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(12) **United States Patent**
**Latham et al.**

(10) **Patent No.: US 10,132,879 B2**
(45) **Date of Patent: Nov. 20, 2018**

(54) **GAIN EQUALIZATION FOR MULTIPLE AXIS MAGNETIC FIELD SENSING**

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(73) Assignee: **Allegro MicroSystems, LLC**, Manchester, NH (US)

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(51) **Int. Cl.**

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| ***G01R 33/07*** | (2006.01) |
| ***G01R 33/09*** | (2006.01) |
| ***G01R 35/00*** | (2006.01) |
| ***G01D 5/14*** | (2006.01) |

(52) **U.S. Cl.**

CPC ........... ***G01R 33/077*** (2013.01); ***G01D 5/147*** (2013.01); ***G01R 35/005*** (2013.01)

(58) **Field of Classification Search**

CPC .... G01R 33/077; G01R 33/07; G01R 33/072; G01R 33/075; G01R 33/09; G01R 33/091; G01R 33/093; G01R 33/095; G01R 33/096; G01R 33/098; G01R 33/06; G01R 33/0206; G01R 33/028; G01R 33/1215; G01R 33/02; G01R 33/022; G01R 33/025; G01R 33/0017; G01R 35/005; G01D 5/142; G01D 5/145; G01D 5/1477

USPC ...... 324/251, 207.12, 207.13, 207.14, 207.2, 324/207.21, 117 H

See application file for complete search history.

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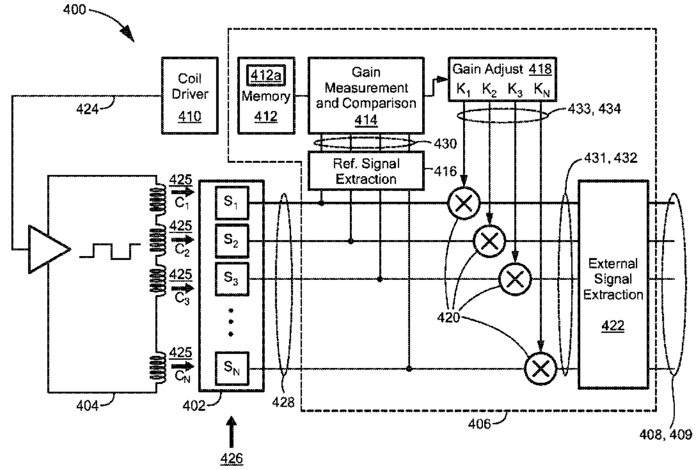
(57) **ABSTRACT**

A magnetic field sensor for sensing external magnetic fields on multiple axes comprises a coil structure and a gain equalization circuit. The coil structure generates reference fields on magnetic field sensing elements in each axis. The gain equalization circuit measures and compares reference fields to generate gain-equalized output signals responsive to the external magnetic fields.

**19 Claims, 9 Drawing Sheets**



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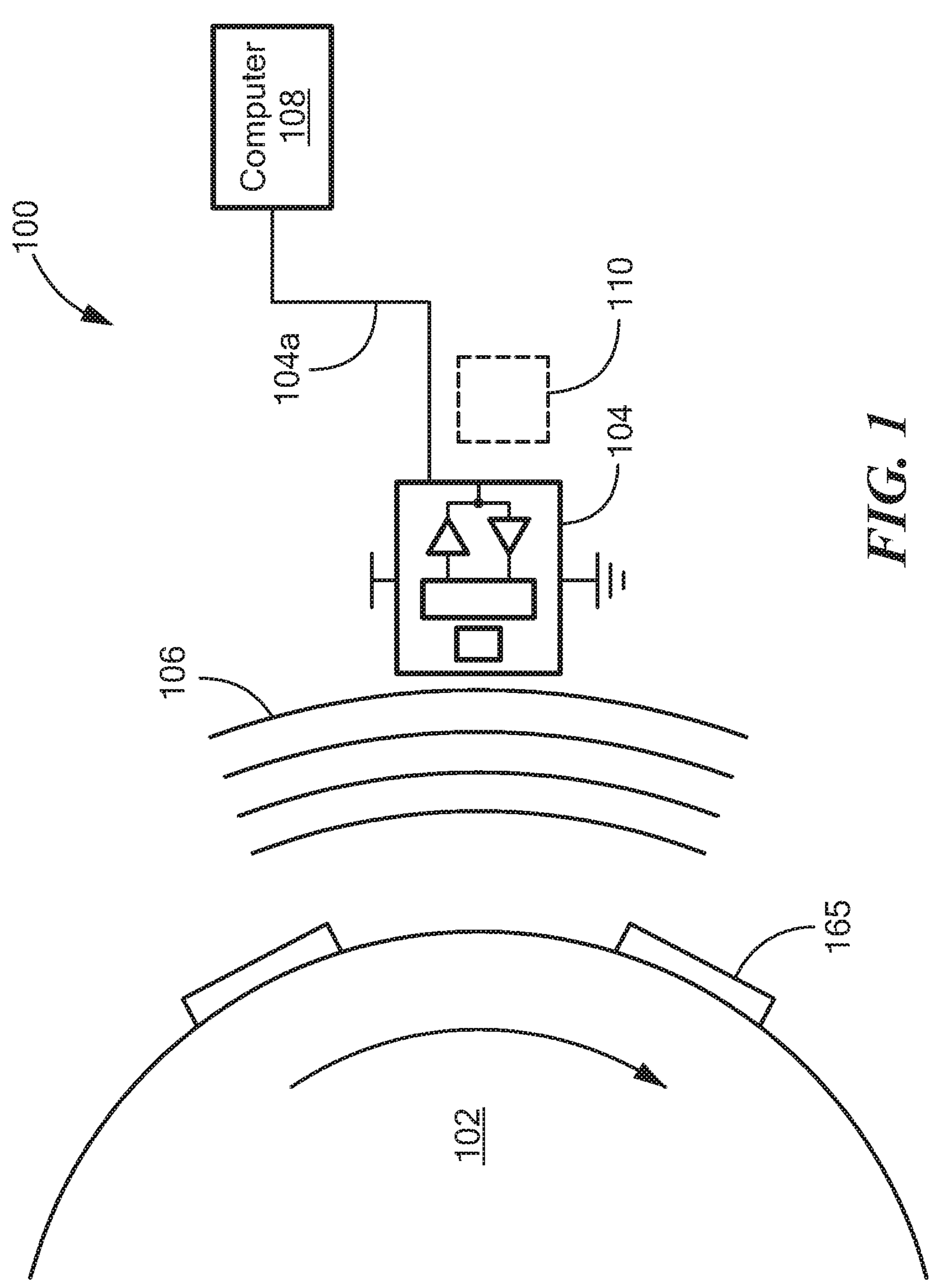
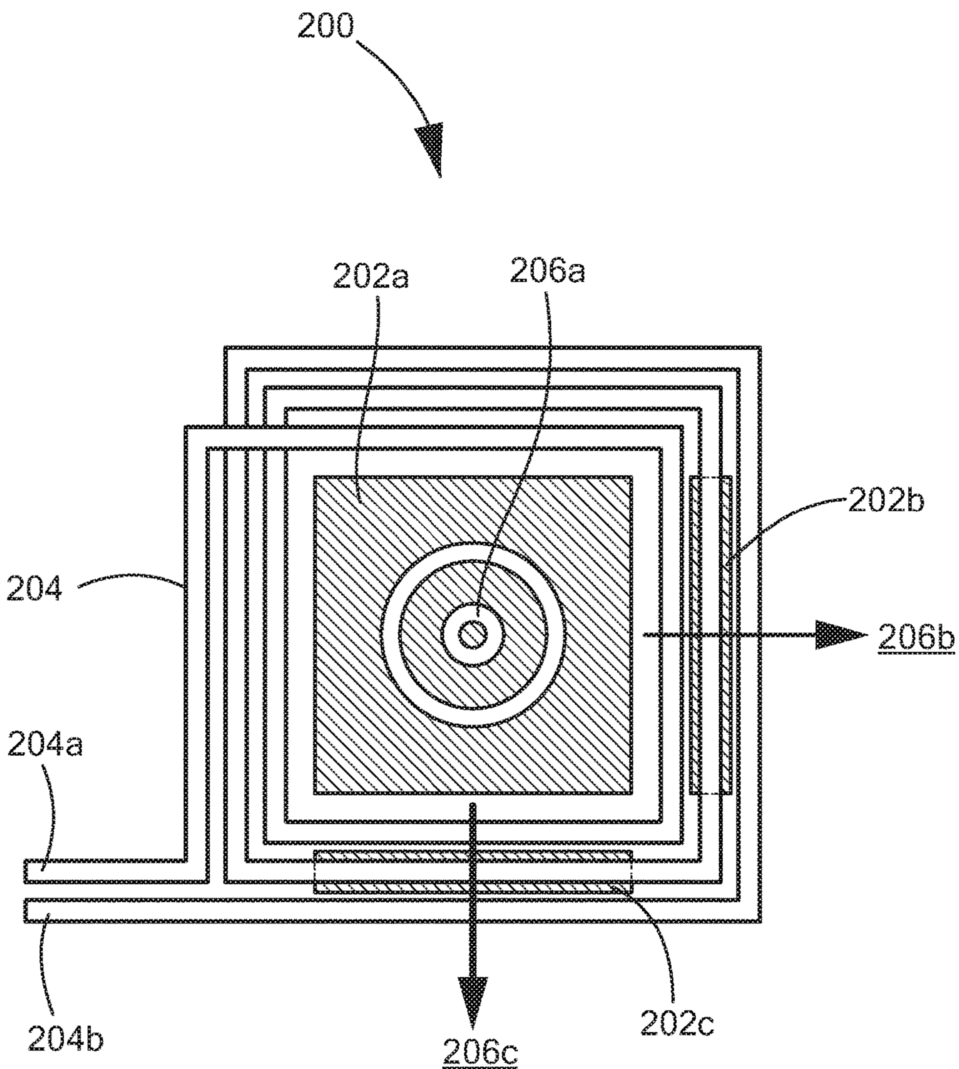



FIG. 1

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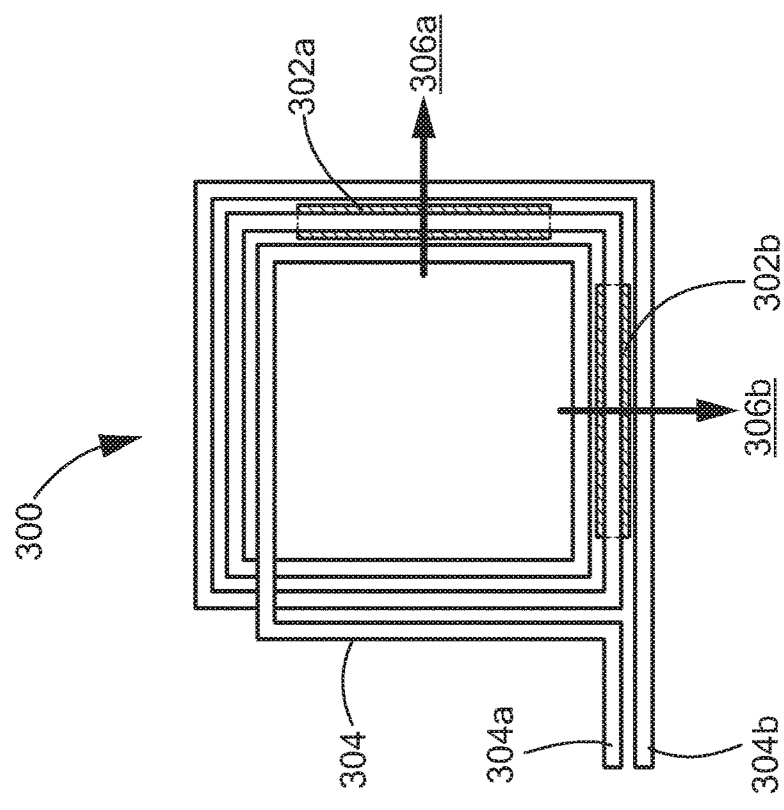
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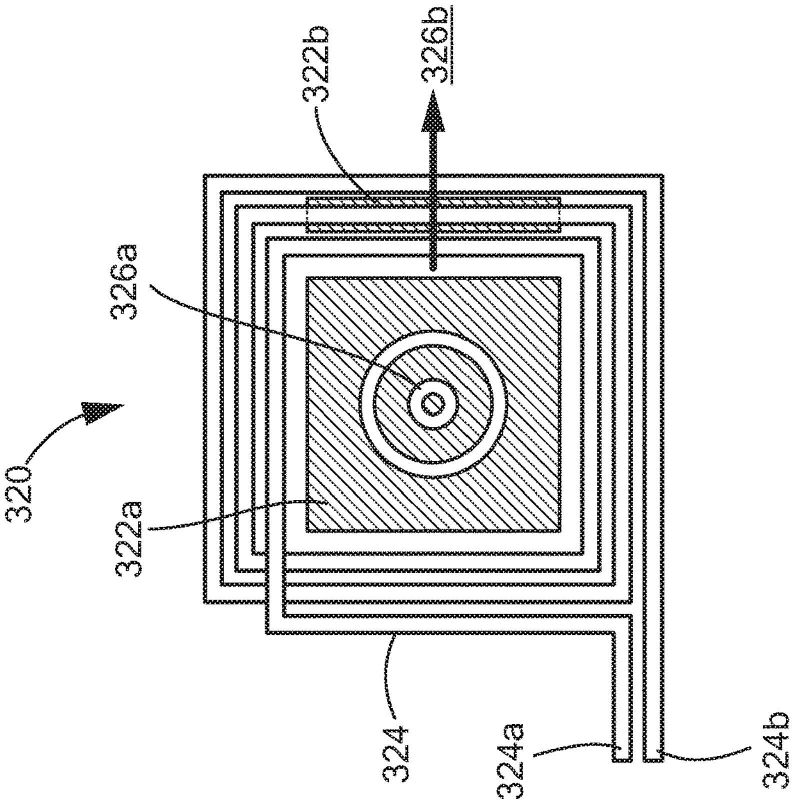
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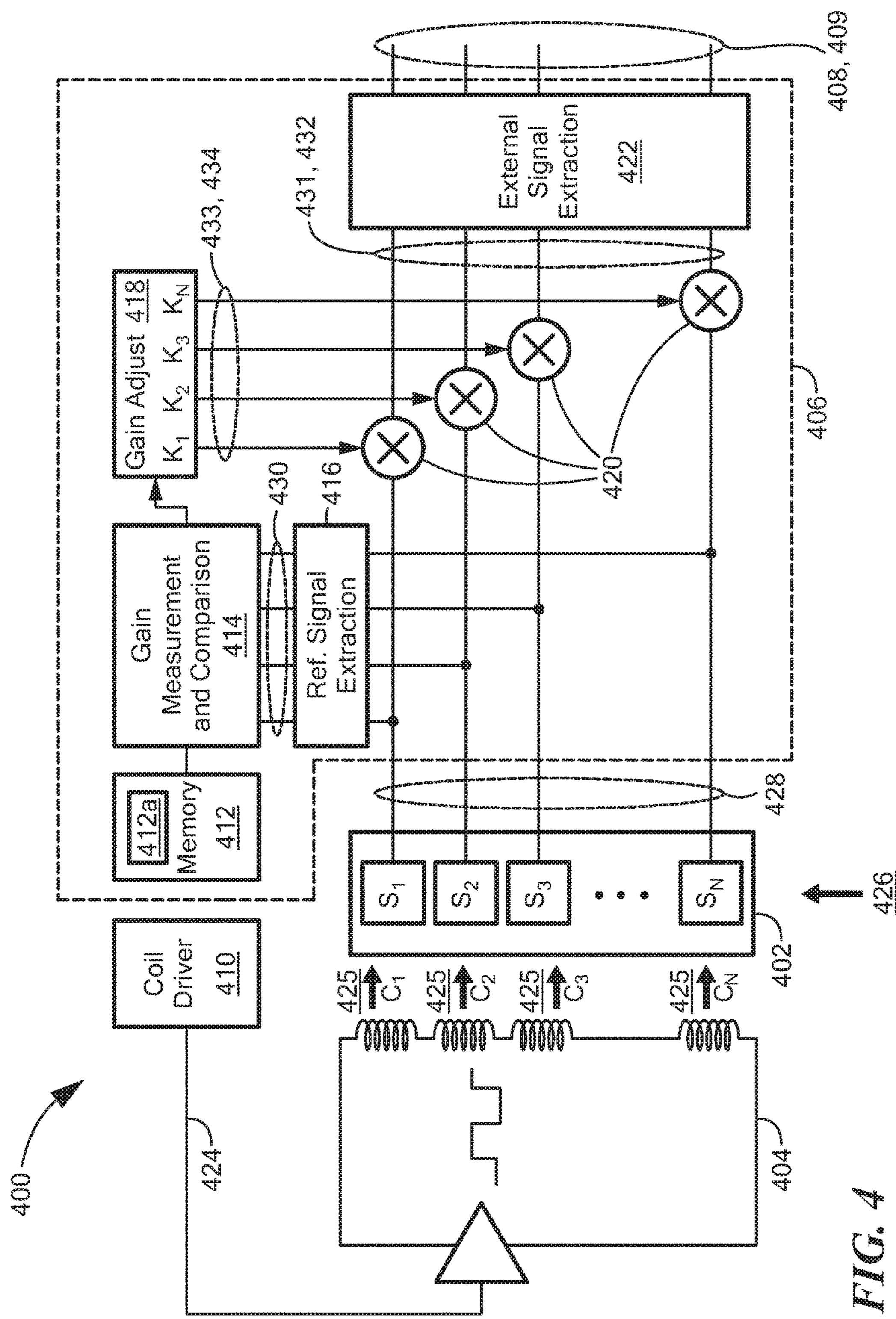
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Gain Measurement and Comparison 414
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408, 409

FIG. 4

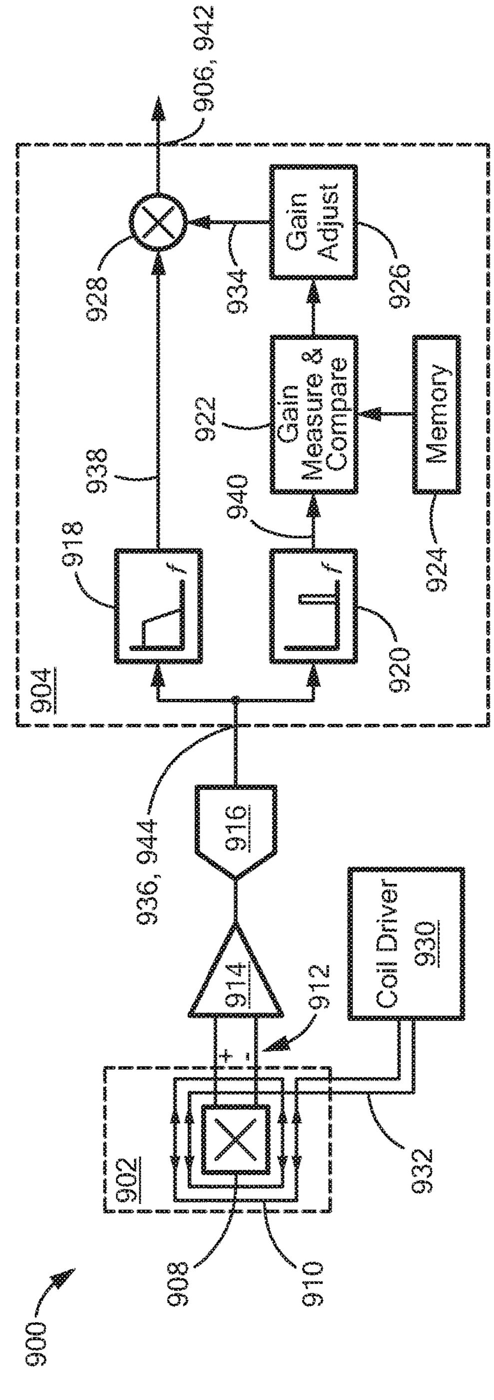
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FIG. 5

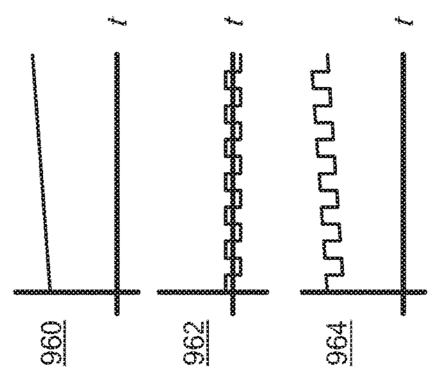
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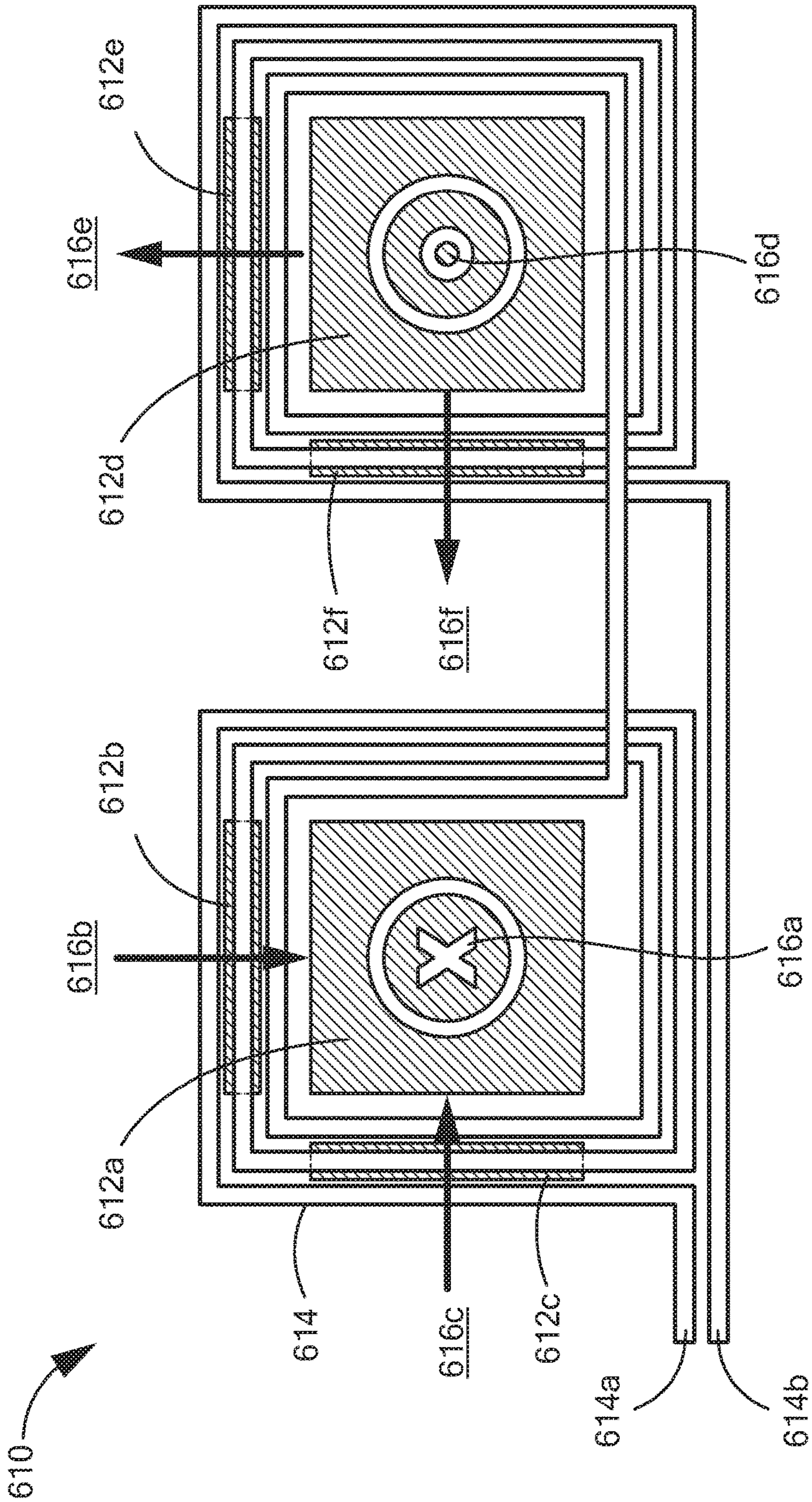
FIG. 5A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610

*FIG. 6*

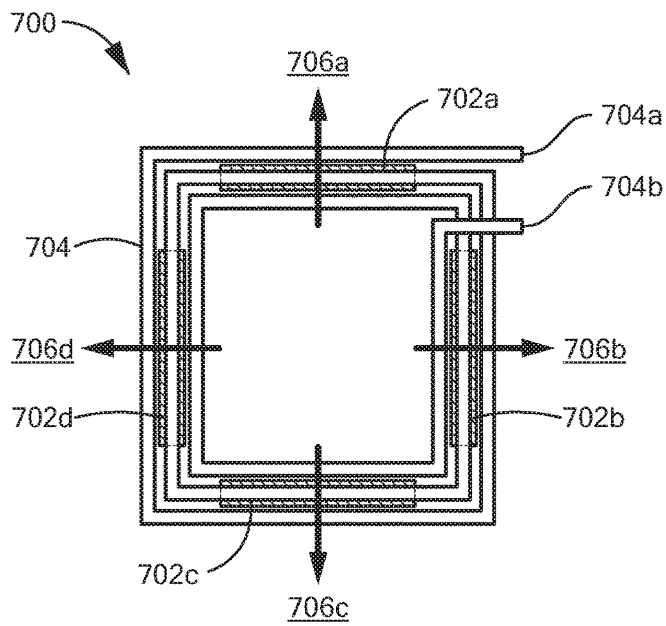
700
706a
702a
704a
704b
704
706d
706b
702d
702b
702c
706c

FIG. 7

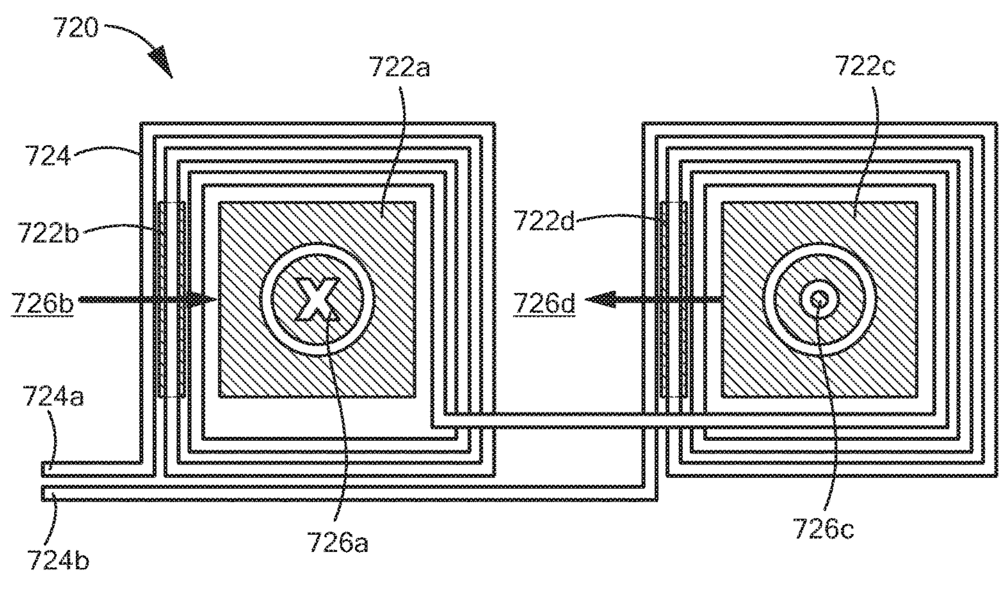
720
722a
722c
724
722b
722d
726b
726d
724a
724b
726a
726c

FIG. 7A

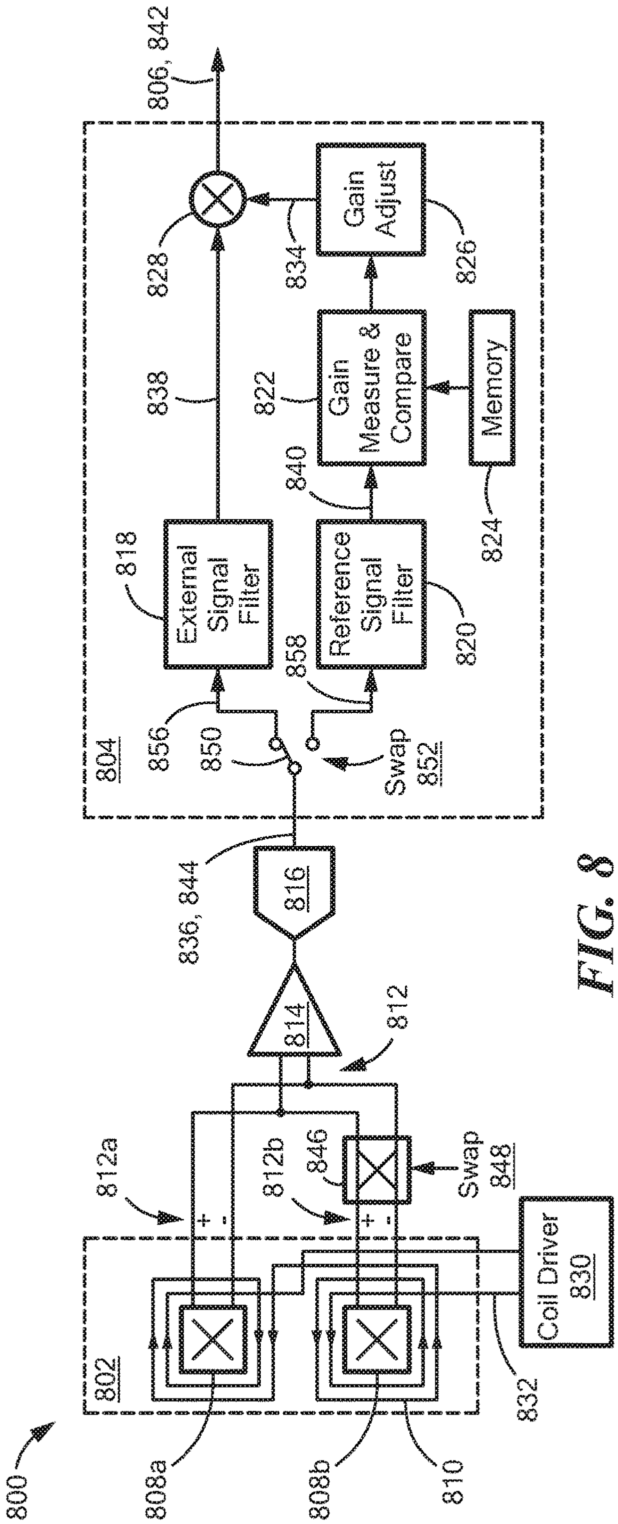
806, 842
828
834
Gain Adjust
826
838
822
Gain Measure & Compare
Memory
824
840
818
External Signal Filter
Reference Signal Filter
820
858
856
850
Swap
852
804
836, 844
816
814
812
812a
812b
846
Swap
848
Coil Driver
830
802
832
800
808a
808b
810

FIG. 8

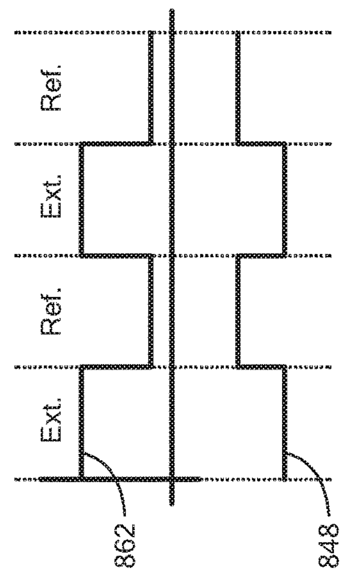
Ext.
Ref.
Ext.
Ref.
862
848

FIG. 8A

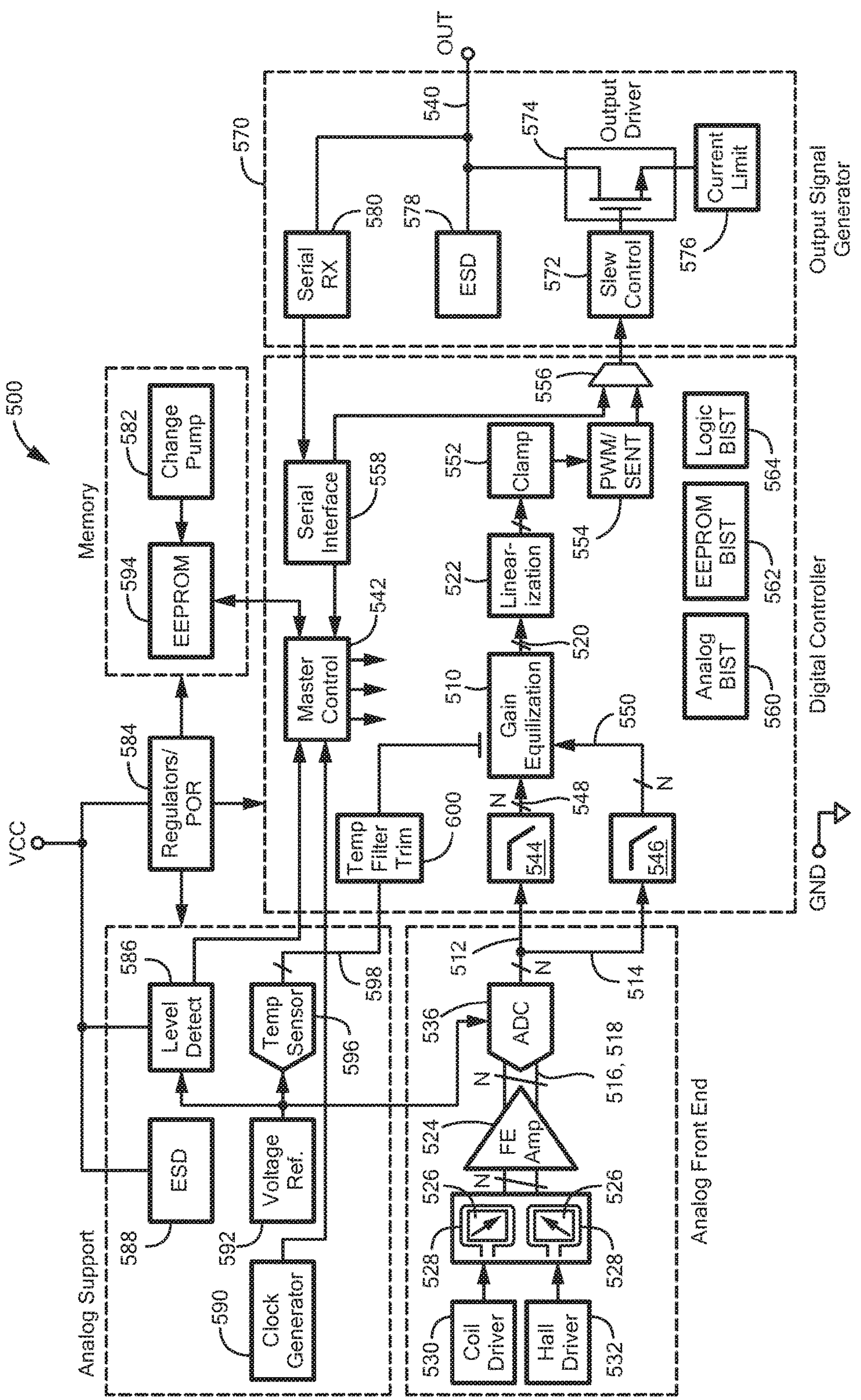
500
VCC
OUT
GND
Memory
Change Pump
582
EEPROM
594
Regulators/ POR
584
Analog Support
Level Detect
586
ESD
588
Temp Sensor
596
598
Voltage Ref.
592
Clock Generator
590
Analog Front End
Coil Driver
530
Hall Driver
532
528
526
FE Amp
524
N
516, 518
ADC
536
512
514
Digital Controller
Master Control
542
Serial Interface
558
Temp Filter Trim
600
544
546
548
550
Gain Equilization
510
520
Linear-ization
522
Clamp
552
PWM/ SENT
554
556
Analog BIST
560
EEPROM BIST
562
Logic BIST
564
Output Signal Generator
570
Serial RX
580
ESD
578
540
Slew Control
572
Output Driver
574
Current Limit
576

*FIG. 9*

# GAIN EQUALIZATION FOR MULTIPLE AXIS MAGNETIC FIELD SENSING

## FIELD OF THE INVENTION

This disclosure relates generally to magnetic field sensors and, more particularly, to magnetic field sensors having circuitry to sense and adjust a sensitivity of the magnetic field sensors to a magnetic field.

## BACKGROUND

Magnetic field sensors employ a variety of types of magnetic field sensing elements, for example, Hall effect elements and magnetoresistance elements, often coupled to a variety of electronics, all supported by a common substrate. Some magnetic field sensors (referred to herein as "two-dimensional" or "2D" magnetic field sensors) can sense magnetic fields in two different axes. Other magnetic field sensors (referred to herein as "three-dimensional" or "3D" magnetic field sensors) can sense magnetic fields in three different axes.

A magnetic field sensing element (and a magnetic field sensor) can be characterized by a variety of performance characteristics, one of which is a sensitivity, which can be expressed in terms of an output signal amplitude versus a magnetic field to which the magnetic field sensing element is exposed. The sensitivity of a magnetic field sensing element, and therefore, of a magnetic field sensor, is known to change in relation to a number of parameters. For example, the sensitivity can change in relation to a change in temperature of the magnetic field sensing element. As another example, the sensitivity can change in relation to a mechanical stress (or "strain") imposed upon the substrate supporting the magnetic field sensing element. Such stress can be imposed upon the substrate at the time of manufacture of an integrated circuit containing the substrate. For example, the strain can be imposed by stresses caused by curing of molding compounds used to form an encapsulation of the substrate, e.g., a plastic encapsulation.

It may be desirable to keep the gain of a magnetic field sensing element (or magnetic field sensor) constant over changes in temperature, mechanical stress, and other phenomena that may affect sensitivity. It is known to adjust the absolute gain of a magnetic field sensing element by applying a reference field and comparing the output signal amplitude to the known input magnetic field. To apply a reference field, a current may be passed through a coil that is located about the sensing element. If the current going into the coil is highly accurate over temperature, stress, etc., the absolute gain of the sensing element may be kept generally invariant. Moreover, it may be necessary to trim the current drive into the coil in order to maintain highly accurate absolute gain. Examples of using coil-generated reference fields with magnetic field sensors are described in U.S. Pat. Nos. 7,923,996, 8,447,556, and 9,201,122, each of which is incorporated by reference herein in its entirety.

## SUMMARY

In some applications that require 2D or 3D sensing—including so-called "slide-by" applications—gain equalization may be as important, or even more important, than maintaining constant absolute gain of magnetic field sensing elements.

According to embodiments of the disclosure, a 2D or 3D magnetic field sensor may include a coil structure to gen-



erate a magnetic field on magnetic field sensing elements configured to sense fields in multiple respective axes. The coil structure can be used to equalize the gains of the magnetic field sensing elements. By forcing current through the coil and monitoring the outputs of each sensing element, the ratio of the gains of the sensing elements can be determined. The measured gain ratios can be compared with reference gain ratios (e.g., ratios fixed by the geometry of the magnetic field sensor structure) and the result of the comparison used to adjust the gain of the sensing elements or of the resulting magnetic field signals to equalize gain. This process can be repeated over time to maintain gain equalization in the presence of temperature, mechanical stress, and other phenomena that may affect sensitivity.

In some embodiments, the current drive into the coil does not have to be trimmed in order to keep the gains equalized.

According to one aspect of the disclosure, a structure for multiple axis magnetic field sensing comprises: a plurality of magnetic field sensing elements including a first magnetic field sensing element arranged to have a maximum response to a magnetic field along a first axis, and a second magnetic field sensing element arranged to have a maximum response to the magnetic field along a second axis; and a coil structure configured to generate magnetic fields on each of the plurality of magnetic field sensing elements when a current passes through the coil structure.

In some embodiments, the first and second magnetic field sensing elements comprise vertical Hall effect elements. In certain embodiments, first magnetic field sensing element comprises a planar Hall effect element and the second magnetic field sensing element comprises a vertical Hall effect element. In some embodiments, at least one of the plurality of magnetic field sensing elements comprises a magnetoresistance element.

In particular embodiments, the plurality of magnetic field sensing elements further includes a third magnetic field sensing element arranged to have a maximum response to the magnetic field along a third axis. In some embodiments, the first magnetic field sensing element comprises a planar Hall effect element, and the second and third magnetic field sensing elements comprise vertical Hall effect elements.

In various embodiments, first magnetic field sensing element comprises a first differential magnetic field sensing element and the second magnetic field sensing element comprises a second differential magnetic field sensing element. The coil structure may be configured to generate differential magnetic fields on the first and second differential magnetic field sensing elements. In some embodiments, the first differential magnetic field sensing element comprises two vertical Hall elements and the second differential magnetic field sensing element comprises two vertical Hall elements. In certain embodiments, the first differential magnetic field sensing element comprises two planar Hall elements and the second differential magnetic field sensing element comprises two vertical Hall elements.

In particular embodiments, the plurality of magnetic field sensing elements further includes a third magnetic field sensing element arranged to have a maximum response to the magnetic field along a third axis, wherein the third magnetic field sensing element comprises a third differential magnetic field sensing element. In some embodiments, the first differential magnetic field sensing element comprises two planar Hall effect elements, the second differential magnetic field sensing element comprises two vertical Hall effect elements, and the third differential magnetic field sensing element comprises two vertical Hall effect elements. In various embodiments, the coil structure comprises windings a first direction around the a first one of the two planar Hall effect elements and windings in a second opposite direction around a second one of the two planar Hall effect elements.

In some embodiment, the coil structure comprises a continuous length of conductive material. In certain embodiments, the coil structure comprises multiple coils each configured to generate a magnetic field on one or more of the magnetic field sensing elements when a current passes through the coil. The currents passing through the multiple coils may be matched. In particular embodiments, the multiple coils are coupled in series.

In some embodiments, the coil structure is configured to generate a first magnetic field substantially parallel to the first axis and a second magnetic field substantially parallel to the second axis.

According to another aspect of the disclosure, a magnetic field sensor comprises: a plurality of magnetic field sensing elements; a coil driver configured to generate a coil drive signal; a coil structure coupled to the coil driver and configured to generate a reference magnetic field on each of the plurality of magnetic field sensing elements in response to the coil drive signal, wherein each of the plurality of magnetic field sensing elements is configured to generate an output signal responsive to the respective reference magnetic field and to external magnetic fields; a memory configured to store reference gains associated with the plurality of magnetic field sensing elements; and a gain equalization circuit having inputs coupled to outputs of the plurality of magnetic field sensing elements and a plurality of outputs, the gain equalization circuit configured to extract a reference signal and an external signal from each of the plurality of magnetic field sensing element output signals, to measure a gain of each of the plurality of reference signals, to compare the measured gains to the reference gains, and to adjust the gain of the external signals based on the comparing. In some embodiments, the sensor further comprises a circuit to adjust gains of the external signals in response to the gain adjustment signals.

In certain embodiments, the coil driver is configured to generate a coil drive signal as an alternating current (AC) signal having a frequency substantially different than a frequency associated with the external magnetic fields. The gain equalization circuit may include an external signal filter to extract the external signals from the plurality of magnetic field sensing element output signals and a reference signal filter to extract the reference signals from the plurality of magnetic field sensing element output signals.

In some embodiments, the plurality of magnetic field sensing elements comprises a plurality of differential magnetic field sensing elements, wherein the coil structure is configured to generate a differential reference magnetic field on each of the plurality of magnetic field sensing elements. The magnetic field sensor may further include a plurality of differential output switches each configured to couple outputs of a respective one of the differential magnetic field sensing elements in multiple different configurations.

In particular embodiments, at least one of the differential output switches is configured to couple the outputs of the respective differential magnetic field sensing element in a first configuration and in a second configuration, wherein in the first configuration, the differential magnetic field sensing element outputs are responsive to the external magnetic fields but not the respective differential reference magnetic field, and wherein in the second configuration, the differential magnetic field sensing element outputs are responsive to the respective differential reference magnetic field but not the external magnetic fields. In some embodiments, the sensor further includes a timing circuit to repeatedly alternate between the first configuration and the second configuration.

In various embodiments, the coil structure comprises multiple coils coupled to the coil driver to receive matched currents.

## BRIEF DESCRIPTION OF THE DRAWINGS

The concepts, structures, and techniques sought to be protected herein may be more fully understood from the following detailed description of the drawings, in which:

FIG. **1** is a block diagram of a system including a magnetic field sensor according to an embodiment;

FIG. **2** is diagram of a structure having three magnetic field sensing elements and a coil structure, according to an embodiment;

FIG. **3** is a diagram of a structure having two magnetic field sensing elements and a coil structure, according to an embodiment;

FIG. **3**A is a diagram of a structure having two magnetic field sensing elements and a coil structure, according to another embodiment;

FIG. **4** is a block diagram of a magnetic field sensor that can provide gain equalization, according to an embodiment;

FIG. **5** is a block diagram of a magnetic field sensor that can provide gain equalization using frequency multiplexing, according to an embodiment;

FIG. **5**A are waveform diagrams of illustrative signals that may be generated and/or processed by the magnetic field sensor of FIG. **5**;

FIG. **6** is a block diagram of a structure having three differential magnetic field sensing elements and a coil structure, according to an embodiment;

FIG. **7** is a block diagram of a structure having two differential magnetic field sensing elements and a coil structure, according to an embodiment;

FIG. **7**A is a block diagram of a structure having two differential magnetic field sensing elements and a coil structure, according to another embodiment;

FIG. **8** is a block diagram of a magnetic field sensor that can provide gain equalization using time sharing, according to an embodiment;

FIG. **8**A are waveform diagrams of illustrative signals that may be generated and/or processed by the magnetic field sensor of FIG. **8**; and

FIG. **9** is a circuit diagram of a magnetic field sensor, according to an embodiment.

The drawings are not necessarily to scale, or inclusive of all elements of a system, emphasis instead generally being placed upon illustrating the concepts, structures, and techniques sought to be protected herein.

## DETAILED DESCRIPTION

As used herein, the term "magnetic field sensing element" is used to describe a variety of electronic elements that can sense a magnetic field. The magnetic field sensing element can be, but is not limited to, a Hall Effect element, a magnetoresistance element, or a magnetotransistor. As is known, there are different types of Hall Effect elements, for example, a planar Hall element, a vertical Hall element, and a Circular Vertical Hall (CVH) element. As is also known, there are different types of magnetoresistance elements, for example, a semiconductor magnetoresistance element such as Indium Antimonide (InSb), a giant magnetoresistance

(GMR) element, an anisotropic magnetoresistance element (AMR), a tunneling magnetoresistance (TMR) element, a magnetic tunnel junction (MTJ), a spin-valve, etc. The magnetic field sensing element may be a single element or, alternatively, may include two or more magnetic field sensing elements arranged in various configurations, e.g., a half bridge or full (Wheatstone) bridge. Depending on the device type and other application requirements, the magnetic field sensing element may be a device made of a type IV semiconductor material such as Silicon (Si) or Germanium (Ge), or a type III-V semiconductor material like Gallium-Arsenide (GaAs) or an Indium compound, e.g., Indium-Antimonide (InSb).

As is known, some of the above-described magnetic field sensing elements may have an axis of maximum sensitivity parallel to a substrate that supports the magnetic field sensing element, and others of the above-described magnetic field sensing elements may have an axis of maximum sensitivity perpendicular to a substrate that supports the magnetic field sensing element. In particular, planar Hall elements tend to have axes of sensitivity perpendicular to a substrate, while metal based or metallic magnetoresistance elements (e.g., GMR, TMR, AMR, spin-valve) and vertical Hall elements tend to have axes of sensitivity parallel to a substrate.

It will be appreciated by those of ordinary skill in the art that while a substrate (e.g. a semiconductor substrate) is described as "supporting" the magnetic field sensing element, the element may be disposed "over" or "on" the active semiconductor surface, or may be formed "in" or "as part of" the semiconductor substrate, depending upon the type of magnetic field sensing element. For simplicity of explanation, while the embodiments described herein may utilize any suitable type of magnetic field sensing elements, such elements will be described here as being supported by the substrate.

As used herein, the term "magnetic field sensor" is used to describe a circuit that uses a magnetic field sensing element, generally in combination with other circuits. Magnetic field sensors are used in a variety of applications, including, but not limited to, an angle sensor that senses an angle of a direction of a magnetic field, a current sensor that senses a magnetic field generated by a current carried by a current-carrying conductor, a magnetic switch that senses the proximity of a ferromagnetic object, a rotation detector that senses passing ferromagnetic articles, for example, magnetic domains of a ring magnet or a ferromagnetic target (e.g., gear teeth) where the magnetic field sensor may be used in combination with a back-biased or other magnet, and a magnetic field sensor that senses a magnetic field density of a magnetic field.

As used herein, the term "multiple axis magnetic field sensor" refers to a device that can measure magnetic fields in two or more different axes (or "dimensions"). The term "relative gain" is used herein to refer to the gain of a magnetic field sensing element relative to the gain of one or more other magnetic field sensing elements. The term "gain equalization" refers to a property of multiple axis magnetic field sensors whereby the relative gain between two or more magnetic field sensing elements is generally invariant over time.

As used herein, the term "target" is used to describe an object to be sensed or detected by a magnetic field sensor or magnetic field sensing element. A target may be ferromagnetic, non-ferromagnetic, or magnetic.

FIG. **1** shows a system **100** for detecting a target **102**, according to an embodiment of the disclosure. The system **100** may include a magnetic field sensor **104** placed adjacent to target **102** so that a magnetic field **106** can be sensed by magnetic field sensor **104**. In an embodiment, target **102** is a magnetic target and produces external magnetic field **106**. In another embodiment, magnetic field **106** is generated by a magnetic source **110** (e.g. a back-bias magnet or electromagnet). A target **102** may be either a magnetic or a non-magnetic target. In these instances, as target **102** moves through or within magnetic field **106**, it causes perturbations to external magnetic field **106** that can be detected by magnetic field sensor **104**.

Magnetic field sensor **104** may detect and process changes in external magnetic field **106**. For example, magnetic field sensor **104** may detect changes in magnetic field **106** as target **102** rotates and features **165** move closer to and away from magnetic field sensor **104**, thus increasing and decreasing the strength of the magnetic field **106** sensed by magnetic field sensor **104**. Magnetic field sensor **104** may include circuitry to determine the speed, direction, proximity, angle, etc. of target **102** based on these changes to magnetic field **106**. Although target **102** is shown as a toothed gear in FIG. **1**, other arrangements and shapes that can affect magnetic field **106** as target **102** rotates are possible. For example, magnetic target **102** may have a non-symmetrical shape (such as an oval), may include sections of different material that affect the magnetic field, etc.

In an embodiment, magnetic sensor **104** is coupled to a computer **108**, which may be a general purpose processor executing software or firmware, a custom processor, or a custom electronic circuit for processing output signal **104*a*** from magnetic sensor **104**. Output signal **104*a*** may provide information about the speed, position, and/or direction of motion of target **102** to computer **108**, which may then perform operations based on the received information. In an embodiment, computer **108** is an automotive computer (also referred to as an engine control unit) installed in a vehicle and target **102** is a moving part within the vehicle, such as a transmission shaft, a brake rotor, etc. Magnetic sensor **104** detects the speed and direction of target **102** and computer **108** controls automotive functions (like all-wheel drive, ABS, speedometer display control, etc.) in response to the information provided by magnetic field sensor **104**.

In an embodiment, computer **108** may be located relatively distant from magnetic field sensor **104**. For example, computer **108** may be located under the hood of a vehicle while magnetic field sensor **104** is located at a wheel or transmission element near the bottom and/or rear of the vehicle. In such an embodiment, having a serial communication interface with a minimal number of electrical connections (e.g. wires) between computer **108** and magnetic field sensor **104** may be beneficial, and may reduce cost and maintenance requirements.

In embodiments, where magnetic field sensor **104** operates as part of a system that affects vehicular safety such as the brake or transmission system, it may be desirable for magnetic field sensor **104** to perform self-tests and report to computer **108** any errors or faults that occur.

In embodiments, magnetic field sensor **104** includes multiple magnetic field sensing elements (e.g., the sensor **104** may be a 2D or a 3D magnetic field sensor). The sensor **104** may further include a coil structure and a gain equalization circuit that, together, can be used to equalize the gain of the magnetic field sensing elements in the presence of temperature, mechanical stress, and other phenomena that may affect sensitivity.

Referring to FIG. **2**, a structure **200** may be used for three-dimensional (3D) magnetic field sensing, according to one embodiment. The structure **200** may include three magnetic field sensing elements (or "sensing elements") **202***a*, **202***b*, **202***c* and a coil structure **204**. In some embodiments, the structure **200** may be provided as an integrated circuit (IC).

In some embodiments, the sensing elements **202***a*-**202***c* may be arranged to have a maximum response along three different axes (e.g., X, Y, and Z axes) to allow for 3D sensing. For example, a first sensing element **202***a* may be arranged to have a maximum response perpendicular to the page, a second sensing element **202***b* may be arranged to have a maximum response across the page, and a third sensing element **202***c* may be arranged to have a maximum response from top to bottom of the page. In this arrangement, the first sensing element **202***a* may be provided as a planar Hall effect element (or "Hall element"), whereas the second and third sensing elements **202***b*, **202***c* may be provided as vertical Hall elements.

The coil structure **204** may be provided from any material and in any orientation suitable to generate magnetic fields on the sensing elements **202***a*-**202***c*. In some embodiments, the coil structure **204** is provided as a continuous length of conductive material (e.g., a metal) having two terminals **204***a*, **204***b*. The terminals **204***a*, **204***b* can be connected to a current source (not shown) to generate a current through the coil.

In some embodiments, the geometry of the coil structure **204** (e.g., the number and direction of windings) may be selected to generate a magnetic field having components substantially parallel to the axis of maximum response for each of the sensing elements **202***a*-**202***c*.

For simplicity of explanation, various coil structures (such as coil structure **204**) may be described herein as generating (or being configured to generate) multiple magnetic fields. It will be understood that such coil structures may actually generate a single magnetic field having field components in multiple different directions (e.g., along multiple different axes).

Referring again to FIG. **2**, the coil structure **204** may be configured to generate a first field **206***a* parallel to the axis of maximum response for sensing element **202***a*, a second field **206***b* parallel to the axis of maximum response for sensing element **202***b*, and a third field **206***c* parallel to the axis of maximum response for sensing element **202***c*.

As explained above, in some embodiments the coil structure **204** comprises a continuous length of conductive material. This arrangement can be useful because the same windings create field on multiple sensing elements **202***a*-**202***c*. In other embodiments, multiple coils may be used (e.g., one coil per sensing elements **202***a*-**202***c*). The multiple coils could be coupled in series so that the same current is used to generate fields on each sensing elements **202***a*-**202***c*. Alternatively, in some embodiments, the multiple coils could be coupled to multiple different current sources. Here, the current sources may use a mirroring technique (or similar methods for matching currents) in order to put nearly the same amount of current through each coil.

The magnetic field sensing elements **202***a*, **202***b*, and **202***c* may have sensitivities $S_1$, $S_2$, and $S_3$, respectively. The sensitivities $S_1$, $S_2$, and $S_3$ may vary with temperature, stress, and other conditions imposed, for example, on an IC substrate. When a current is passed through the coil structure **204**, a magnetic field may be generated on each of the sensing elements **202***a*-**202***c*. The magnitude of the field generated in the ith sensing element, which may be determined by the geometry of the coil structure **204**, can be expressed in terms of a coupling factor $C_i$. The coupling factor $C_i$ for the ith sensing element **202** can be defined as the ratio of magnetic field sensed by that sensing element to the amount of current flowing through the coil structure **204**. For a given structure **200**, the ratios $C_1$:$C_2$, $C_1$:$C_3$, and $C_2$:$C_3$ may be generally invariant (e.g., not subject to changing temperature or stress conditions). In some embodiments, these relationships can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

As mentioned above, in some embodiments, the structure **200** may be provided as an integrated circuit. Here, the ratio of the coupling factors (i.e., $C_1$:$C_2$, $C_1$:$C_3$, and $C_2$:$C_3$) may be generally invariant from one die to the next. Thus, in certain embodiments, these ratios can be characterized prior to operation (e.g., during design or testing) and configured within the structure **200**. In some embodiments, these pre-configured values can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

Embodiments of the structures described above in conjunction with FIG. **2** can be used in conjunction with systems and circuits described below in conjunction with FIGS. **4** and **5**.

Referring to FIG. **3**, a structure **300** may be used for 2D magnetic field sensing, according to one embodiment. The structure **300** may include two magnetic field sensing elements **302***a*, **302***b* and a coil structure **304**. In some embodiments, the structure **300** may be provided as an integrated circuit.

The magnetic field sensing elements **302***a*, **302***b* may be arranged to have maximum responses along two different axes to allow for 2D sensing. For example, as shown in FIG. **3**, a first sensing element **302***a* may be arranged to have a maximum response across the page and a second sensing element **302***b* may be arranged to have a maximum response from top to bottom of the page. In this arrangement, both sensing elements **302***a*, **302***b* may be provided as vertical Hall elements.

The coil structure **304** may be provided from any material and in any orientation suitable to generate magnetic fields on both sensing elements **302***a*, **302***b*. In some embodiments, the coil structure **304** may be provided as a continuous length of conductive material having two terminals **304***a*, **304***b* that can be connected to a current source (not shown) to generate a current through the coil. In other embodiments, the coil structure **304** may be provided as multiple coils coupled in series or multiple coils coupled to different current sources.

In some embodiments, the geometry of the coil structure **304** may be selected to generate a magnetic field substantially parallel to the axis of maximum response for each of the sensing elements **302***a*, **302***b*. For example, as shown in FIG. **3**, the coil structure **304** may be configured to generate a first field **306***a* parallel to the axis of maximum response for sensing element **302***a*, and a second field **306***b* parallel to the axis of maximum response for sensing element **302***b*.

The magnetic field sensing elements **302***a*, **302***b* may have sensitivities $S_1$ and $S_2$, respectively. The sensitivities $S_1$ and $S_2$ may vary with temperature, stress, and other conditions imposed, for example, on an IC substrate. When a current is passed through the coil structure **304**, the magnetic field generated in the ith sensing element may be determined by the geometry of the coil structure **304** and can be expressed in terms of a coupling factor $C_i$. For a given structure **300**, the ratio $C_1$:$C_2$ may be generally invariant (e.g., not subject to changing temperature or stress conditions). In some embodiments, these relationships can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

As mentioned above, in some embodiments, the structure **300** may be provided as an integrated circuit. Here, the ratio of the coupling factors (i.e., $C_1:C_2$) may be generally invariant from one die to the next. Thus, in certain embodiments, these ratios can be characterized prior to operation (e.g., during design or testing) and configured within the structure **300**. In some embodiments, these pre-configured values can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

Embodiments of the structures described above in conjunction with FIG. **3** can be used in conjunction with systems and circuits described below in conjunction with FIGS. **4** and **5**.

Referring to FIG. **3**A, a structure **320** may be used for 2D magnetic field sensing, according to another embodiment. The structure **320** may include two magnetic field sensing elements **322***a*, **322***b* and a coil structure **324**. A first sensing element **324***a* may be arranged to have a maximum response perpendicular to the page and a second sensing element **322***b* may be arranged to have a maximum response across the page. In this arrangement, first sensing element **322***a* may be provided as a planar Hall element and second sensing element **322***b* may be provided as vertical Hall element. In some embodiments, the structure **320** may be provided as an integrated circuit.

The coil structure **324** may be provided from any material and in any orientation suitable to generate magnetic fields on both sensing elements **322***a*, **322***b*. In some embodiments, the coil structure **324** may be provided as a continuous length of conductive material having two terminals **324***a*, **324***b* that can be connected to a current source (not shown) to generate a current through the coil. In other embodiments, the coil structure **324** may be provided as multiple coils coupled in series or multiple coils coupled to different current sources.

In some embodiments, the geometry of the coil structure **324** may be selected to generate a magnetic field substantially parallel to the axis of maximum response for each of the sensing elements **322***a*, **322***b*. For example, as shown in FIG. **3**A, the coil structure **324** may be configured to generate a first field **326***a* parallel to the axis of maximum response for sensing element **322***a*, and a second field **326***b* parallel to the axis of maximum response for sensing element **322***b*.

The magnetic field sensing elements **322***a* and **322***b* may have sensitivities $S_1$ and $S_2$, respectively. The sensitivities $S_1$, $S_2$ may vary with temperature, stress, and other conditions imposed, for example, on an IC substrate. When a current is passed through the coil structure **324**, the magnetic field generated in the ith sensing element may be determined by the geometry of the coil structure **324** and can be expressed in terms of a coupling factor $C_i$. For a given structure **320**, the ratio $C_1:C_2$ may be generally invariant (e.g., not subject to changing temperature or stress conditions). In some embodiments, these relationships can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

As mentioned above, in some embodiments, the structure **320** may be provided as an integrated circuit. Here, the ratio of the coupling factors (i.e., $C_1:C_2$) may be generally invariant from one die to the next. Thus, in certain embodiments, these ratios can be characterized prior to operation (e.g., during design or testing) and configured within the structure **320**. In some embodiments, these pre-configured values can be used to provide gain equalization, as described below in conjunction with FIG. **4**.

Embodiments of the structures described above in conjunction with FIG. **3**A can be used in conjunction with systems and circuits described below in conjunction with FIGS. **4** and **5**.

FIG. **4** shows a magnetic field sensor **400** that can provide gain equalization, according to an embodiment. The sensor **400** may comprise a plurality (N) of magnetic field sensing elements **402**, a coil structure **404**, a coil driver **410** coupled to the coil structure **404**, a gain equalization circuit **406**, and a plurality (N) of outputs **408**. Each of the plurality of sensing elements **402** may have a respective sensitivity $S_1$, $S_2$, . . . , $S_N$ and a respective coil coupling factor $C_1$, $C_2$, . . . , $C_N$, as shown. The ratios of the coupling factors (e.g., $C_1:C_2$, $C_2:C_3$, etc.) may be generally invariant (e.g., not subject to changing temperature or stress conditions).

In some embodiments, the magnetic field sensors **402** and coil structure **404** may be provided as a structure that is the same as or similar to structures **200**, **300**, or **320** of FIG. **2**, **3**, or **3**A, respectively.

The gain equalization circuit **406** may include a memory **412**; a gain measurement and comparison processor (or "measurement-comparison processor") **414** having access to the memory **412**; a reference signal extraction processor **416** having a plurality of inputs, each coupled to an output of a respective one of the sensing elements **402**, and a plurality of outputs, each coupled to a respective one of a plurality of measurement-comparison processor **414** inputs; a gain adjustment processor **418** having an input coupled to an output of the measurement-comparison processor **414** and a plurality of outputs **433**; a plurality of multipliers **420**, each having a first input coupled to an output of a respective one of the sensing elements **402**, a second input coupled to a respective one of the gain adjustment processor **418** outputs **433**, and an output; and an external signal extraction processor **422** having a plurality of inputs **431**, each coupled to an output of a respective one of the multipliers **420**, and a plurality of outputs that may correspond to sensor outputs **408**.

The coil driver **410** may be configured to generate a coil drive signal **424**, which may be applied to the coil structure **404** to generate a current there through. In response, the coil structure **404** may generate reference magnetic fields (or "reference fields") **425** on each of the sensing elements **402**, whereby the magnitude of the reference field **425** on the ith sensing element **402** is determined by the respective coupling factor $C_i$.

Each sensing element **402** may generate a corresponding output signal **428** that can be responsive to both the reference field **425** and to other magnetic fields ("external fields") **426** about the sensor **400**. For example, external fields **426** may include fields generated by a target, such as target **102** in FIG. **1**. The portion of a sensing element output signal **428** responsive to the reference field **425** is referred to herein as the "reference signal" and the portion responsive to external fields **426** is referred to herein as the "external signal."

In some embodiments, the coil driver **410** may be configured to generate a coil drive signal **424** having a particular waveform that enables gain equalization circuit **406** to extract the reference signal and the external signal portions from a sensing element's output signal **428**. In some embodiments, sensor **400** may use a frequency multiplexing technique, whereby the frequency of the coil drive signal **424** is selected to be substantially higher than that of external fields **426** being measured by the sensor. In this arrangement, the reference signal extraction processor **416** and external signal extraction processor **422** may be configured to filter reference and external signals, respectively, from a sensing element output signal **428**, as described further below in conjunction with FIG. **5**.

In other embodiments, the coil structure **404** may be configured to generate a differential field in each axis of measurement, meaning that, in each axis, the coil structure **614** can generate fields in both positive and negative directions (e.g., +X and −X). Further, each of the sensing elements **426** may represent a pair of magnetic field sensing sub-elements (e.g., two Hall plates) physically separated from each other but measuring fields in the same axis. In this arrangement, a sensing element output signal **428** may correspond to the sum or difference of the sub-elements, which can be selected to cancel out either the reference signal or the external signal, as described further below in conjunction with FIG. **8**.

The measurement-comparison processor **414** may be configured to receive the reference signals **430** and to generate corresponding gain adjustment values $K_1, K_2, \ldots, K_N$ that can be used to equalize the gains of the sensing element output signals **428**. In some embodiments, the measurement-comparison processor **414** may use a two step procedure to calculate gain adjustment values $K_1, K_2, \ldots, K_N$.

In a first step, the measurement-comparison processor **414** may measure a gain for each of reference signals **430**. The magnitude (e.g., voltage or amplitude) of the ith reference signal **430** (herein denoted $M_i$) may be proportional to the gain $C_i \times S_i$, where $C_i$ is generally invariant and the sensitivity $S_i$ represents an instantaneous magnetic field sensitivity that can vary due to temperature, stress, and other phenomena.

In some embodiments, the measurement-comparison processor **414** may measure an absolute gain for each of the reference signals **430**. Here, the current going into the coil structure **404** may be accurately controlled over temperature, stress, etc. and, thus, the reference field **425** may be known. The absolute gain of the ith reference signal **430** (herein denoted $G_i$) may be calculated using the known reference field **425** and the measured magnitude $M_i$.

In other embodiments, the measurement-comparison processor **414** may measure a relative gain for each of the reference signals **430**. The relative gains can be determined even if the reference field **425** may be unknown because (a) the same current may be used to generate each of the reference fields **425** (e.g., via a continuous coil structure **404**) and (b) the ratio of the coupling factors (e.g. $C_1$:$C_2$) is generally invariant. Thus, the relative gain of the ith reference signal **430** (herein denoted $G_i$) may be calculated using the known reference field **425** and the measured magnitude $M_i$.

In a second step, the measurement-comparison processor **414** may compare the measured gains $G_1, G_2, \ldots G_N$ (which, as indicated above, may be absolute gains or relative gains) to reference gains in order to calculate the gain adjustment values $K_1, K_2, \ldots, K_N$. The reference gains may be stored within memory **412**. In some embodiments, the reference gains may include N absolute gains (herein denoted $R_1, R_2, \ldots R_N$), one for each of the N sensing elements **402**. The absolute reference gains $R_1, R_2, \ldots R_N$ can be directly compared to respective ones of the measured gains $G_1, G_2, \ldots G_N$. For example, the ith gain adjustment value may be calculated as $K_i = R_i / G_i$. In other embodiments, the reference gains may include relative gains between two or more of the sensing elements **402**. The relative reference gains may be expressed as ratios, where the relative reference gain between the ith and jth sensing elements is herein denoted $R_{i:j}$. Here, the measurement-comparison processor **414** may select adjustment values $K_1, K_2, \ldots, K_N$ such that the ratio of measured gains multiplied by the respective gain adjustment values equals the reference ratios, e.g., $G_1 {*} K_1 : G_2 {*} K_2 = R_{1:2}$.

It is appreciated herein that controlling the ratio of sensing element gains can be used to indirectly control for absolute gain in some situations. For example, in certain embodiments, at least one of the sensing elements **202** may be highly accurate whereas other ones of the sensing elements may be less accurate. In this case, the gain adjustment value K for the highly accurate sensing element may be fixed to a constant value (e.g., one) and the other gain adjustment values may be selected dynamically as described above. Thus, even if the current in the current **424** in the coil drifts (e.g., due to temperature), all sensor outputs **408** may be highly accurate.

In some embodiments, memory **412** may include writable memory and the reference gains may be determined during operation of the sensor **400** and written thereto. In some embodiments, the reference gains are determined when operation commences using the measured gains $G_1, G_2, \ldots G_N$. For example, at time zero, the measurement-comparison processor **414** may set N reference gains equal to the measured gains (e.g., $R_1 = G_1$, $R_2 = G_2$, etc.) and store the new reference gains in memory **412**.

In certain embodiments, memory **412** may include non-volatile memory and the reference gains may be determined prior to operation and stored therein. In some embodiments, the non-volatile memory may be provided as EEPROM (Electrically Erasable Programmable Read-Only Memory) or another type of read-only memory. Prior to operation (e.g., during design or testing) a known magnetic field may be applied to one or more of the sensing elements **402** in order to determine the relative/absolute reference gains. The reference gains can be stored in non-volatile memory for use during subsequent operation.

In some embodiments, memory **412** may be configured to store user-adjustable trim values **412***a*. In various embodiments, the trim values **412***a* may be stored within non-volatile memory. The trim values **412***a* may be used to control various aspects of gain equalization. For example, in some embodiments, the reference gains (either relative or absolute) may be stored as trim values **412***a* so that they can be accessed and adjusted by a user. As another example, the reference gains in memory **412** (e.g., reference gains determined by measuring) may be scaled by trim values **412***a* to allow a user to adjust gain in one or more axes of measurement.

As discussed above, in some embodiments, the sensor **400** (or portions thereof) may be provided as an integrated circuit and, as a result, the ratio of the sensing element coupling factors (e.g., $C_1$:$C_2$, $C_2$:$C_3$, etc.) may be generally invariant from one die to the next. In such embodiments, relative reference gains $R_{1:2}$, $R_{2:3}$, etc. can be derived using a priori knowledge of coupling factors and a single gain measurement. In certain embodiments, the coupling factor ratios $C_1$:$C_2$, $C_2$:$C_3$, etc. may be characterized prior to operation (e.g., during design or testing) and stored within the sensor **400** (e.g., the coupling factors could be "hardwired" or stored in non-volatile memory). The sensor **400** may then be trimmed in multiple axes by measuring the gain from a single sensing element **426**. In certain embodiments, the coil drive current **424** may be trimmed.

In some embodiments, the trim values **412***a* may include a coil current trim value which may be used by the coil driver **410** to determine the current through the coil structure

**404**. The coil current trim value can be adjusted by a user to maintain highly accurate current through the coil structure **404**. As discussed above, if the current through the coil structure **404** can be accurately controlled over temperature, stress, etc., then the sensor **400** can keep the absolute gain of each sensing element **402** relatively constant.

The gain adjustment processor **418** may be configured to receive the gain adjustment values $K_1, K_2, \ldots, K_N$ values from the measurement-comparison processor **414** and to generate respective gain adjustment signals **434**.

Each of the multipliers **420** may be configured to receive a respective one of the sensing element output signals **428** and a respective one of the gain adjustment signals **434**, and to scale the sensing element output signal **428** according to the gain adjustment signal **434** to generate a gain-adjusted signal **432**. It will be appreciated that the relative gain (and, in some embodiments, the absolute gain) of the gain-adjusted signals **432** will be equalized based on the reference gains in memory **412**.

In some embodiments, multipliers **420** may be provided as analog circuitry and the gain adjust signals **434** may be analog signals. In other embodiments, multipliers **420** may be provided as one or more digital components and the gain adjust signals **434** may be digital signals.

In some embodiments, such as the embodiment shown in FIG. **4**, the gain-adjusted signals **432** may be responsive to both reference fields **425** and external fields **426**. Thus, the external signal extraction processor **422** may be configured to extract gain-adjusted external signals **409** from the gain-adjusted signals **432**, where the gain-adjusted external signals **409** are generally responsive to the external fields **426** but not the reference fields **425**. In some embodiments, and as shown in FIG. **4**, the gain-adjusted external signals **409** may be provided at the sensor outputs **408**. In other embodiments, additional signal processing may be performed on the gain-adjusted external signals **409**. In one embodiment, the external signal extraction processor **422** may utilize structures and techniques described below in conjunction with FIG. **5**.

The embodiment shown in FIG. **4** may be characterized as having a feed forward design because inputs of the measurement-compensation processor **414** are directly coupled to outputs of the sensing elements **402**. In other embodiments, a feedback design may be employed, wherein inputs of the measurement-compensation processor **414** may receive gain-adjusted signals, resulting in a feedback loop between the gain adjustment portions of the circuit and the gain measurement portions of the circuit. For example, in one embodiment, outputs of the multipliers **420** could be directly coupled to inputs of the measurement-compensation processor **414**.

The operation of the sensor **400**, according to some embodiments, is described next. Initially, each of the gain adjustment values $K_1, K_2, \ldots, K_N$ may be set to a value of one such that the gain adjustment signals **434** will have no effect on the sensing element output signals **428** (i.e., initially, the sensor output signals **408** may not be equalized).

The coil driver **410** may generate a coil drive signal **424** that, in turn, results in a current through the coil structure **404** and reference fields **425** generated on the magnetic field sensing elements **402**. The magnitude of the field on the ith sensing element **402** may be determined by the respective coupling factor $C_i$. The sensing elements **402** may generate output signals **428** responsive to the reference fields **425** and external fields **426**. The reference signal extraction processor **416** may receive the sensing element output signals **428** and extract reference signals **430** therefrom. The measurement-comparison processor **414** may measure gains $G_1, G_2, \ldots, G_N$ for each of the N reference signals **430** and compare the measured gains against reference gains (if any) stored within memory **412** to generate new gain adjustment values $K_1, K_2, \ldots, K_N$.

In some embodiments, reference gains may not be stored in memory **412** prior to sensor start-up. Here, the relative/absolute reference gains may be calculated based on initial gain measurements $G_1, G_2, \ldots, G_N$ and stored in memory **412**. In other embodiments, reference gains may be stored in non-volatile memory prior to sensor start-up. In certain embodiments, trim values **412*a*** may also be used to determine and/or scale reference gains.

The gain adjustment processor **418** may generate gain adjustment signals **434** based on the gain adjustment values $K_1, K_2, \ldots, K_N$. Each of the multipliers **420** may receive a respective sensing element output signal **428** and a respective gain adjustment signal **434**, and generate a gain-adjusted signal **432**. The external signal extraction processor **422** may extract the portion of the gain-adjusted signals **432** responsive to the external field to generate gain-adjusted external signals **409**. The relative gains (and, in some embodiments, the absolute gains) of the gain-adjusted external signals **409** will be equalized based on the reference gains in memory **412**. This process can be repeated over time, adjusting the gain of the sensing element output signals **428** in order to maintain gain equalization.

FIG. **5** shows a magnetic field sensor **900** that can provide gain equalization using frequency multiplexing (sometimes referred to as "frequency-division multiplexing" or "FDM"), according to an embodiment of the disclosure. The sensor **900** may include a structure **902** for (N-dimensional) magnetic field sensing, a gain equalization circuit **904**, and a plurality (N) of outputs **906**. The magnetic field sensor **900** may further include a coil driver **930** coupled to the coil structure **910**.

The structure **902** may include a plurality (N) of magnetic field sensing elements **908** and a coil structure **910** configured to generate reference fields thereon. In some embodiments, N=3 and the structure **902** may be the same as or similar to embodiments of the structure **200** shown in FIG. **2** and described above in conjunction therewith. In other embodiments, N=2 and the structure **902** may be the same as or similar to embodiments of the structures **300**, **320** shown in FIGS. **3**, **3**A and described above in conjunction therewith.

The gain equalization circuit **904** may include a plurality (N) of inputs **936** each coupled to an output **912** of a respective one of the sensing elements **908**. A given sensing element **908** may be coupled to the gain equalization circuit **904** via a signal path comprising one or more circuit elements. In the illustrated embodiment, each such signal paths may include a front-end (FE) amplifier **914**.

In some embodiments, the gain equalization circuit **904** may process digital signals (e.g., 16-bit digital signals) and, thus, the sensor **900** may include a plurality (N) of analog-to-digital converters (ADC) **916** to convert analog sensing element output signals to digital signals.

The gain equalization circuit **904** may further include a plurality (N) of external signal filters **918** each having an input coupled to an output of a respective circuit input **936**; a plurality (N) of reference signal filters **920** each having an input also coupled to a respective circuit input **936**; a gain measurement and comparison processor (or "measurement-comparison processor") **922** having a plurality of inputs coupled to respective ones of the plurality of reference signal filter **920** outputs; a memory **924** accessible by the measurement-comparison processor **922**; a gain adjustment processor **926** having an input coupled to an output of the measurement-comparison processor **922**; and a plurality (N) of multipliers **928** each having an first input coupled to an output of a respective external signal filter **918**, a second input coupled to an output of the gain adjustment processor **926**, and an output coupled to a respective circuit output **906**.

For clarity in the drawing, only one magnetic field sensing element **908**, one amplifier **914**, one ADC **916**, one external signal filter **918**, one reference signal filter **920**, and one multiplier **928** are shown. Thus, the illustrated magnetic field sensing element **908** may represent a sensing element along one axis, and the other components **914**, **916**, **918**, **920**, **928** may be coupled to process output from that single sensing element **908**. It should be understood that, in general, the sensor **900** may include a plurality (N) of sensing elements **908** (one for each axis of measurement) and a respective plurality of each of the components **914**, **916**, **918**, **920**, **928**.

In some embodiments, measurement-comparison processor **922** may be the same as or similar to embodiments of the measurement-comparison processor **414** described above in conjunction with FIG. **4**. In certain embodiments, gain adjustment processor **926** may be the same as or similar to embodiments of the gain adjustment processor **418** described above in conjunction with FIG. **4**. In some embodiments, memory **924** may be configured the same as or similar to memory **412** as described above in conjunction with FIG. **4**. In particular embodiments, coil driver **930** may be configured the same as or similar to coil driver **410** as described above in conjunction with FIG. **4**.

The coil driver **930** may be configured to generate a coil drive signal **932** through the coil structure **910** to generate reference fields on each of the sensing elements **908**. In response, each of the sensing elements **908** may generate an output signal **912** that is responsive to the respective reference field and to external fields. In other words, a sensing element output signal **912** may include a reference signal portion and an external signal portion.

Referring to FIG. **5**A, in various embodiments, the sensor **900** may use frequency multiplexing to distinguish between reference signals and external signals. The coil driver **930** may be configured to generate coil drive signal **962** having a frequency that is significantly higher than that of external fields **960**. In some embodiments, the coil drive signal **962** may be generated as an alternating current (AC) signal having a relatively high frequency. The resulting sensing element output signal **964** may be responsive to both the low-frequency external field **960** and the high-frequency reference field **962**, as shown.

Referring again to FIG. **5**, each of the sensing element output signals **912** may be amplified and digitized to generate digital sensing element output signals **944** as input to the gain equalization circuit **904**. Each of the digital sensing element output signals **944** may be passed as input to both a respective external signal filter **918** and a respective reference signal filter **920**. The external signal filter **918** may be configured to isolate or extract an external signal **938** and the reference signal filter **920** may be configured to isolate or extract a reference signal **940**.

In some embodiments, the external signal filter **918** may comprise a lowpass filter to reject high-frequency reference field response. In certain embodiments, the reference signal filter **920** may comprise a bandpass filter to reject low-frequency external field response. In other embodiments, the reference signal filter **920** may utilize a mixer to reject low-frequency external field response.

The measurement-comparison processor **922** may be configured to calculate gain adjustment values $K_1, K_2, \ldots, K_N$ using measurements of the reference signals **940**, and using reference gains stored within memory **924**. In some embodiments, the measurement-comparison processor **922** may utilize techniques described above in conjunction with measurement-comparison processor **414** of FIG. **4** to calculate gain adjustment values $K_1, K_2, \ldots, K_N$.

The gain adjustment processor **926** may be configured to generate a gain adjustment signal **934** based a respective one of the gain adjustment values $K_1, K_2, \ldots, K_N$. The multiplier **928** may be configured to scale the external signal **938** by the gain adjustment signal **934** to generate a gain-adjusted external signal **942**.

It will be appreciated that the magnetic field sensor **900** shown in FIG. **5** differs from the magnetic field sensor **400** of FIG. **4** in certain respects. As one example, in FIG. **4**, external signal extraction occurs after gain adjustment (i.e., output of multipliers **420** is coupled to input of the external signal extraction processor **422**), whereas, in FIG. **5**, external signal extraction occurs before gain adjustment (i.e., output of external signal filter **918** is coupled to input of multiplier **928**). It should be understood that the concepts sought to be protected herein are not limited to the specific embodiments shown in the figures.

While embodiments of the sensor **900** shown in FIG. **5** and described herein may include an analog portion and a digital portion, it will be appreciated that the particular delineation of which circuit functions are implemented in an analog fashion or with digital circuitry and signals can be varied. Further, some of the described circuit functions can be implemented on an integrated circuit and other circuitry and functionality can be implemented on separate circuits (e.g., additional substrates within the same integrated circuit package, or additional integrated circuit packages, and/or on circuit boards).

Referring to FIG. **6**, a structure **610** may be used for 3D magnetic field sensing, according to one embodiment. The structure **610** may include six magnetic field sensing elements (or "sensing elements") **612***a*, **612***b*, **612***c*, **612***d*, **612***e*, **616***f* and a coil structure **614**.

The six sensing elements **612***a*-**612***f* may be arranged to provide three so-called "differential magnetic field sensing elements," each comprising a pair of sensing elements oriented along a common axis of measurement. For example, as shown, sensing elements **612***a* and **612***d* may form a first differential magnetic field sensing element (or "differential sensing element") having a maximum response perpendicular to the page, sensing elements **612***b* and **612***e* may form a second differential magnetic field sensing element having a maximum response up and down the page, and sensing elements **612***c*, **612***f* may form a third differential magnetic field sensing element having a maximum response across the page. In this arrangement, sensing elements **612***a* and **612***d* may be provided as a planar Hall element, whereas the sensing elements **612***b*, **612***c*, **612***e*, and **612***f* may be provided as vertical Hall elements.

The coil structure **614** may be provided from any material and in any orientation suitable to generate magnetic fields on the sensing elements **612***a*-**612***f*. In some embodiments, the coil structure **614** is provided as a continuous length of conductive material having two terminals **614***a*, **614***b*. The terminals **614***a*, **614***b* can be connected to a current source (not shown) to generate a current through the coil. In other embodiments, the coil structure **614** may be provided as multiple coils coupled in series or multiple coils coupled to different current sources.

The coil structure **614** may be configured to generate a "differential magnetic field" in each axis of measurement, meaning that, in each axis, the coil structure **614** can generate fields in both positive and negative directions (e.g., +X and −X). Each of the differential fields may be generated on a respective one of the differential sensing elements. For example, as shown in FIG. **6**, the coil structure **614** may be configured to generate a first differential field **616***a*, **616***d* perpendicular to the page, with field **616***a* generated on sensing element **612***a* and opposing field **616***d* generated on sensing element **612***d*; a second differential field **616***b*, **616***e* up and down the page, with field **616***b* generated on sensing element **612***b* and opposing field **616***e* generated on sensing element **612***e*; and a third differential field **616***c*, **616***f* across the page, with field **616***c* generated on sensing element **612***c* and field **616***f* generated on sensing element **612***f*.

In some embodiments, differential fields can be generated using a coil structure **614** having two sets of windings wound in opposing directions. For example, as shown in FIG. **6**, the coil structure **614** may be wound in a first direction around sensing element **612***a* and in the opposite direction around sensing element **612***d*. Likewise, the coil structure **614** may be wound in opposing directions around sensing elements **612***b* and **612***e*, and also in opposing directions around sensing elements **612***c* and **612***f*.

Positive current entering terminal **614***b* flows clockwise around sensing element **612***d* and counterclockwise around hall element **612***a*. The coil structure **614** may be positioned over the top of the sensing elements **612** and positive magnetic fields may be generated in the direction shown by arrows **616***b*, **616***c*, **616***e*, and **616***f* In additional, positive magnetic fields may be generated in the direction going into the page as shown by "X" **616***a* and in the direction coming out of the page as shown by circle **616***d*.

As explained below in conjunction with FIG. **8**, using differential fields can allow external signals and reference signals to be distinguished by adding or subtracting the signals from two sensing elements having a common axis of measurement. In particular, outputs of each half of a differential sensing elements can be connected in such a way to either pass or reject the signal generated by the coil structure. When connected in parallel, opposing coil signals may average to zero and identical external signals may average to form a single external signal, thus the coil signal is rejected and the external signal is passed. When connected in anti-parallel, opposing coil signals may average to form a single coil signal and identical external signals may average to zero.

Turning back to FIG. **6**, the magnitude of the differential field generated in the ith sensing element **612** may be expressed in terms of a coupling factor $C_i$, which may be determined by the geometry of the coil structure **614**. In some embodiments, the multiple sensing elements **612***a*-**612***f* may be fabricated on a common die using mass production techniques that reduce variance between different sensing elements. For a given structure **610** design, the ratio of the coupling factors (e.g., $C_1:C_2$, $C_2:C_3$, etc.) may remain generally invariant from one die to the next.

Embodiments of the structures described above in conjunction with FIG. **6** can be used in conjunction with systems and circuits described in conjunction with FIGS. **4** and **8**.

Referring to FIG. **7**, a structure **700** may be used for 2D magnetic field sensing, according to one embodiment. The sensor **700** may include four magnetic field sensing elements (or "sensing elements") **702***a*, **702***b*, **702***c*, **702***d* and a coil structure **704**.

The four sensing elements **702***a*-**702***d* may be arranged to provide two differential sensing elements in two different axes of measurement. For example, sensing elements **702***a*, **702***c* may form a first differential sensing element having a maximum response up and down the page, whereas sensing elements **702***b*, **702***d* may form a second differential sensing element having a maximum response across the page. In this arrangement, all four sensing elements **702***a*-**702***d* may be provided as vertical Hall elements.

The coil structure **704** may be provided from any material and in any orientation suitable to generate magnetic fields on the sensing elements **702***a*-**702***d*. In some embodiments, the coil structure **704** is provided as a continuous length of conductive material having two terminals **704***a*, **704***b*. The terminals **704***a*, **704***b* can be connected to a current source (not shown) to generate a current through the coil. In other embodiments, the coil structure **704** may be provided as multiple coils coupled in series or multiple coils coupled to different current sources.

The coil structure **704** may be configured to generate differential fields in both axes of measurement. For example, as shown in FIG. **7**, the coil structure **704** may be configured to generate a first differential field **706***a*, **706***c* up and down the page, with field **706***a* generated on sensing element **702***a* and opposing field **706***c* generated on sensing element **702***c*; and a second differential field **706***b*, **706***d* across the page, with field **706***b* generated on sensing element **702***b* and opposing field **706***d* generated on sensing element **702***d*. The coil structure **704** may be wound as shown in FIG. **7** or in any other configuration capable of generating said differential fields. Positive current entering terminal **704***b* flows clockwise through the coil structure **704**. The coil structure **704** may be positioned over the top of the sensing elements **702** and positive magnetic fields may be generated in the direction shown by arrows **706***a*-**706***d*.

As explained below in conjunction with FIG. **8**, using differential fields can allow external signals and reference signals to be distinguished by adding or subtracting the signals from two sensing elements having a common axis of measurement.

The magnitude of the field generated in the ith sensing element **702** may be expressed in terms of a coupling factor $C_i$, which may be determined by the geometry of the coil structure **704**. In some embodiments, the multiple sensing elements **702***a*-**702***d* may be fabricated on a common die using mass production techniques that reduce variance between different sensing elements. For a given structure **700** design, the ratio of the coupling factors (e.g., $C_1:C_2$) may remain generally invariant from one die to the next.

Embodiments of the structures described above in conjunction with FIG. **7** can be used in conjunction with systems and circuits described in conjunction with FIGS. **4** and **8**.

Referring to FIG. 7A, a structure **720** may be used for 2D magnetic field sensing, according to another embodiment. The structure **720** may include four magnetic field sensing elements (or "sensing elements") **722***a*, **722***b*, **722***c*, **722***d* and a coil structure **724**.

The four sensing elements **722***a*-**722***d* may be arranged to provide two differential sensing elements in two different axes of measurement. For example, sensing elements **722***a*, **722***c* may form a first differential sensing element having a maximum response perpendicular to the page, whereas sensing elements **722***b*, **722***d* may form a second differential sensing element having a maximum response across the page. In this arrangement, sensing elements **722***a*, **722***c* may be provided as planar Hall elements, whereas sensing elements **722***b*, **722***d* may be provided as vertical Hall elements.

The coil structure **724** may be provided from any material and in any orientation suitable to generate magnetic fields on the sensing elements **722***a*-**722***d*. In some embodiments, the coil structure **724** is provided as a continuous length of conductive material having two terminals **724***a*, **724***b*. The terminals **724***a*, **724***b* can be connected to a current source (not shown) to generate a current through the coil. In other embodiments, the coil structure **724** may be provided as multiple coils coupled in series or multiple coils coupled to different current sources.

The coil structure **724** may be configured to generate differential fields in both axes of measurement. For example, as shown in FIG. 7A, the coil structure **724** may be configured to generate a first differential field **726***a*, **726***c* perpendicular to the page, with field **726***a* generated on sensing element **722***a* and opposing field **726***c* generated on sensing element **722***c*; and a second differential field **726***b*, **726***d* across the page, with field **726***b* generated on sensing element **722***b* and opposing field **726***d* generated on sensing element **722***d*. The coil structure **724** may be wound as shown in FIG. **7**A or in any other configuration capable of generating the differential fields.

Positive current entering terminal **724***b* flows clockwise around sensing element **722***c* and counterclockwise around hall element **726***a*. The coil structure **724** may be positioned over the top of the sensing elements **722** and positive magnetic fields may be generated in the direction shown by arrows **726***b*, **726***d*, in the direction going into the page as shown by "X" **726***a*, and in the direction coming out of the page as shown by circle **726***c*.

As explained below in conjunction with FIG. **8**, using differential fields can allow external signals and reference signals to be distinguished by adding or subtracting the signals from two sensing elements having a common axis of measurement.

The magnitude of the field generated in the ith sensing element **722** may be expressed in terms of a coupling factor $C_i$, which may be determined by the geometry of the coil structure **724**. In some embodiments, the multiple sensing elements **722***a*-**722***d* may be fabricated on a common die using mass production techniques that reduce variance between different sensing elements. For a given structure **720** design, the ratio of the coupling factors (e.g., $C_1$:$C_2$) may remain generally invariant from one die to the next.

Embodiments of the structures described above in conjunction with FIG. 7A can be used in conjunction with systems and circuits described in conjunction with FIGS. **4** and **8**.

FIG. **8** shows a magnetic field sensor **800** that can provide gain equalization using time sharing (sometimes also referred to as "time-division multiplexing" or "TDM"), according to an embodiment of the disclosure. The sensor **800** may include a structure **802** for (N-dimensional) magnetic field sensing, a gain equalization circuit **804**, and a plurality (N) of outputs **806**. The magnetic field sensor **800** may further include a coil driver **830** coupled to the coil structure **810**.

The structure **802** may include a plurality (N) of differential magnetic field sensing elements, a coil structure **810**, and a sensing element output **812**. Each of the differential sensing elements (generally denoted **808** hereinafter) may be formed from a pair of sensing elements **808***a*, **808***b* having a common axis of measurement. The coil structure **810** may be configured to generate differential reference fields on each of the differential sensing elements **808**. In some embodiments, N=3 and the structure **802** may be the same as or similar to embodiments of the structure **610** shown in FIG. **6** and described above in conjunction therewith. In other embodiments, N=2 and the structure **802** may be the same as or similar to embodiments of the structures **700**, **720** shown in FIGS. **7**, **7**A and described above in conjunction therewith.

The gain equalization circuit **804** may include a plurality (N) of inputs **836** each coupled to a respective sensing element output **812**. A given differential sensing element **808** may be coupled to the gain equalization circuit **804** via a signal path comprising one or more circuit elements. In the illustrated embodiment, each such signal paths may include a front-end (FE) amplifier **814**.

In one embodiment, a swap signal (e.g., signal **848**) may be used to change the gain of the FE amplifier **814**. This approach may provide better amplification of the reference signal and/or to avoid saturating other circuitry.

In some embodiments, the gain equalization circuit **804** may process digital signals (e.g., 16-bit digital signals) and, thus, the sensor **800** may include a plurality (N) of analog-to-digital converters (ADC) **816** to convert analog sensing element output signals to digital signals.

The gain equalization circuit **804** may further include a plurality (N) of 2-way signal select switches **850** each having an input coupled to an input of a respective one of the circuit inputs **836**; a plurality (N) of external signal filters **818** each having an input coupled to a first output of a respective signal select switch **850**; a plurality (N) of reference signal filters **820** each also having an input coupled to a second output of a respective signal select switch **850**; a gain measurement and comparison processor (or "measurement-comparison processor") **822** having a plurality of inputs coupled to respective ones of the plurality of reference signal filter **820** outputs; a memory **824** accessible by the measurement-comparison processor **822**; a gain adjustment processor **826** having an input coupled to an output of the measurement-comparison processor **822**; and a plurality (N) of multipliers **828** each having an first input coupled to an output of a respective external signal filter **818**, a second input coupled to an output of the gain adjustment processor **826**, and an output coupled to a respective circuit output **806**.

For clarity in the drawing, only one differential sensing element **808**, one differential output switch **846**, one amplifier **814**, one ADC **816**, one signal select switch **850**, one external signal filter **818**, one reference signal filter **820**, and one multiplier **828** are shown. Thus, the illustrated differential magnetic field sensing element **808** may represent a sensing element along a single axis of measurement, and the other components **846**, **814**, **816**, **818**, **820**, **828** may be coupled to process output from that single sensing element **808**. It should be understood that, in general, the sensor **800** may include a plurality (N) of sensing elements **808** (one for each axis of measurement) and a respective plurality of each of the components **846**, **814**, **816**, **818**, **820**, **828**.

In some embodiments, measurement-comparison processor **822** may be the same as or similar to embodiments of the measurement-comparison processor **414** described above in conjunction with FIG. **4**. In certain embodiments, gain adjustment processor **826** may be the same as or similar to embodiments of the gain adjustment processor **418** described above in conjunction with FIG. **4**. In some embodiments, memory **824** may be configured the same as or similar to memory **412** as described above in conjunction with FIG. **4**.

The coil driver **830** may be configured to generate a coil drive signal **832** through the coil structure **810** to generate a differential reference field on each of differential sensing element **808**. Thus, in each axis of measurement, two sensing elements **808***a*, **808***b* may generate opposite responses to a differential reference field and similar (or identical) responses to external fields. In some embodiments, the coil driver signal **832** may generate the coil drive signal **832** as a DC signal.

As shown, each of the differential sensing elements **808** may have two outputs **812***a*, **812***b*. The two outputs **812***a*, **812***b* may be coupled together in one or more different configurations to provide a single sensing element output **812**. In some embodiments, the sensor **800** may include a differential output switch **846** operable to alternately couple the sensing element outputs **812***a*, **812***b* in multiple different configurations.

Referring to FIG. **8**A, in various embodiments, the sensor **800** may use time sharing to distinguish between reference signals and external signals. The differential output switch **846** may receive a logic signal ("swap signal") **848** to select between the two different configurations.

When the swap signal **848** is in a first state (e.g., low or zero), a positive terminal of a first output **812***a* may be coupled to a positive terminal of a second output **812***b*. In this configuration, the sensing element output **812** may be responsive to external fields but not the differential reference field generated by the coil structure **810**. In particular, an external field may cause a similar (or identical) response in both sensing elements **808***a*, **808***b* that may be averaged, whereas the differential reference field will cause opposite responses that may cancel out.

When the swap signal **848** is in a second state (e.g., high or non-zero), a positive terminal of a first output **812***a* may be coupled to a negative terminal of a second output **812***b*. In this second configuration, the sensing element output **812** may be responsive to the differential reference field but not external fields. Here, the similar (or identical) external responses will cancel out, whereas the opposite reference field responses will be averaged.

Thus, as illustrated in FIG. **8**A, a sensing element output signal **862** (which may be the same as or similar to signal **812** in FIG. **8**) may be responsive to external fields during some time periods and responsive to reference fields during other time periods.

Referring again to FIG. **8**, each of the sensing element output signals **812** may be amplified and digitized to generate digital sensing element output signals **844** as input to the gain equalization circuit **804**. A signal select switch **850** may be configured to alternately pass a digital sensing element output signal **844** to either the external signal filter **818** or the reference signal filter **820**. In some embodiments, the signal select switch **850** may be configured to receive a logic signal ("swap signal") **852** that selects between the first and second outputs. In some embodiments, the same swap signal **848**, **852** may be used to control both the differential output switch **846** and the signal select switch **850**. In other embodiments, swap signals **848**, **852** may be synchronized such that the switches **846**, **850** change state at generally the same times.

The external signal filter **818** and reference signal filter **820** may include filters to process external signals **838** and reference signals **840**, respectively, in the presence of noise. In some embodiments, filters **818**, **820** may be provided as decimation lowpass finite impulse response (FIR) filters.

The measurement-comparison processor **822** may be configured to calculate gain adjustment values $K_1, K_2, \ldots, K_N$ using measurements of reference signals **840**, and using reference gains stored within memory **824**. In some embodiments, the measurement-comparison processor **822** may utilize techniques described above in conjunction with measurement-comparison processor **414** of FIG. **4** to calculate gain adjustment values $K_1, K_2, \ldots, K_N$.

The gain adjustment processor **826** may be configured to generate a gain adjustment signal **834** based a respective one of the gain adjustment values $K_1, K_2, \ldots, K_N$. The multiplier **828** may be configured to scale the external signal **838** by the gain adjustment signal **834** to generate a gain-adjusted external signal **842**.

While embodiments of the sensor **800** shown in FIG. **8** and described herein may include an analog portion and a digital portion, it will be appreciated that the particular delineation of which circuit functions are implemented in an analog fashion or with digital circuitry and signals can be varied. Further, some of the described circuit functions can be implemented on an integrated circuit and other circuitry and functionality can be implemented on separate circuits (e.g., additional substrates within the same integrated circuit package, or additional integrated circuit packages, and/or on circuit boards).

Referring to FIG. **9**, a magnetic field sensor **500** may include a gain equalization circuit **510** that is responsive to a plurality (N) of digital external magnetic field signals **512** and to a plurality (N) of digital reference magnetic field signals (or "reference signals") **514** to generate a plurality (N) of gain-adjusted external signals **520**. The gains of the gain-adjusted external signals **520** may be equalized according to reference gains stored in memory. The gain-adjusted external signals **520** may be further processed to generate one or more output signals **540** of the sensor that are indicative of the external magnetic field.

The digital external field signal **512** and the reference magnetic field signal **514** can be the same as or similar to signals **856** and **858** shown in FIG. **8** and, thus, can be generated by switching between an external mode of operation in which an external magnetic field signal **516** is generated by magnetic field sensing elements **526**, such as the illustrated Hall effect elements, under the control of a Hall driver **532** and a reference mode of operation in which a reference magnetic field signal **518** is generated by a coil structure **528** under the control of a coil driver **530**. The coil structure **528** may be configured to carry a reference current to generate the reference magnetic field. At least one, and in the illustrated embodiment two, magnetic field sensing elements **526** are thus configurable to generate the external magnetic field signal **516** during a first time period and to generate the reference magnetic field signal **518** during a second, non-overlapping time period. In some embodiments, the sensing elements **526** may be provided as differential magnetic field sensing elements.

The external magnetic field signal and the reference magnetic field signal may be processed by a Front End (FE) amplifier **524** and converted into respective digital signals **512**, **514** by an ADC **536** using a fixed reference from a voltage reference **592**. In some embodiments, amplifier **524** may be the same as or similar to amplifier **814** in FIG. **8**. In certain embodiments, ADC **536** may be the same as or similar to ADC **816** in FIG. **8**.

The digital external magnetic field signal **512** may be filtered by a filter **544** to provide a filtered digital external magnetic field signal **548** (referred to herein alternatively as the digital external magnetic field signal) and the digital reference magnetic field signal **514** is filtered by a filter **546** to provide a filtered reference magnetic field signal **550** (referred to herein alternatively as the digital reference magnetic field signal). In general, the digital external magnetic field signal **512** may have a larger amplitude than the digital reference magnetic field signal **514** and thus, filter **546** may provide a higher degree of filtering than filter **544** to more accurately distinguish the reference magnetic field signal in the presence of noise. Various types of filters are possible. As one example, each of the filters **544**, **546** is a low pass FIR filter with optional decimation. IIR filters could also be used.

The gain equalization circuit **510** may be configured to combine the digital external magnetic field signal **548** and the digital reference magnetic field signal **550** in a manner that generates a plurality (N) of gain-adjusted external signals **520** having relative gains (or, in some cases, absolute gain) that are generally invariant. In some embodiments, gain equalization circuit **510** may be the same as or similar to gain equalization circuit **804** described above in conjunction with FIG. **8**. Operation of the gain equalization circuit **510** may be controlled by a master control circuit **542**, which additionally may control various other circuit functionality.

A gain-adjusted external signal **520** may be processed by a linearization circuit **522** in certain applications. As one example, the gain-adjusted external signal **520** may be transformed into a signal representative of a position of a target by correlating values of the gain-adjusted external signal **520** to values stored in a lookup table. The output of the linearization circuit **522** may be clamped by a clamp **552** to limit the output to a programmable range and further processed by a PWM/SENT encoder circuit **554** to generate a signal having a PWM format with a programmable frequency or a SENT signal format. A multiplexer **556** can be used to select between providing the output of the PWM/SENT circuit **554** or an output of a serial interface circuit **558** to an output signal generator **570**.

Additional elements of the sensor **500** can include an analog Built-in-Self-Test (BIST) circuit **560** as may implement the above-described techniques for diagnostic signal processing to detect errors in the analog front end of the sensor, an EEPROM BIST circuit **562** to test the EEPROM **594**, and a logic BIST circuit **564** to test various logic functionality within the sensor **500**.

The output signal generator **570** may be coupled to the multiplexer **556** and includes various elements used to reliably generate the sensor output signal **540** indicative of the external magnetic field, such as a slew control circuit **572**, an output driver **574**, a current limit circuit **576**, an ESD protection device **578**, and a serial Receiver (RX) circuit **580**. In applications in which the output signal **540** is provided in the SENT signal format, the serial receiver **580** may implement bidirectional communication. The sensor **500** may include additional supporting elements such as an EEPROM **594**, a charge pump **582**, a regulator and Power On Reset (POR) circuit **584**, a level detector **586**, an ESD protection device **588** and a clock generator **590**.

A temperature sensor **596** may be provided to sense the ambient temperature to which the sensor **500** is subjected, convert the sensed temperature into a digital signal, and provide the digital sensed temperature signal **598** to a temperature filter and trim circuit **600** for further coupling to the gain equalization circuit **510**. In some embodiments, the temperature sensor **596** could be used for trimming over temperature. For example, if the current source drifts over temperature, the temperature sensor can be used to "flatten" drift. In other embodiments, the sensitivity of a sensing element can be trimmed over temperature using the temperature sensor **596**.

While embodiments of the sensor **500** shown in FIG. **9** and described herein may include an analog front end portion and a digital portion, it will be appreciated that the particular delineation of which circuit functions are implemented in an analog fashion or with digital circuitry and signals can be varied. Further, some of the described circuit functions can be implemented on an integrated circuit and other circuitry and functionality can be implemented on separate circuits (e.g., additional substrates within the same integrated circuit package, or additional integrated circuit packages, and/or on circuit boards).

While the embodiment shown in FIG. **9** includes a differential analog front end (and thus is equated to use with the embodiment of FIG. **8**), the remainder of the circuitry shown in FIG. **9** could be used with other embodiments described herein. For example, the analog front end shown in FIG. **9** could be swapped with that shown in FIG. **5**.

All references cited herein are hereby incorporated herein by reference in their entirety.

Having described certain embodiments, which serve to illustrate various concepts, structures, and techniques sought to be protected herein, it will be apparent to those of ordinary skill in the art that other embodiments incorporating these concepts, structures, and techniques may be used. Elements of different embodiments described hereinabove may be combined to form other embodiments not specifically set forth above and, further, elements described in the context of a single embodiment may be provided separately or in any suitable sub-combination. Accordingly, it is submitted that scope of protection sought herein should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed is:

**1**. A magnetic field sensor comprising:

a plurality of magnetic field sensing elements including:

a first magnetic field sensing element arranged to have a maximum response to an external magnetic field and a reference magnetic field along a first axis and having an output that provides a first signal representing the magnetic fields as detected by the first magnetic field sensing element; and

a second magnetic field sensing element arranged to have a maximum response to the external magnetic field and the reference magnetic field along a second axis and having an output that provides a second signal representing the magnetic field as detected by the second magnetic field sensing element;

a coil structure configured to generate the reference magnetic field when a current passes through the coil structure;

a memory containing at least one reference gain value comprising a relative gain between the first and second magnetic field sensing elements;

a gain equalization circuit coupled to receive the first signal and the second signal and configured to:

extract a first reference portion of the first signal representing the reference field;

extract a second reference portion of the second signal representing the reference field;

measure a first gain of the first reference portion;

measure a second gain of the second reference portion;

compare the first gain to the at least one reference gain;

compare the second gain to the at least one reference gain;

adjust the first gain based on the comparison of the first gain and the reference gain value so that the first gain is normalized to an expected value; and

adjust the second gain based on the comparison of the second gain and the reference gain value so that the second gain is normalized to the expected value.

2. The structure of claim 1 wherein the first and second magnetic field sensing elements comprise vertical Hall effect elements.

3. The structure of claim 1 wherein the first magnetic field sensing element comprises a planar Hall effect element and the second magnetic field sensing element comprises a vertical Hall effect element.

4. The structure of claim 1 wherein the plurality of magnetic field sensing elements further includes a third magnetic field sensing element arranged to have a maximum response to the magnetic field along a third axis.

5. The structure of claim 4 wherein the first magnetic field sensing element comprises a planar Hall effect element, and the second and third magnetic field sensing elements comprise vertical Hall effect elements.

6. The structure of claim 1 wherein at least one of the plurality of magnetic field sensing elements comprises a magnetoresistance element.

7. The structure of claim 1 wherein the first magnetic field sensing element comprises a first differential magnetic field sensing element and the second magnetic field sensing element comprises a second differential magnetic field sensing element, wherein the coil structure is configured to generate differential magnetic fields on the first and second differential magnetic field sensing elements.

8. The structure of claim 7 wherein the first differential magnetic field sensing element comprises two vertical Hall elements and the second differential magnetic field sensing element comprises two vertical Hall elements.

9. The structure of claim 7 wherein the first differential magnetic field sensing element comprises two planar Hall elements and the second differential magnetic field sensing element comprises two vertical Hall elements.

10. The structure of claim 7 wherein the plurality of magnetic field sensing elements further includes a third magnetic field sensing element arranged to have a maximum response to the magnetic field along a third axis, wherein the third magnetic field sensing element comprises a third differential magnetic field sensing element.

11. The structure of claim 10 wherein the first differential magnetic field sensing element comprises two planar Hall effect elements, the second differential magnetic field sensing element comprises two vertical Hall effect elements, and the third differential magnetic field sensing element comprises two vertical Hall effect elements.

12. The structure of claim 11 wherein the coil structure comprises windings a first direction around the a first one of the two planar Hall effect elements and windings in a second opposite direction around a second one of the two planar Hall effect elements.

13. The magnetic field sensor of claim 11 further comprising a coil driver circuit coupled to the coil structure;

wherein the coil driver circuit is configured to generate a coil drive signal as an alternating current (AC) signal having a frequency substantially different than a frequency of the external magnetic field, and the first, second, and third signals represent; and

wherein the gain equalization circuit comprises:

an external signal filter to extract a portion of the first and second signals representing the external magnetic field; and

a reference signal filter to extract the first and second reference portions.

14. The structure of claim 1 wherein the coil structure comprises a continuous length of conductive material.

15. The structure of claim 1 wherein the coil structure comprises multiple coils each configured to generate a magnetic field on one or more of the magnetic field sensing elements when a current passes through the coil, wherein the currents passing through the multiple coils are matched.

16. The structure of claim 15 wherein the multiple coils are coupled in series.

17. The structure of claim 1 wherein the coil structure is configured to generate a first magnetic field substantially parallel to the first axis and a second magnetic field substantially parallel to the second axis.

18. The magnetic field sensor of claim 1 wherein the reference gain value comprises a ratio of an absolute gain associated with the first magnetic field sensing element and an absolute gain associated with the second magnetic field sensing element.

19. The magnetic field sensor of claim 1 wherein the coil structure comprises multiple coils coupled to a coil driver circuit so that each of the multiple coils receives a current of the same magnitude.

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