

ON THE ENHANCEMENTS OF PLANAR BASED RF SENSOR TECHNOLOGY

CROSS-REFERENCE TO RELATED APPLICATIONS

5 **[1]** This application claims the benefit of U.S. Provisional Application No. 61/684,013, filed on August 16, 2012. The entire disclosure of the above application is incorporated herein by reference.

FIELD

10 **[2]** The present disclosure relates to radio frequency sensors and, more particularly, to an orthogonal radio frequency voltage/current sensor.

BACKGROUND

15 **[3]** The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

20 **[4]** A radio frequency (RF) current sensor, which is also known as a probe, generates a signal that represents the magnitude of current flow through an RF conductor. The current probe can be combined with a voltage probe to form an RF voltage/current (VI) probe that generates a second signal that represents the RF voltage with respect to a reference potential, such as an RF ground or shield conductor.

[5] RF current and VI probes are used in RF control circuits to provide feedback information. The feedback information may be used to control an RF amplifier that

provides the RF power that is being measured. In some applications the RF power is employed to generate plasma for semiconductor manufacturing, metal coating, or micromachining processes.

[6] Further areas of applicability of the present disclosure will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

SUMMARY

[7] A radio frequency sensor system includes a printed circuit board (PCB). The PCB includes a first exterior layer, a second exterior layer, a first interior layer, a second interior layer, and an inner perimeter that defines an aperture through the PCB. The PCB also includes a first loop. The first loop includes a first plurality of sensor pads coupled to a first plurality of vias by a first plurality of traces. The first plurality of sensor pads is arranged on the inner perimeter. The PCB also includes a second loop. The second loop includes a second plurality of sensor pads coupled to a second plurality of vias by a second plurality of traces. The second plurality of sensor pads is arranged on the inner perimeter. A core ring is embedded within the first interior layer proximal to the first plurality of sensor pads, the first plurality of vias, and the first plurality of traces. A center conductor, for carrying RF current, extends through the aperture. The first and second loops generate an electrical signal based on the first and second plurality of sensor pads, the first and second plurality of vias, the first and second plurality of traces, and the core ring.

[8] In other features, a radio frequency sensing method includes defining an aperture through a printed circuit board (PCB). The PCB includes a first exterior layer, a second exterior layer, a first interior layer, a second interior layer, and an inner perimeter. Coupling a first loop to a first plurality of vias by a first plurality of traces.

5 The first loop includes a first plurality of sensor pads. Arranging the first plurality of sensor pads on the inner perimeter. Coupling a second loop to a second plurality of vias by a second plurality of traces. The second loop includes a second plurality of sensor pads. Arranging the second plurality of sensor pads on the inner perimeter. Embedding a core ring within the first interior layer proximal to the first plurality of
10 sensor pads, the first plurality of vias, and the first plurality of traces. A center conductor for carrying RF current extends through the aperture and the first and second loops generate an electrical signal based on the first and second plurality of sensor pads, the first and second plurality of vias, the first and second plurality of traces, and the core ring.

15 [9] Further areas of applicability of the present disclosure will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

20 [10] The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

[11] FIG. 1 is a plan view of an orthogonal radio frequency (RF) current and voltage sensor according to various embodiments of the present disclosure;

[12] FIG. 2 is an isometric view of current sensor traces of an orthogonal radio frequency (RF) current and voltage sensor according to various embodiments of the present disclosure;

[13] FIGS. 3(a)-(c) are plan views of the current sensor traces of FIG. 2;

5 [14] FIG. 4 is a plan view of current sensor traces of an orthogonal radio frequency (RF) current and voltage sensor according to various embodiments of the present disclosure;

[15] FIG. 5(a) is schematic diagram of a current sensor of the prior art;

[16] FIGS. 5(b)-(c) and 6 are schematic diagrams of a current sensor according to
10 various embodiments of the present disclosure;

[17] FIG. 7 is a circuit diagram of a circuit that represents the capacitive coupling relationship between the voltage at points A and B to that of the conductor in the current sensor of FIG. 6;

[18] FIG. 8 is a schematic diagram of a voltage current sensor according to
15 various embodiments of the present disclosure; and

[19] FIGS. 9(a)-(b) are plan views of circular conductive rings of a voltage current sensor according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

20 [20] A radio frequency (RF) current sensor, which is also known as a probe, generates a signal that represents the magnitude of current flow through an RF conductor. The current probe can be combined with a voltage probe to form an RF

voltage/current (VI) probe that generates a second signal that represents the RF voltage with respect to a reference potential, such as an RF ground or shield conductor.

[21] RF current and VI probes are used in RF control circuits to provide feedback information. The feedback information may be used to control an RF amplifier that provides the RF power that is being measured. In some applications the RF power is employed to generate plasma for semiconductor manufacturing, metal coating, or micromachining processes. While operating at certain frequencies, for example low frequencies or high frequencies, the VI probe may experience interference due to parasitic resonance within the components of the VI probe. Additionally, the low frequency coupling of the sensor to the center conductor may be low. Accordingly, the principles of the present disclosure may be arranged to improve VI probe frequency responses.

[22] Referring now to FIG. 1, an orthogonal radio frequency (RF) voltage/current (VI) probe 10 is shown. VI probe 10 includes a printed circuit board (PCB) 12 with at least four conductive layers. A first exterior layer 14a and a second exterior layer 14b are parallel with each other and maintained in spaced relationship by an insulating substrate of the PCB 12. First and second layers 14a, 14b are collectively referred to as ground planes 14. A number of vias 16 electrically connect ground planes 14 to each other. Vias 16 can be radially spaced around a perimeter of an aperture 18. Vias 16 are electrically insulated from the inner layers of the PCB 12, which are described below. Ground planes 14 and vias 16 connect to an outer layer of a coaxial cable (not shown) that carries the RF current being measured. A center conductor of the coaxial cable connects to a conductor 20 that is axially and concentrically positioned within

aperture 18. VI probe 10 may also include a plurality of mounting holes 13 to assist in coupling the VI probe 10 to the RF power generator (not shown) to be controlled.

[23] A second plurality of vias 22 are electrically insulated from ground planes 14 and connect current loop-back traces that are located on inner layers of the PCB 12. A third plurality of vias 24 are also electrically insulated from ground planes 14 and implement part of a voltage sensor H field cancellation structure. Vias 22 and 24 and their associated traces on inner layers of the PCB 12 are described below in more detail.

[24] The PCB 12 may also include an embedded core ring 42. The core ring 42 is embedded in at least one layer of the PCB 12. Further, the core ring 42 is arranged between the vias 22 and 24 and current sensor pads 30. The core ring 42 is arranged to increase a magnetic flux of the VI probe 10.

[25] The core ring 42 comprises material that increases a permeability of a medium in a magnetic field of the VI probe 10. For example, the medium in the magnetic field may be comprised of air and the core ring 42 comprises material with a higher permeability than air. For example only, the core ring 42 may comprise a ferromagnetic material or a ferrimagnetic material. By embedding the core ring 42 in the PCB 12 between the vias 22 and 24 and the current sensor pads 30, the permeability of the medium (i.e., the core ring 42 material) is increased in the magnetic field. As the permeability of the medium in the magnetic field increases, the related magnetic flux increases. The dynamic range of the VI probe 10 may be controlled by selectively adjusting the magnetic flux. In order to reduce stress on the PCB 12, the

core ring 42 may be constructed of a material with a coefficient of thermal expansion the same or less than the non-conductive material of the PCB 12.

[26] The PCB 12 may also include traces and pads, which are generically indicated at 28, for mounting electronic circuit components that may be connected to ground plane 14 and the various traces of the inner layers of the PCB 12. Examples of components include: connectors for providing power to the electronic circuits and/or taking electrical signals from them, amplifiers, transformers, and/or filters that buffer and/or condition the signals that represent the RF voltage and/or current of conductor 20, and the like.

[27] Referring now to FIGS. 2-3, various views of the PCB 12 are shown. Ground planes 14, vias 16 and vias 24 are omitted for clarity. A first inner layer 32 includes traces 44a and 44b that are formed on insulating substrate 36. A second inner layer 34 includes more traces 44a and 44b on the opposing side of substrate 36. Traces 44a and 44b are collectively referred to as traces 44. Traces 44 are patterned and connected by vias 22 to form a pair of entwined electrical loops or windings. It should be appreciated that substrate 36 may contain one or more additional conductive layers that are not shown. The additional conductive layers may, e.g., implement a voltage sensor that is described below.

[28] First and second inner layers 32, 34 are positioned underneath and insulated from respective ones of ground planes 14. Vias 22 extend between and connect associated traces 44 on the first and second inner layers as is described below. Associated traces 44 are also connected by respective current sensor pads 30 that are formed along walls of aperture 18. Current sensor pads 30 can be plated to the edge of

aperture 18 in substrate 36 and cut to shape by laser, mechanical abrasion or other manufacturing technique.

[29] Insulator substrate 36 gives current sensor pads 30 a length L. While RF current flows through conductor 20, a magnetic field rotates around conductor 20. The

5 magnetic field can be defined by Biot-Savart Law, which provides

$$B(radius) = \frac{\mu_0 (AC_{current})}{2\pi radius}$$

where *radius* is the distance between conductor 20 and current sensor pads 30, $AC_{current}$ is the current flowing through conductor 20, and μ_0 is the magnetic constant, equal to

10 $4\pi \times 10^{-7} \text{ H/m}$. The magnetic field crosses current sensor pads 30.

[30] From Faraday's law, the induced voltage is a function of the length L of current sensor pads 30, a rate of change of the magnetic field, and a height of a loop formed by current sensor pads 30, traces 44, and vias 22. Increasing the length L, such as by increasing a thickness of substrate 36, increases coupling between the RF coaxial
15 cable (not shown) and VI probe 10.

[31] As L increases, the diameter of vias 22 may also need to be increased in order to reduce the risk of breaking drills during PCB 36 fabrication. Increasing the diameter of vias 22 also increases the size of the sensor and/or reduces the number of current sensor pads 30 or loops (described below) that fit along the perimeter of
20 aperture 18. Increasing the diameter of vias 22 also yields a proportional increase to the capacitive coupling to conductor 20, which allows the electric field ("E field") produced by conductor 20 to contaminate the desired current signals and reduce the

dynamic range of the VI probe 10. In various embodiments, the width of the current sensor pads 30 may be made as narrow as is practicable to mitigate E field contamination and dynamic range issues. Edge plated current sensor pads 30 reduce the size and number of vias 22 required to make VI probe 10, which reduces E field contamination of the current signal. The current signal represents the current flowing through conductor 20 and is taken from traces 44.

[32] In another embodiment, the dynamic range of the VI probe 10 is increased by increasing the current sensor pad 30 length (L). In order to increase the length of the current sensor pads 30, a second PCB 15 may be coupled to the PCB 12 as shown in FIG. 2. The second PCB 15 may be coupled to the PCB 12 with a coupling layer (not show) between the second PCB 15 and the PCB 12. The coupling layer consists of a conductive material arranged to electrically bind the second PCB 15 to the PCB 12. For example, the coupling layer may consist of copper. In some embodiments, the current sensor pads 30 may be connected in series from the second PCB15 to the PCB 12. In yet another embodiment, the current sensor pads 30 may be connected in parallel from the second PCB 15 and the PCB 12. While only a second PCB 15 is shown coupled to the PCB 12, it is understood that any number of PCBs may be coupled to the PCB 12, for example, a third, fourth, or fifth PCB.

[33] In another embodiment, the dynamic range of the VI probe 10 may be increased by embedding the core ring 42 into the second PCB 15 and the PCB 12. The core ring 42 may be embedded between the vias 22 and 24, the current sensor pads 30, and traces 44 on the second PCB 15 and the PCB 12 respectively. The core ring 42 is arranged to increase a magnetic flux of the VI probe 10. For example, the core

ring 42 is made of a material that increases the permeability of the medium in a magnetic field of the VI probe 10. As the permeability of the medium in the magnetic field increases, the related magnetic flux increases. While FIG. 2 shows the core ring 42 embedded on both the second PCB 15 and the PCB 12; it is understood that the core ring 42 may be embedded in either, both, or neither of the second PCB 15 and the PCB 12.

[34] The dynamic range of the VI probe 10 may be further increased by selectively adjusting the parameters of the vias 22 and 24, the current sensor pads 30, and the traces 44. For example, the core ring 42 is encircled by a plurality of windings. The plurality of windings is constructed of the vias 22 and 24, the current sensor pads 30, and the traces 44. The resonance of the VI probe 10 can be controlled by selectively adjusting the number of windings and/or selectively adjusting the size of the vias 22 and 24, the current sensor pads 30, and the traces 44. By controlling the resonance of the VI probe 10, the dynamic range of the VI probe 10 may be increased.

[35] Traces 44 are shown in more detail in FIGS. 3(a)-3(c). Traces 44a and traces 44b are connected to form two entwined loops of wire. Traces 44a and 44b of FIG. 3(a) connect the current sensor pads 30 to the loop back vias 22. The loop back vias 22 connect to the backside of the sensor to another trace 44a or 44b and to the next current sensor pad 30, as shown in FIG. 3(c). For ease of understanding, FIG. 3 depicts the two loops as traces 44a and 44b. The dotted lines are the traces on the back of the board. The hexagon 40 of FIG. 3 may be a common ground point for both loops as one of the RF path ground vias 16. This common ground system may be used to reduce ground loops.

[36] By alternating the current sensor pads 30 with spatial uniformity along the inner perimeter of the opening 18, the current loops provide an autocorrecting feature from movement of the conductor 20, such as from assembly/disassembly of VI probe 10 or thermal changes in the VI probe 10 during operation. The autocorrecting feature of the design works by maintaining a constant sum total distance from the conductor 20 to the current sensor pads 30. If, for example, the conductor 20 moves to the right, the right current sensor pad 30 to conductor 20 distance decreases, but the left current sensor pad 30 to center conductor 20 increases by the same amount, keeping the sum total distance and current signal level the same.

[37] Another view of the PCB 12 according to various embodiments of the present disclosure is shown in FIG. 4. Ground planes 14 and vias 16 are omitted for clarity. A first inner layer 32 includes traces 44a and 44b that are formed on insulating substrate 36. A second inner layer 34 includes more traces 44a and 44b on the opposing side of substrate 36. Traces 44a and 44b are collectively referred to as traces 44. Traces 44 are patterned and connected by vias 22 to form a pair of entwined electrical loops or windings. It should be appreciated that substrate 36 may contain one or more additional conductive layers that are not shown. The additional conductive layers may, e.g., implement a voltage sensor that is described below. In the PCB 12 illustrated in FIG. 4, vias 24 are electrically connected to current sensor pads 30 to implement a voltage sensor in the manner described below (see, for example, FIG. 8).

[38] A schematic representation of a prior art current sensor is illustrated in FIG. 5(a). From Ampere's law, with the RF current traveling into the page, a magnetic field will be generated in a clockwise direction around the conductor 20. The magnetic field

will induce a current on the pickup loops 60 to flow through the transformer 50. Any electric fields picked up by the loops 60 will be shorted to ground. The circuit of FIG. 5(a) may act as a current sensor with the sensor loops 60 placed end to end (in series) such that there is no coupling between the loops 60.

5 **[39]** A schematic representation of a current sensor according to various embodiments of the present disclosure is illustrated in FIG. 5(b). In the circuit of FIG. 5(b), a common ground is utilized for the loops 60. From Ampere's law, with the RF current traveling into the page, a magnetic field will be generated in a clockwise direction around the conductor 20. The magnetic field will induce a current on the
10 pickup loops 60 to flow through the transformer 50. Any electric fields picked up by the loops 60 will be shorted to ground. The circuit of FIG. 5(b) includes two loops 60 next to each other (or parallel to each other) and there is no coupling between the loops 60.

[40] A schematic representation of a current sensor according to various embodiments of the present disclosure is illustrated in FIG. 5(c). In the circuit of FIG.
15 5(c), the loops 60 are not connected to a common ground. From Ampere's law, with the RF current traveling into the page, a magnetic field will be generated in a clockwise direction around the conductor 20. A resistor 55 in series with each of the two current pick up loops 60 may be included. The resistors 55 may be used to match the sensor impedance to any accompanying processing unit that may be utilized with the VI probe
20 10, which will result in lower reflected signals, lower noise and maximum sensor signal power transfer to the processing unit. The magnetic field will induce a current on the pickup loops 60 to flow through the transformer 50 and resistors 55. The electric field picked up by loops 60 will not be shorted to ground, as in the case of FIGS. 5(a) and

5(b). The E fields at points A and B on the transformer 50, however, will be equal, resulting in no current flow through the transformer 50 due to the E field. Therefore, the E field will be effectively canceled on the secondary or output side 57 of the transformer 50. Furthermore, points A and B of transformer 50 will be at relatively the same electrical potential, which will correspond to the electrical potential of the conductor 20 plus an additional component due to contamination from the current signals generated on loops 60 by the magnetic field.

[41] By placing the loops next to each other as depicted in FIGS. 5(b) and 5(c), the two current loops 60 will be exposed to the same magnetic and electric fields, which results in better cancellation of the E fields and an increase in the current sensor dynamic range. The length of the current sensor pick up lines (for example, current sensor pads 30) is related to the frequency response and coupling of the sensor 10. A longer current sensor pick up will improve signal coupling and the low frequency response of sensor 10, without decreasing the voltage breakdown of the VI probe 10 and other adverse effects.

[42] The transformer 50 generally has a turn ratio ("N") with respect to the primary and secondary windings. The resistors 55 compensate for the real portion of the output impedance. The imaginary portion of the output impedance may be compensated for by presenting real transmission line sensor sections or matching/filter circuits. In various embodiments, the values of the resistors 55 may be defined by:

$$R_{series} = \frac{Z_{output}}{2N^2},$$

where Z_{output} is the desired output impedance presented to the analysis unit and N is the transformer turns ratio.

[43] Referring now to FIG. 6, a schematic representation of yet another current sensor according to various embodiments of the present disclosure is illustrated. In the circuit of FIG. 6, the circuit of FIG. 5(c) is modified by removing the ground and connecting the loops 60 (for example, end-to-end) to form one continuous loop 60. This may be accomplished, for example, by connecting the traces 44a and 44b (as shown in FIGS. 3(a)-3(c)) by a via at the position of the hexagon 40. In this arrangement, the electric field impinged on the current sensor is not shorted to ground and, therefore, the E field potential will cause current to flow through the series resistors 55. The current from the E field will aid in one current loop while reduce the current in the other current loop, which may result in a portion of the E field signal to pass through the transformer 50. This E field contamination may reduce the dynamic range of the current sensor. By removing the current sensor ground from the RF ground, the current sensor ground will not be affected by the RF currents flowing through the PCB board 12 and the current sensor will only measure the current of the conductor 20.

[44] From Ampere's law, with the RF current traveling into the page, a magnetic field will be generated in a clockwise direction around the conductor 20. The resistors 55 may be used to match the sensor impedance to any accompanying processing unit that may be utilized with the VI probe 10, which will result in lower reflected signals, lower noise and maximum sensor signal power transfer to the processing unit. The magnetic field will induce a current on the pickup loops 60 to flow through the transformer 50 and resistors 55. As discussed above, the electric field picked up by

loops 60 will not be shorted to ground, as in the case of FIGS. 5(a) and 5(b). The E fields at points A and B on the transformer 50, however, will be equal, resulting in no current flow through the transformer 50 due to the E field. Therefore, the E field will be effectively canceled on the secondary or output side 57 of the transformer 50.

5 Furthermore, points A and B of transformer 50 will be at relatively the same electrical potential.

[45] As described above, the voltage potential at points A and B are proportional to the electric potential in the conductor 20, due to capacitive coupling. The voltage potential at points A and B can be thought of as the electrical potential of the conductor
10 20 plus an additional component due to contamination from the current signals generated on loops 60 by the magnetic field.

[46] FIG. 7 is a circuit diagram that represents a circuit showing a capacitive coupling relationship between the voltage at points A and B to that of the voltage of the conductor 20 of FIG. 6. In FIG. 7, the resistor R_m is the measurement input impedance,
15 such as in an analog-to-digital converter or receiver; I_m represents the current produced by the changing magnetic field around the conductor 20; C_c represents the distributed coupling capacitance between the conductor 20 and the current loops 60; and V_e is the RF voltage of the conductor 20.

[47] Utilizing the arrangement of FIG. 7, the RF voltage potential of conductor 20
20 may be defined by Guass's law. Using nodal equations to determine the voltage at points A and B (V_A and V_B , respectively) and letting:

$$V_e = V \sin(\omega t);$$

$$I_m = I \cos(\omega t); \text{ and}$$

$$s = j\omega.$$

Kirchhoffs current law equations for each node yields:

$$\frac{V_A}{R_m} + \frac{V_A - V_e}{\frac{1}{sCc}} - I_m = 0$$

$$\frac{V_B}{R_m} + \frac{V_B - V_e}{\frac{1}{sCc}} - I_m = 0$$

5 If we collect like terms:

$$\left(\frac{1}{R_m} + sCc \right) V_A - V_e sCc - I_m = 0$$

$$\left(\frac{1}{R_m} + sCc \right) V_B - V_e sCc + I_m = 0$$

Solving for V_A and V_B yields:

$$V_A = R_m \frac{V_e sCc + I_m}{1 + sCc R_m}$$

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$$V_B = -R_m \frac{-V_e sCc + I_m}{1 + sCc R_m}$$

Adding V_A and V_B signals ($V_{sum} = V_A + V_B$) with a center tap of the transformer 50 (or, alternatively, by an analog-to-digital converter/digital signal processing ("ADC/DSP") system) yields:

$$V_{sum} = R_m \frac{(V_e sCc + I_m)}{(1 + sCc R_m)} + -R_m \frac{(-V_e sCc + I_m)}{(1 + sCc R_m)}$$

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$$V_{sum} = V_e \frac{2sCc R_m}{(1 + sCc R_m)}$$

The result is the E Field of conductor 20, V_e , and an attenuation term. Subtracting V_B from V_A ($V_{diff} = V_A - V_B$) with a transformer 50 (secondary winding) or ADC/DSP system yields:

$$V_{diff} = R_m \frac{(V_e s_{Cc} + I_m)}{(1 + s_{Cc} R_m)} - R_m \frac{(-V_e s_{Cc} + I_m)}{(1 + s_{Cc} R_m)}$$

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$$V_{diff} = I_m \frac{2R_m}{(1 + s_{Cc} R_m)}$$

The result is current flowing through conductor 20, I_m , and an attenuation term. From these equations, the voltage (V_e) and current (I_m) of conductor 20 may be determined.

[48] A schematic representation of a voltage/current sensor according to various embodiments of the present disclosure is illustrated in FIG. 8. From Ampere's law, with the RF current traveling into the page, a magnetic field will be generated in a clockwise direction around the conductor 20. The magnetic field will induce a current on the pickup loops 60 to flow through the transformer 50. Similar to the circuit illustrated in FIG. 6, the electric field impinged on the voltage/current sensor is not shorted to ground and, therefore, the E field potential will cause current to flow through the series resistors 55. The current from the E field will aid in one current loop while reduce the current in the other current loop, which may result in a portion of the E field signal to pass through the transformer 50. This E field contamination may reduce the dynamic range of the current sensor.

[49] By removing the current sensor ground from the RF ground, the current sensor ground will not be affected by the RF currents flowing through the PCB board 12 and the current sensor will only measure the current of the conductor 20. The electrical signal representing the current of the conductor 20 may be obtained from the secondary

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side 57 of the transformer 50. A center tap 59 of the transformer 50 may be utilized to obtain the electrical signal representing the voltage of the conductor 20. From these electrical signals, the voltage and current of the conductor 20 may be determined, e.g., based on the equations set forth above.

5 **[50]** Referring now to FIGS. 9(a) and 9(b), various views of the PCB 12 are shown. Ground planes 14, vias 16 and vias 22 are omitted for clarity. A third inner layer 33 includes a circular conductive ring 102a that is formed on insulating substrate 36. A fourth inner layer 35 includes another circular conductive ring 102b on the opposite side of substrate 36. Circular conductive rings 102a and 102b are collectively
10 referred to as circular conductive rings 102. Circular conductive rings 102 are patterned and connected to each other by vias 24. Each of the circular conductive rings 102 defines a plane that is orthogonal to the longitudinal axis of the conductor 20. Furthermore, traces 104 couple each of the circular conductive rings 102 to voltage sensor pads 100 that are formed along walls of aperture 18.

15 **[51]** In some embodiments, the voltage sensor pads 100 may be the same as the current sensor pads 30 described above. Voltage sensor pads 100 can be plated to the edge of aperture 18 in substrate 36 and cut to shape by laser, mechanical abrasion or other manufacturing technique. Hexagon 40 may be utilized as a reference ground for determining a voltage of the conductor 20. The inner layer 33 also includes an
20 embedded core ring 42. The core ring 42 is embedded in the inner layer 33 between circular conductive rings 102a and 102b.

[52] The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the

disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. For purposes of clarity, the same reference
5 numbers will be used in the drawings to identify similar elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A or B or C), using a non-exclusive logical OR. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure.

CLAIMS

What is claimed is:

1. A radio frequency (RF) sensor system comprising:

a printed circuit board (PCB) including a first exterior layer, a second exterior
5 layer, a first interior layer, a second interior layer, and an inner perimeter that defines an aperture through the PCB;

a first loop comprising a first plurality of sensor pads coupled to a first plurality of
vias by a first plurality of traces, the first plurality of sensor pads being arranged on the
inner perimeter;

10 a second loop comprising a second plurality of sensor pads coupled to a second
plurality of vias by a second plurality of traces, the second plurality of sensor pads being
arranged on the inner perimeter; and

a core ring embedded within the first interior layer proximal to the first plurality of
sensor pads, the first plurality of vias, and the first plurality of traces;

15 wherein a center conductor for carrying RF current extends through the aperture
and the first and second loops generate an electrical signal based on the first and
second plurality of sensor pads, the first and second plurality of vias, the first and
second plurality of traces, and the core ring.

2. The RF sensor system of claim 1 wherein the core ring consists of a medium with
20 a greater permeability than air.

3. The RF sensor system of claim 1 wherein the core ring consists of a
ferromagnetic material.

4. The RF sensor system of claim 1 wherein the core ring has a coefficient of thermal expansion equal to the coefficient of expansion of the first and second exterior layers and the first and second interior layers.
5. The RF sensor system of claim 1 wherein the core ring has a coefficient of thermal expansion of less than the coefficient of expansion of the first and second exterior layers and the first and second interior layers.
6. The RF sensor system of claim 1 wherein at least one of a plurality of characteristics of the plurality of vias is selectively adjusted based on a resonance of the RF sensor.
- 10 7. The RF sensor system of claim 1 further comprising a second PCB including a third exterior layer, a fourth exterior layer, a third interior layer, a fourth interior layer, and an second inner perimeter that defines a second aperture through the second PCB;
a third loop comprising a third plurality of sensor pads coupled to a third plurality of vias by a third plurality of traces, the third plurality of sensor pads being arranged on
15 the second inner perimeter; and
a fourth loop comprising a fourth plurality of sensor pads coupled to a fourth plurality of vias by a fourth plurality of traces, the fourth plurality of sensor pads being arranged on the second inner perimeter.
- 20 8. The RF sensor system of claim 7 wherein the fourth exterior layer is electrically bound to the first exterior layer.

9. The RF sensor system of claim 8 wherein the first plurality of sensor pads, the second plurality of sensor pads, third plurality of sensor pads, and the fourth plurality of sensor pads are electronically connected in series.

10. The RF sensor system of claim 8 wherein the first plurality of sensor pads, the
5 second plurality of sensor pads, third plurality of sensor pads, and the fourth plurality of sensor pads are electronically connected in parallel.

11. A radio frequency (RF) sensing method comprising:

defining an aperture through a printed circuit board (PCB), wherein the PCB includes a first exterior layer, a second exterior layer, a first interior layer, a second
10 interior layer, and an inner perimeter;

coupling a first loop comprising a first plurality of sensor pads to a first plurality of vias by a first plurality of traces, arranging the first plurality of sensor pads on the inner perimeter;

coupling a second loop comprising a second plurality of sensor pads to a second
15 plurality of vias by a second plurality of traces, arranging the second plurality of sensor pads on the inner perimeter; and

embedding a core ring within the first interior layer proximal to the first plurality of sensor pads, the first plurality of vias, and the first plurality of traces;

wherein a center conductor for carrying RF current extends through the aperture
20 and the first and second loops generate an electrical signal based on the first and second plurality of sensor pads, the first and second plurality of vias, the first and second plurality of traces, and the core ring.

12. The RF sensing method of claim 11 wherein the core ring consists of a medium with a greater permeability than air.

13. The RF sensing method of claim 11 wherein the core ring consists of a ferromagnetic material.

5 14. The RF sensing method of claim 11 wherein the core ring has a coefficient of thermal expansion equal to the coefficient of expansion of the first and second exterior layers and the first and second interior layers.

15. The RF sensing method of claim 11 wherein the core ring has a coefficient of thermal expansion of less than the coefficient of expansion of the first and second
10 exterior layers and the first and second interior layers.

16. The RF sensing method of claim 11 wherein at least one of a plurality of characteristics of the plurality of vias is selectively adjusted based on a resonance of the RF sensor.

17. The RF sensing method of claim 11 further comprising defining a second
15 aperture a second PCB, wherein the second PCB includes a third exterior layer, a fourth exterior layer, a third interior layer, a fourth interior layer, and a second inner perimeter;
coupling a third loop comprising a third plurality of sensor pads to a third plurality of vias by a third plurality of traces, the third plurality of sensor pads being arranged on the second inner perimeter; and

coupling a fourth loop comprising a fourth plurality of sensor pads to a fourth plurality of vias by a fourth plurality of traces, the fourth plurality of sensor pads being arranged on the second inner perimeter.

18. The RF sensing method of claim 17 further comprising electrically binding the
5 fourth exterior layer to the first exterior layer.

19. The RF sensing method of claim 18 further comprising electrically connected in series the first plurality of sensor pads, the second plurality of sensor pads, third plurality of sensor pads, and the fourth plurality of sensor pads.

20. The RF sensing method of claim 18 further comprising electrically connecting in
10 parallel the first plurality of sensor pads, the second plurality of sensor pads, third plurality of sensor pads, and the fourth plurality of sensor pads.