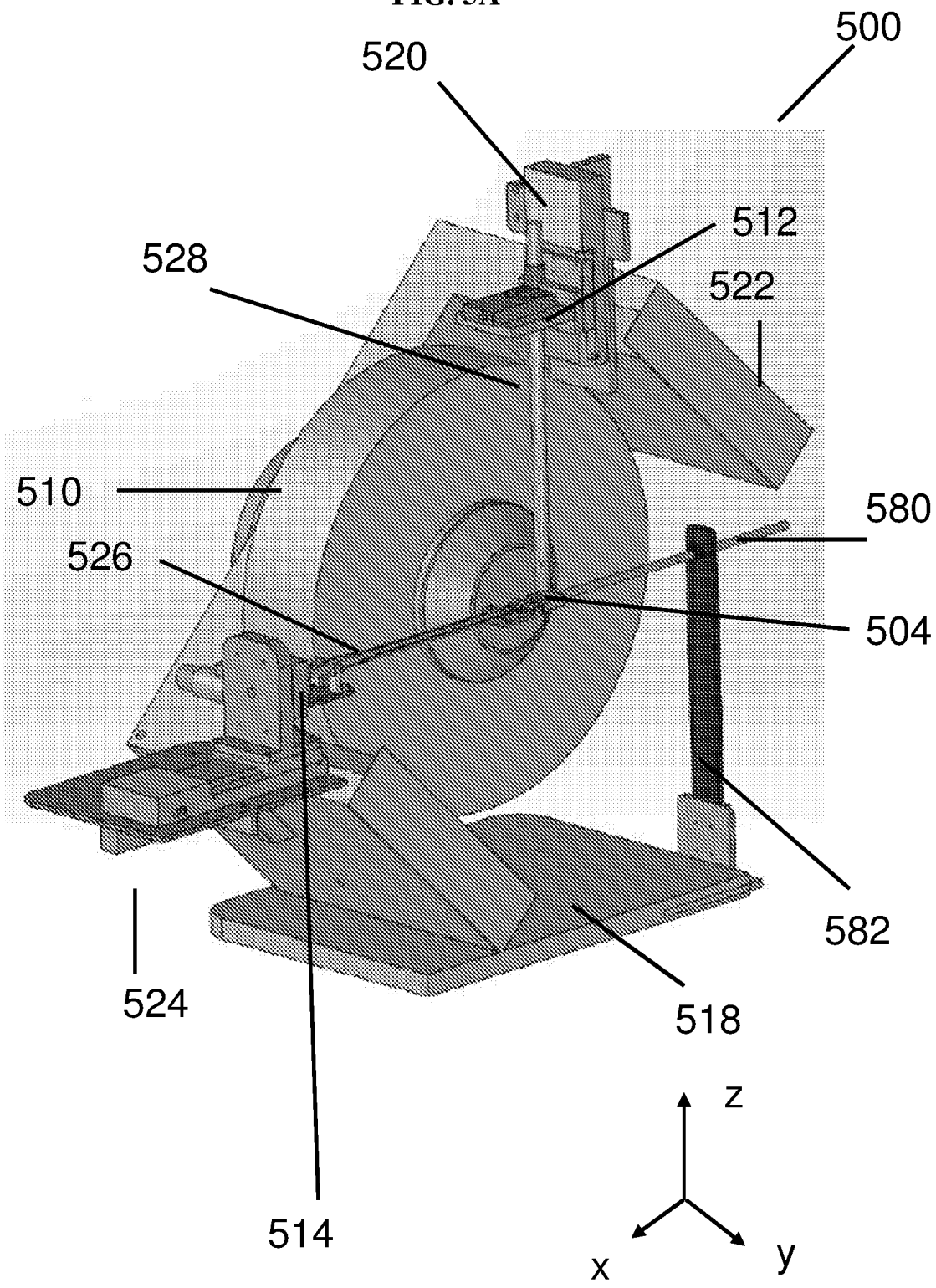
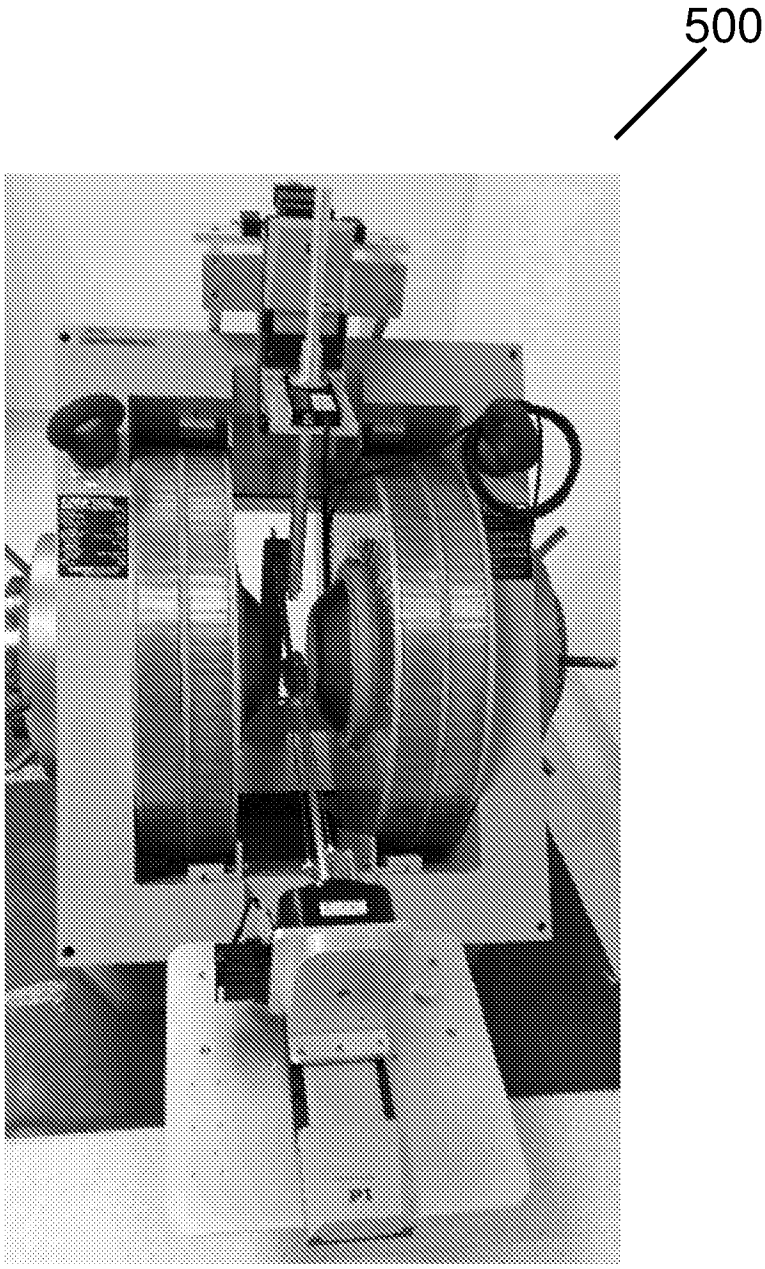


FIG. 5B



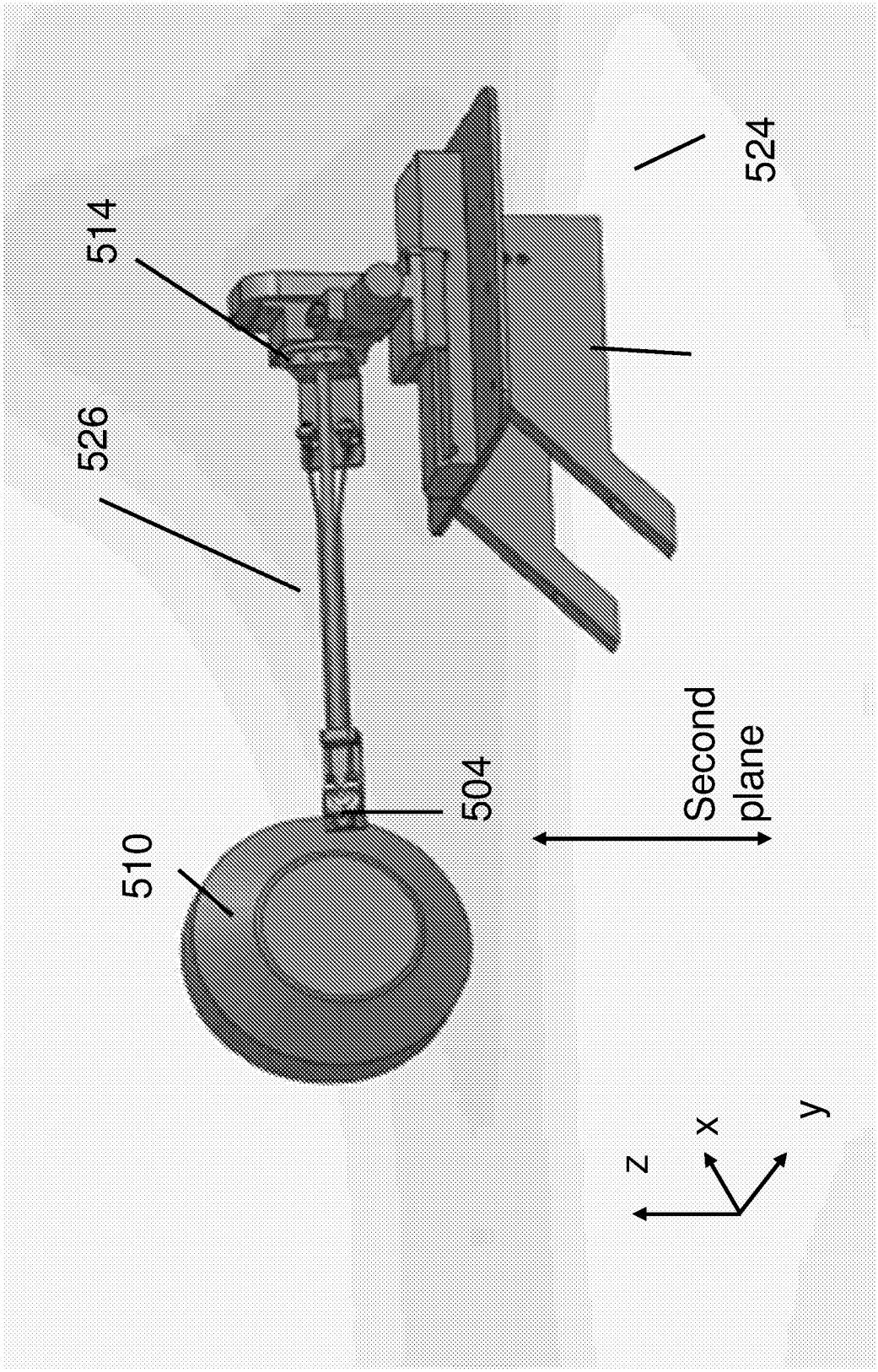


FIG. 5C

FIG. 5D

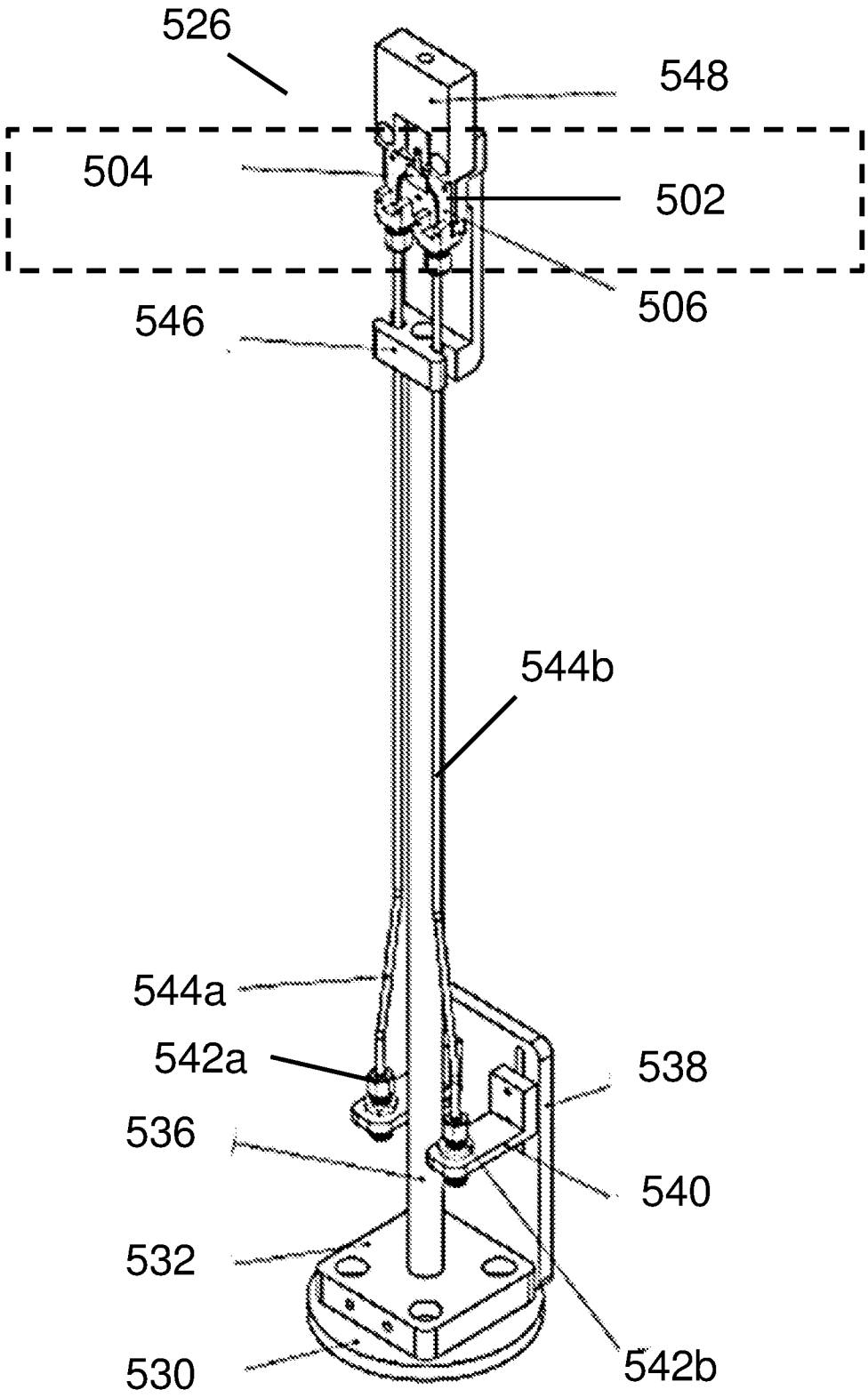


FIG. 5E

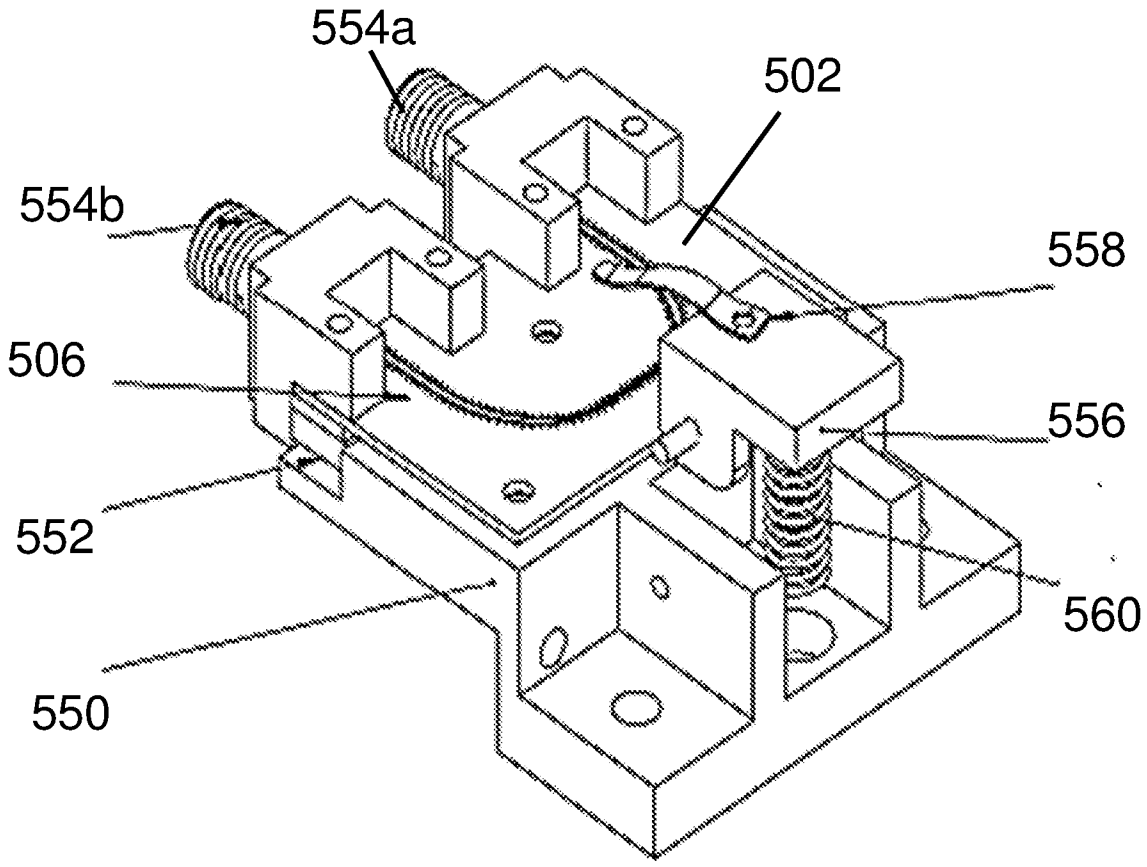
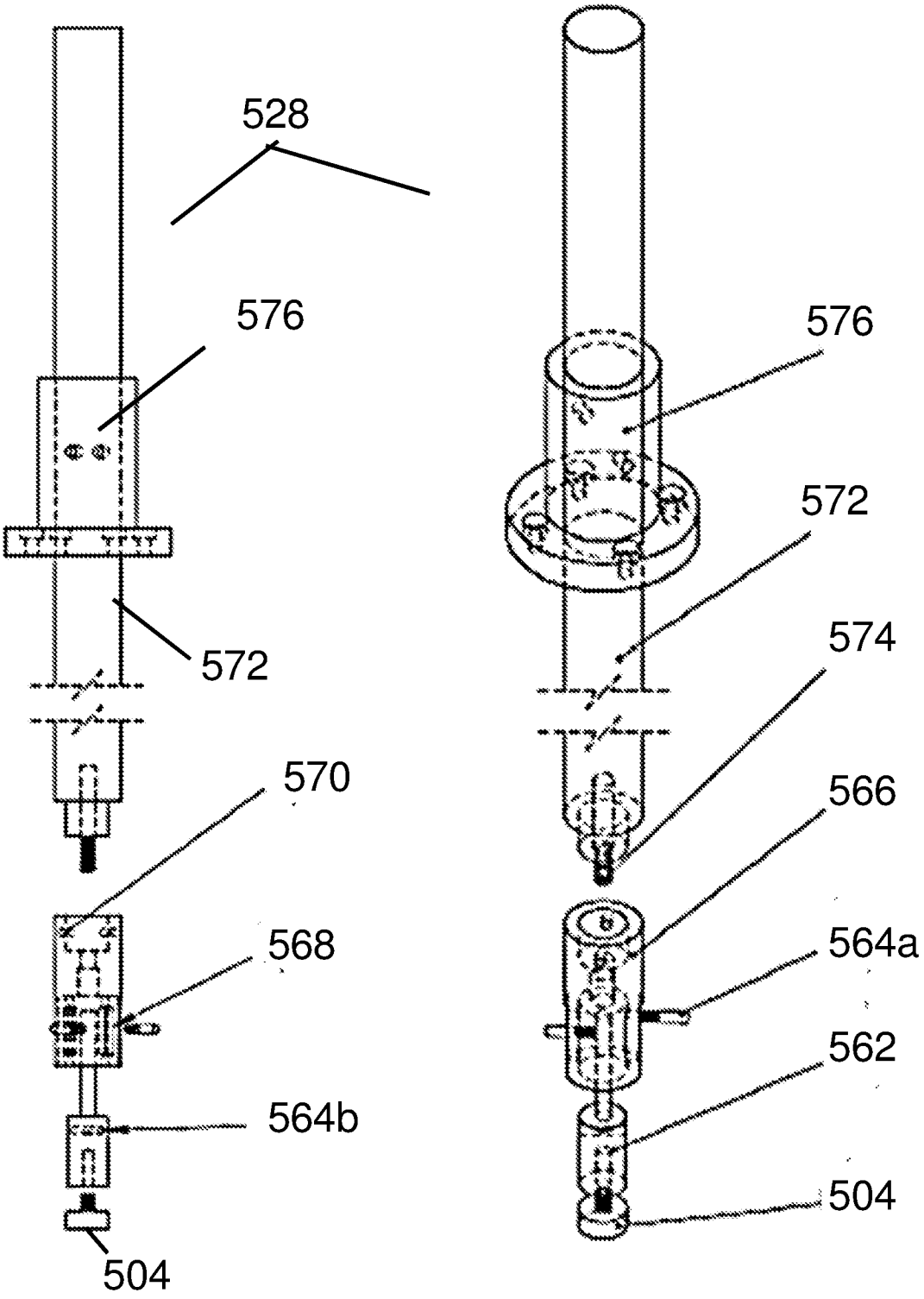


FIG. 5F



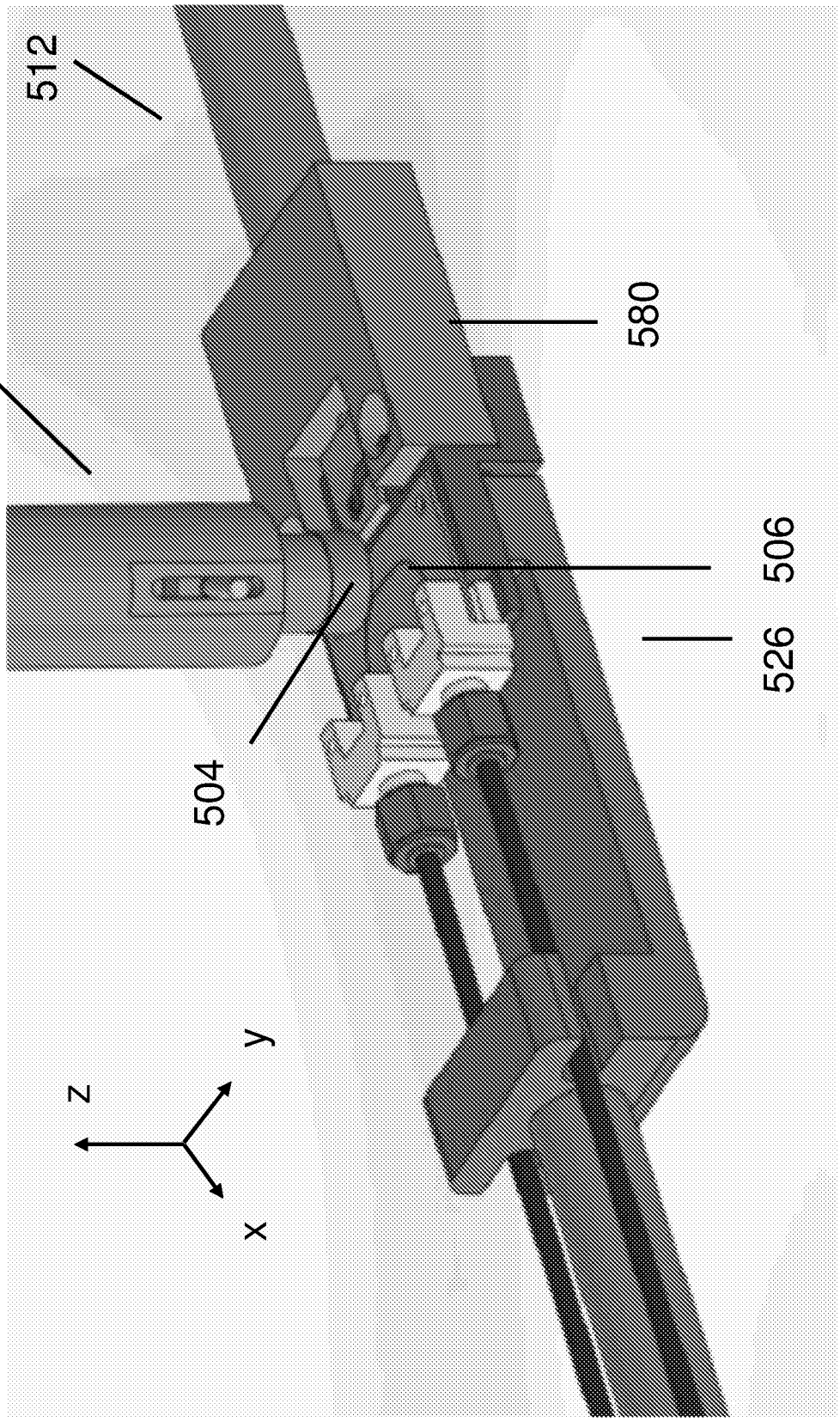


FIG. 5G

FIG. 6A

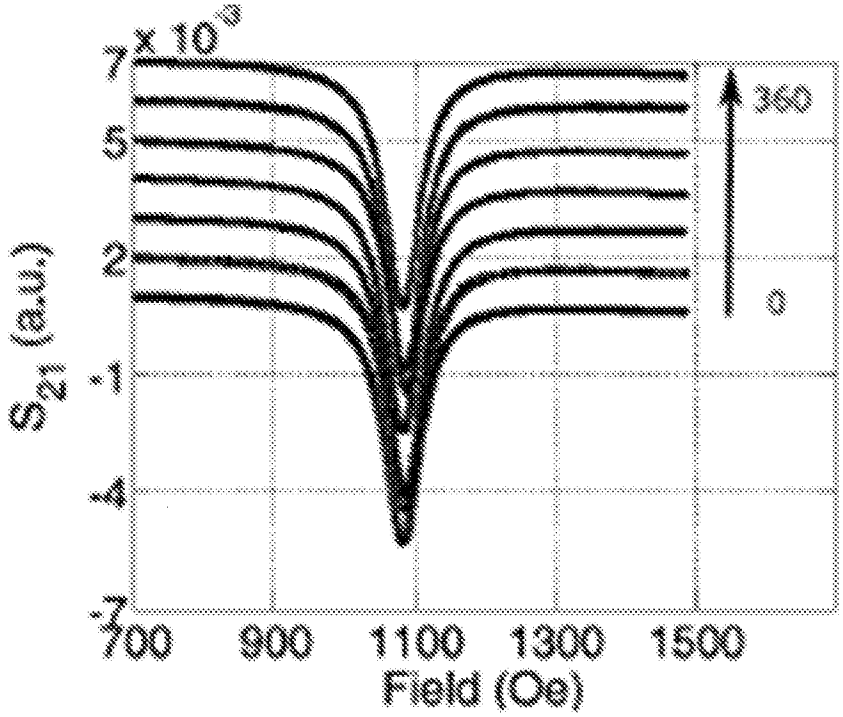

x 10^-3
7
5
2
-1
-4
-7
S21 (a.u.)
360
0
700
900
1100
1300
1500
Field (Oe)

FIG. 6B

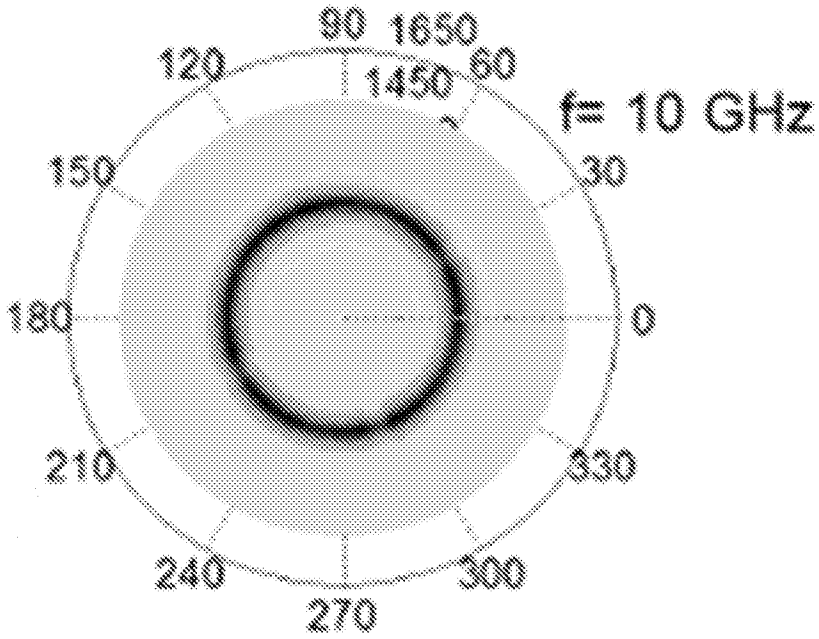

90
1650
1450
60
120
150
30
180
0
210
330
240
300
270
f= 10 GHz

FIG. 6C

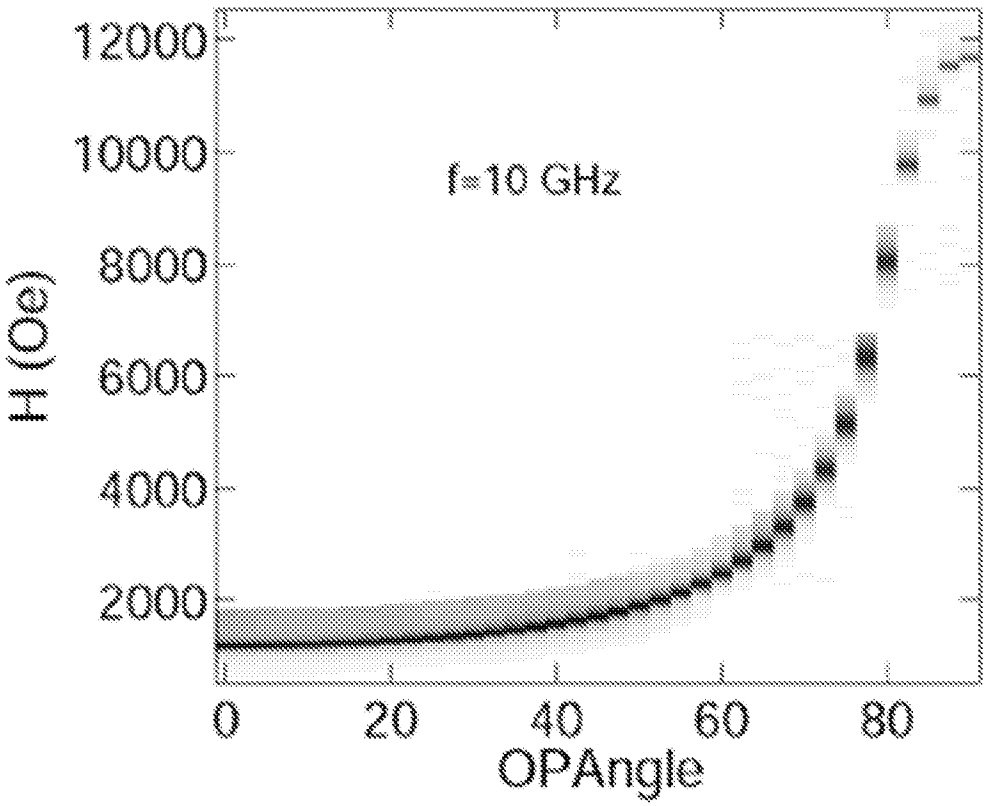

12000
10000
8000
6000
4000
2000
H (Oe)
f=10 GHz
0
20
40
60
80
OPAngle

FIG. 7A

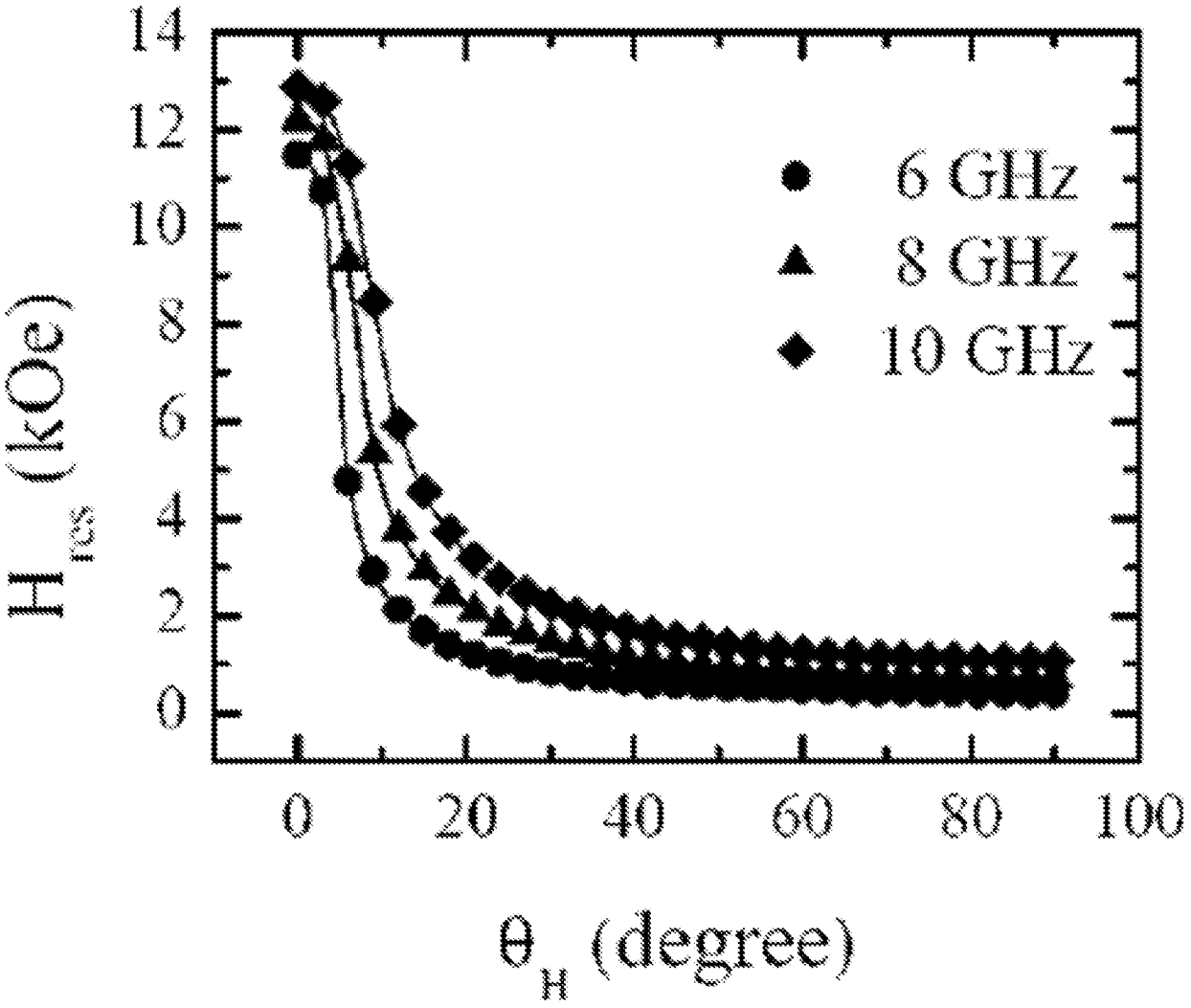

14
12
10
8
6
4
2
0
H_{pp} (kOe)
0
20
40
60
80
100
θ_H (degree)
6 GHz
8 GHz
10 GHz

FIG. 7B

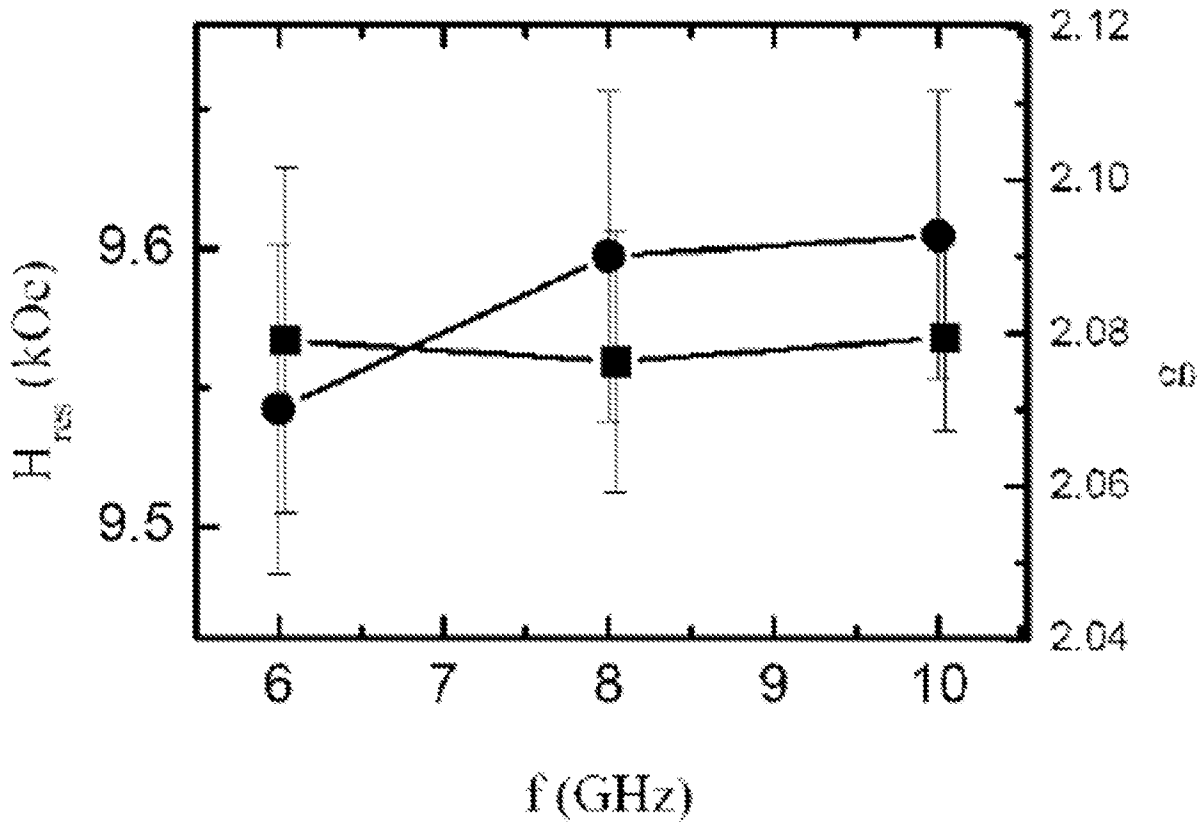


FIG. 8A

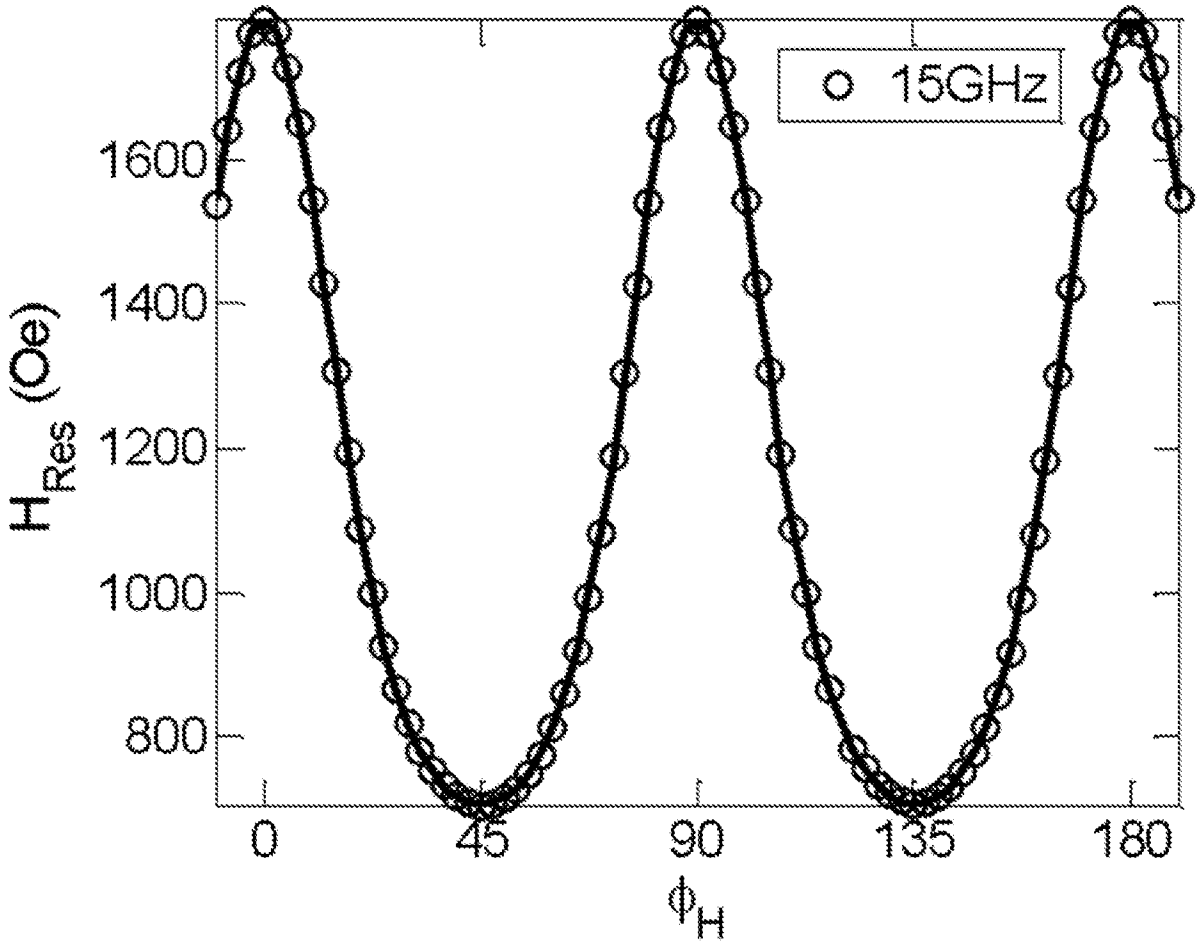


FIG. 8B

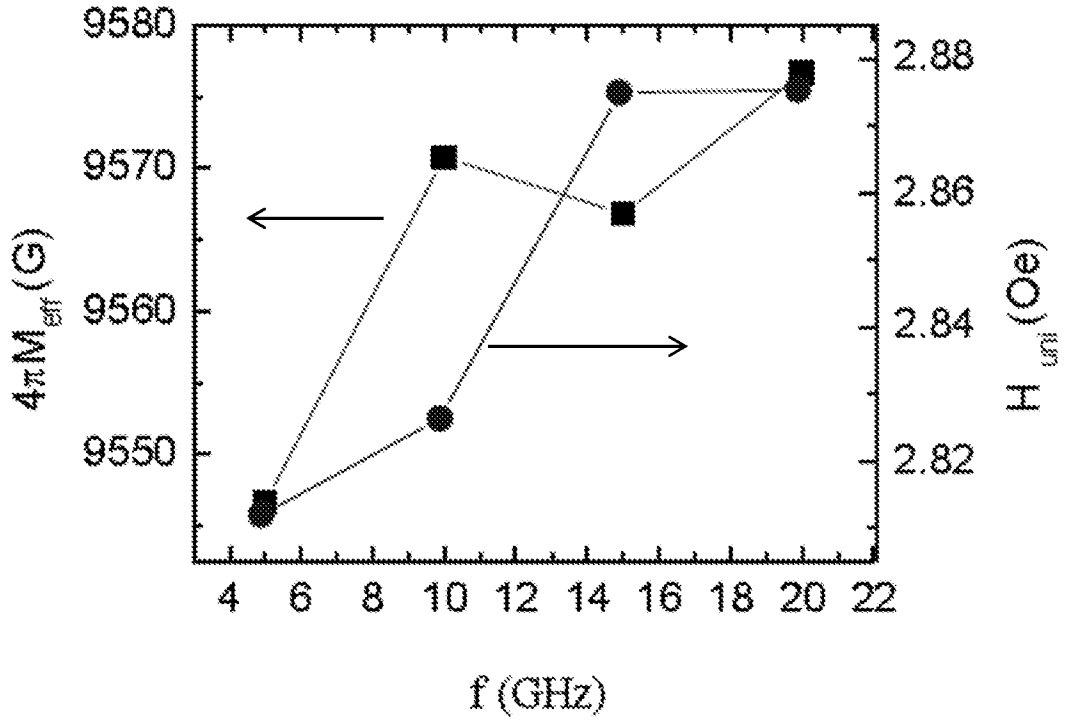

9580
9570
9560
9550
2.88
2.86
2.84
2.82
4πM_eff (G)
H_um (Oe)
4
6
8
10
12
14
16
18
20
22
f (GHz)

FIG. 9A

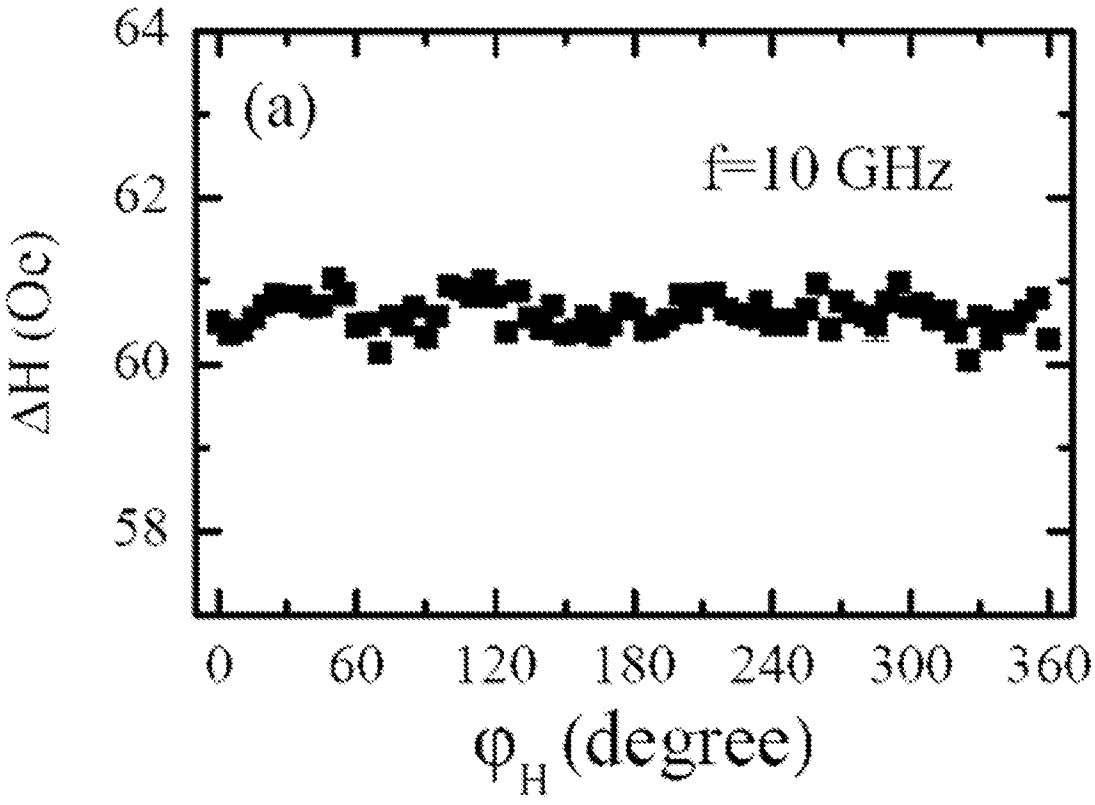


FIG. 9B

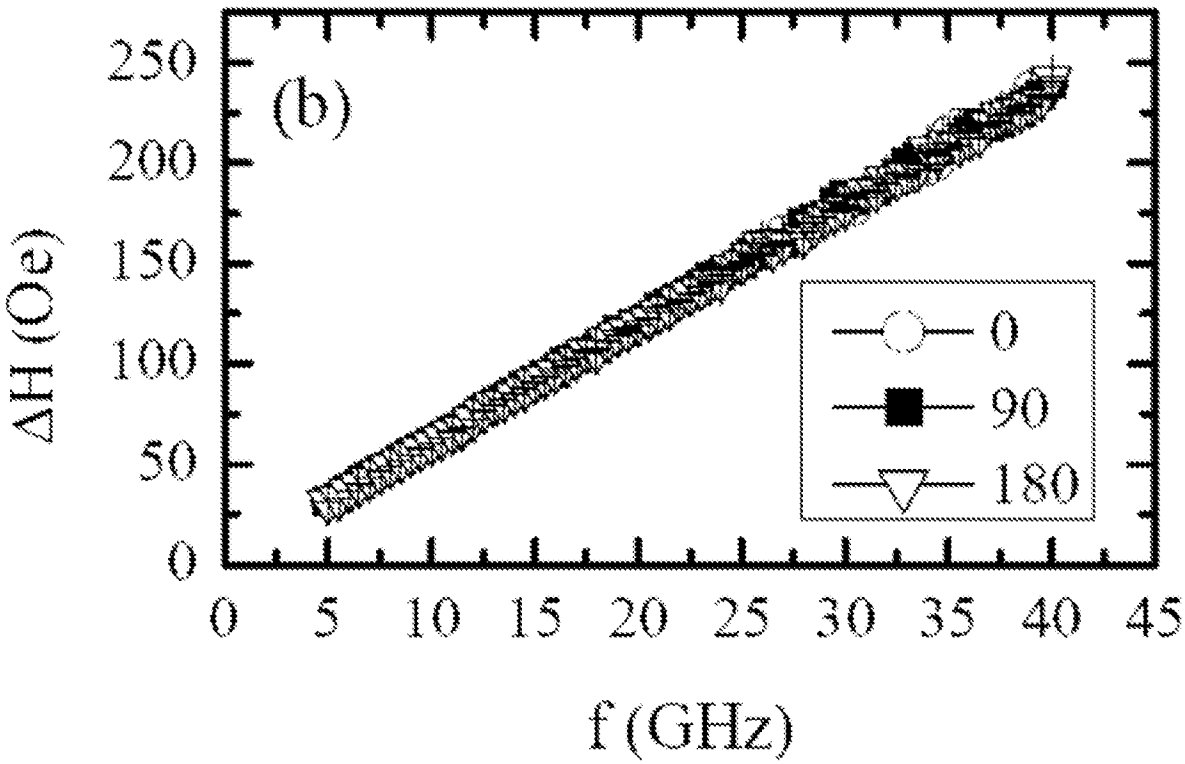


FIG. 9C

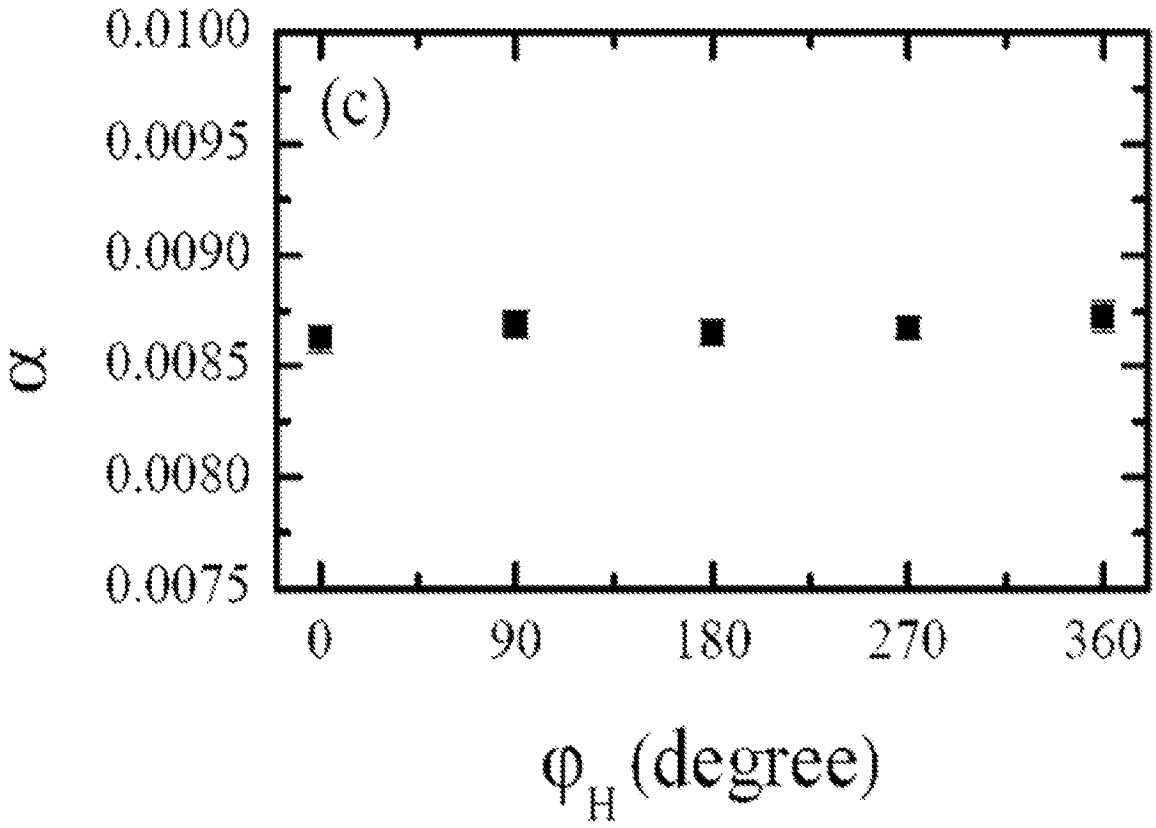

(c)
0.0100
0.0095
0.0090
0.0085
0.0080
0.0075
α
0
90
180
270
360
φH (degree)

FIG. 10A

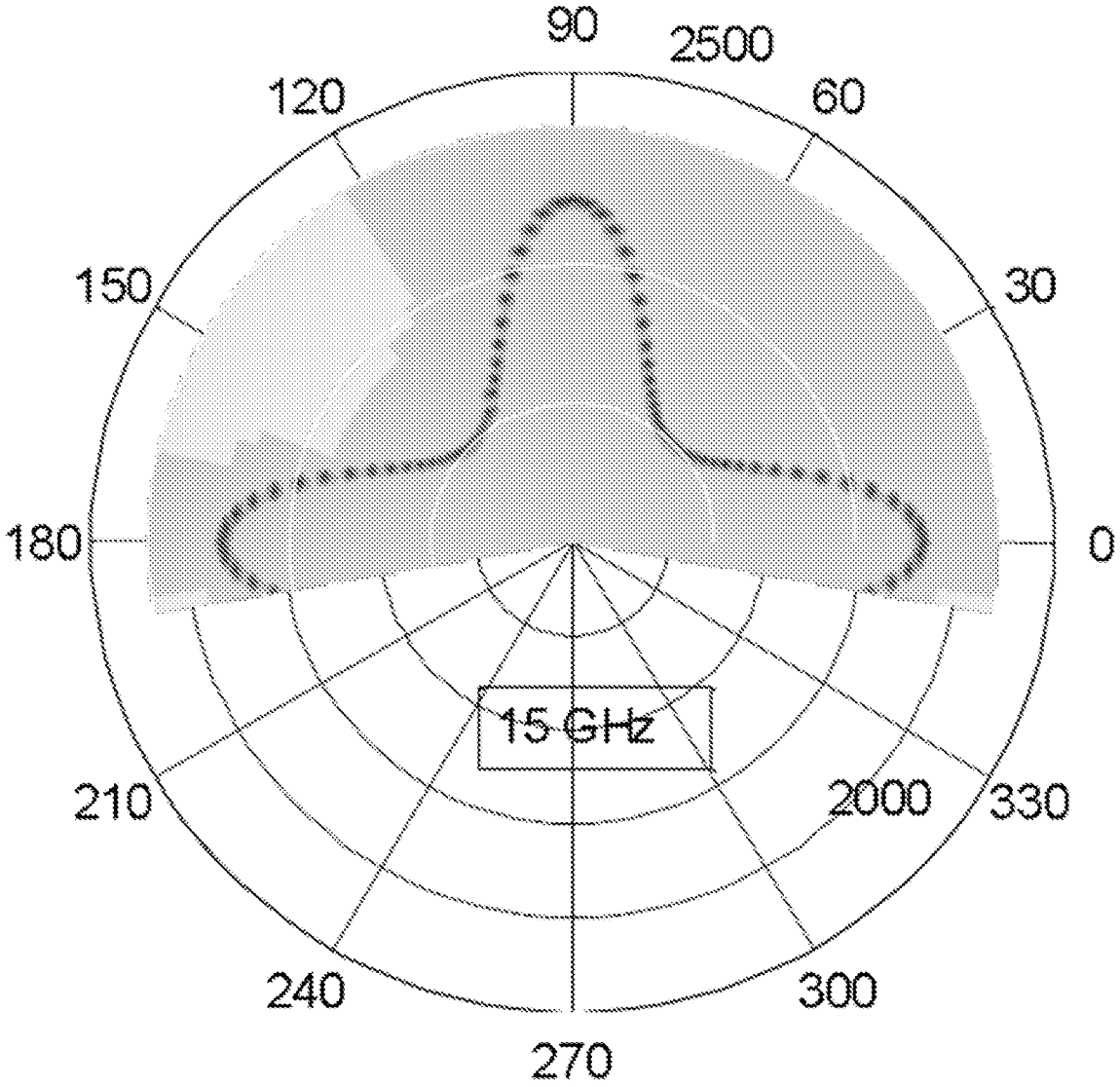


FIG. 10B

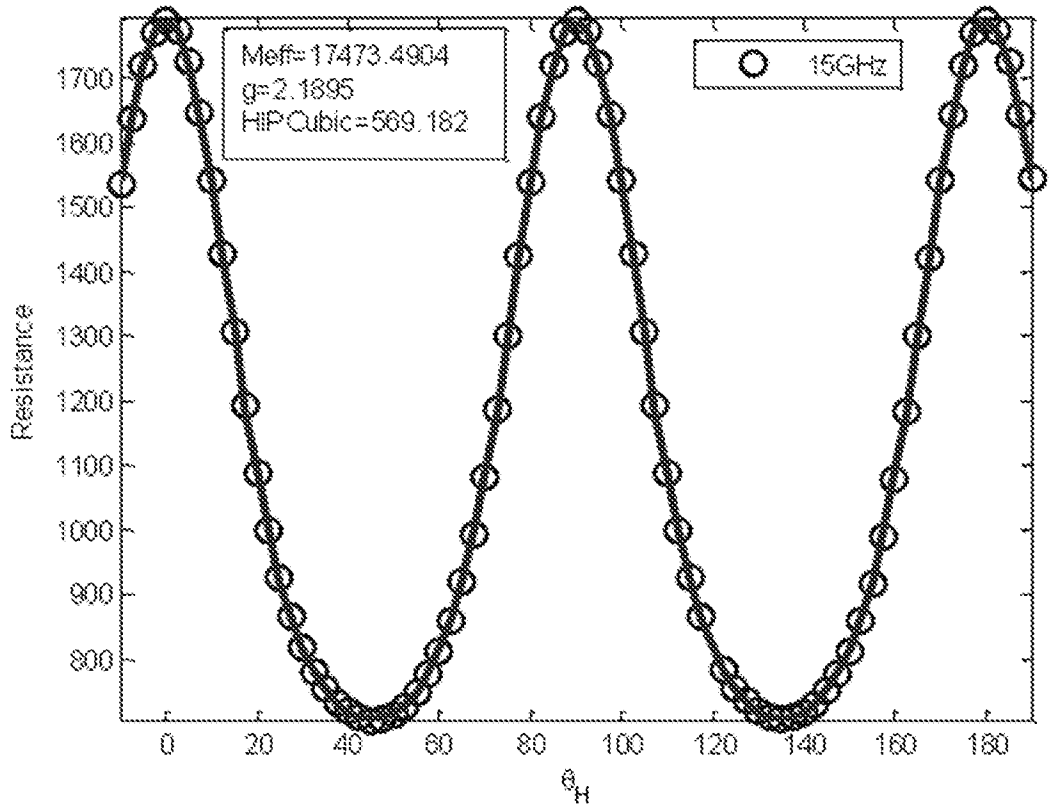

Meff=17473.4904
g=2.1695
HIPCubic=569.182
15GHz
Resistance
1700
1600
1500
1400
1300
1200
1100
1000
900
800
0
20
40
60
80
100
120
140
160
180
θH

FIG. 11

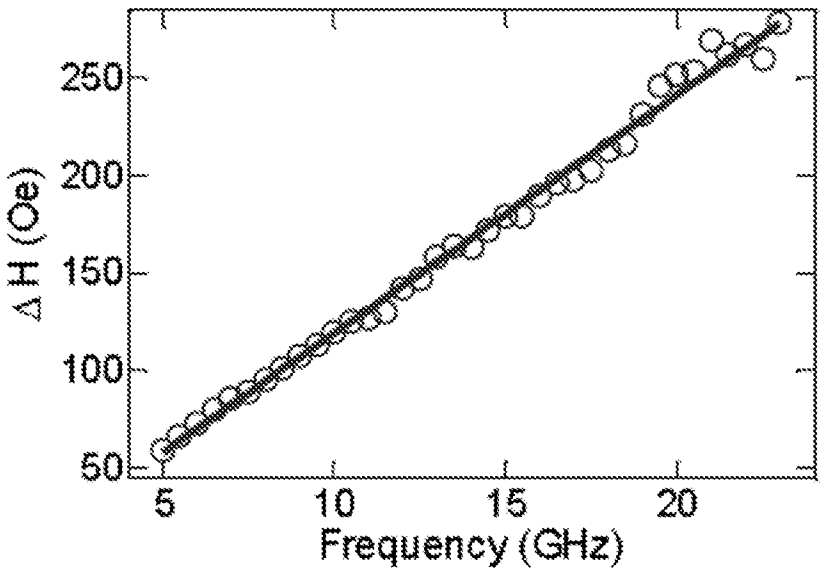


FIG. 12

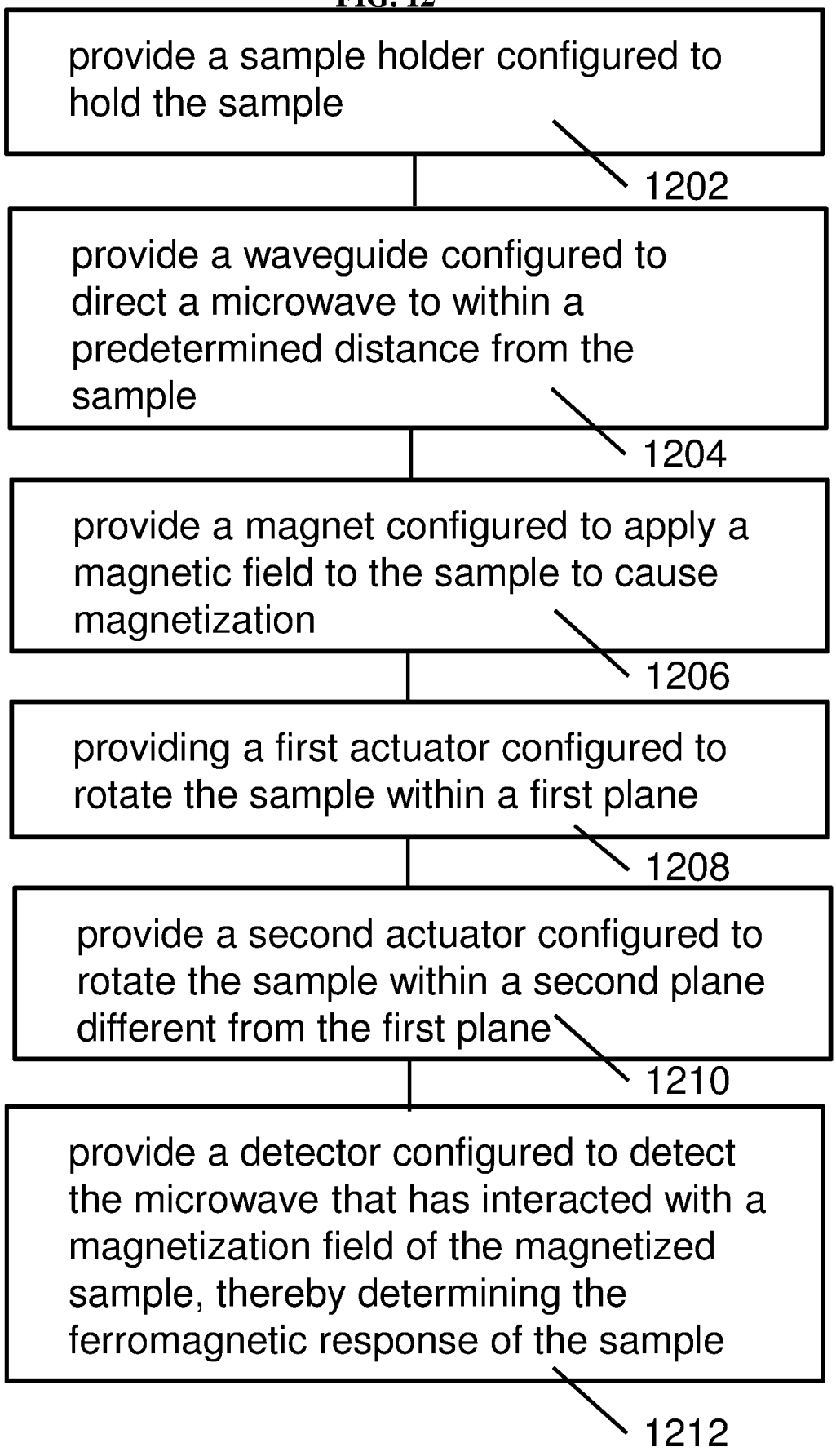
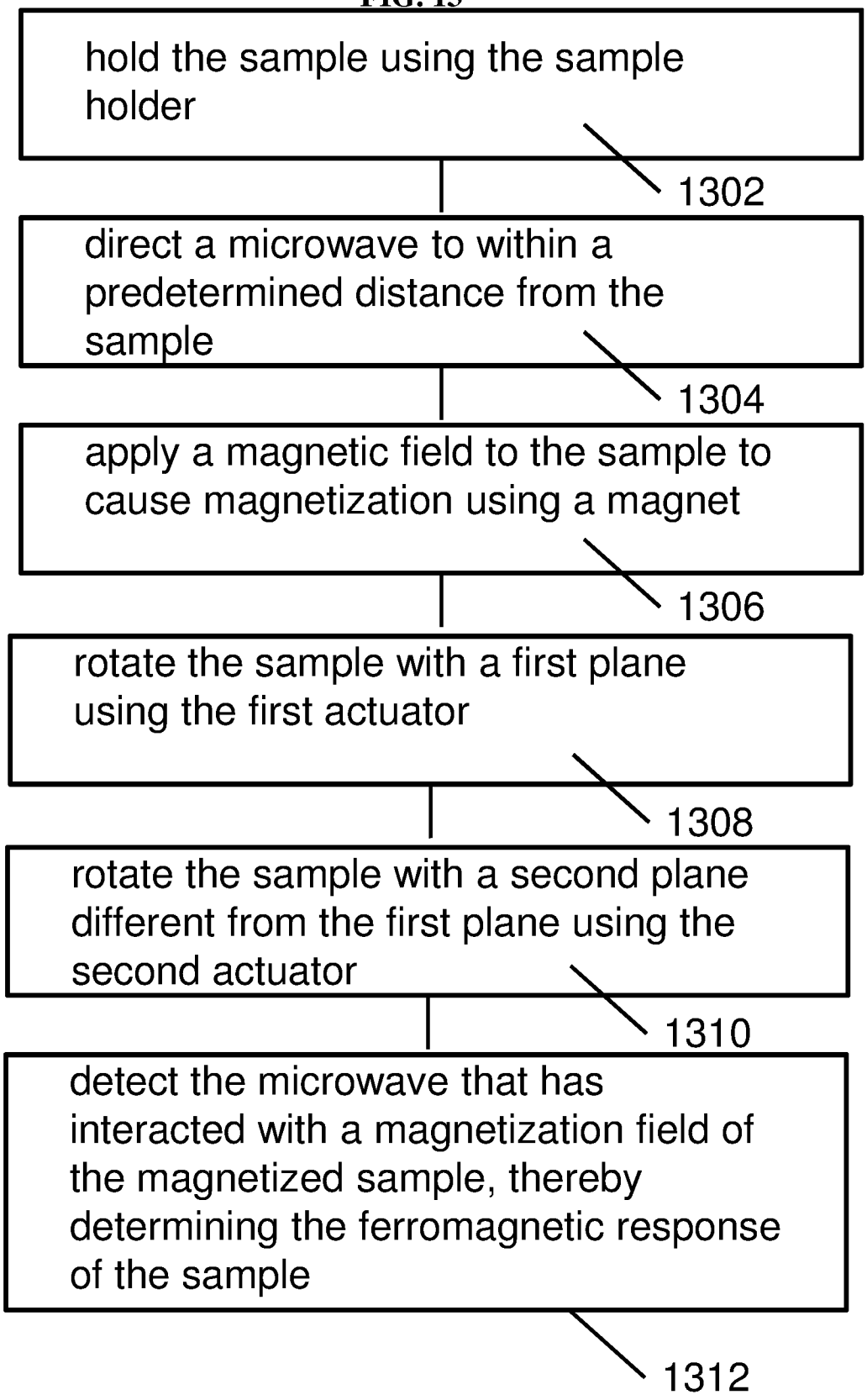

provide a sample holder configured to hold the sample
1202
provide a waveguide configured to direct a microwave to within a predetermined distance from the sample
1204
provide a magnet configured to apply a magnetic field to the sample to cause magnetization
1206
providing a first actuator configured to rotate the sample within a first plane
1208
provide a second actuator configured to rotate the sample within a second plane different from the first plane
1210
provide a detector configured to detect the microwave that has interacted with a magnetization field of the magnetized sample, thereby determining the ferromagnetic response of the sample
1212

FIG. 13


hold the sample using the sample holder
1302
direct a microwave to within a predetermined distance from the sample
1304
apply a magnetic field to the sample to cause magnetization using a magnet
1306
rotate the sample with a first plane using the first actuator
1308
rotate the sample with a second plane different from the first plane using the second actuator
1310
detect the microwave that has interacted with a magnetization field of the magnetized sample, thereby determining the ferromagnetic response of the sample
1312

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2017/050506

A. CLASSIFICATION OF SUBJECT MATTER

G01R 33/30 (2006.01) *G01R 33/345 (2006.01)* *G01R 33/381 (2006.01)* *G01N 22/00 (2006.01)*

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R; G01N 22/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT, Scopus: Ferromagnetic resonance, waveguide, rotating sample, detect microwave, angle, and related terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	He S. ET AL., A versatile rotary-stage high frequency probe station for studying magnetic films and devices. 15 July 2016 [Retrieved on 2017-11-15 from https://arxiv.org/abs/1607.04356] Pages 2-6, 9; Figures 2-4	1-20
A	He S. ET AL., A broadband Ferromagnetic Resonance dipper probe for magnetic damping measurements from 4.2 K to 300 K. 16 April 2016 [Retrieved on 2017-11-15 from https://arxiv.org/abs/1604.04688] Abstract; Figure 4	
A	CN 101819262 A (NANJING UNIVERSITY) 1 September 2010 Abstract; Figures 1, 2 of the machine translation	

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
15/11/2017 *(day/month/year)*	11/12/2017 *(day/month/year)*

Name and mailing address of the ISA/SG	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2017/050506

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 101819262 A	01/09/2010	NONE	