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(54) **Title:** VERIFYING STRUCTURAL INTEGRITY OF MATERIALS USING ONE OR MORE CURRENT INJECTION POINTS AND MULTIPLE CURRENT EXTRACTION POINTS

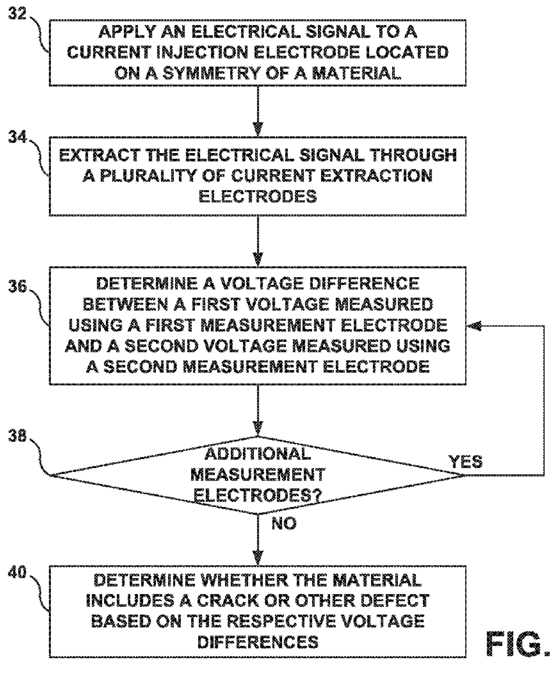

FIG. 2

(57) **Abstract:** A system may include a computing device and an electrical signal source. The computing device may cause the electrical signal source to apply an electrical signal, such as a current, to a current injection electrode electrically coupled to a material. Current may be extracted through a plurality of current extraction electrodes. The plurality of current extraction electrodes may be arranged symmetrically with reference to the symmetry of the material. While the electrical signal is being applied to the material, the computing device may measure a first voltage using a first measurement electrode and a second voltage using a second measurement electrode. In some examples, the first measurement electrode and the second measurement electrode may be positioned symmetrically with reference to the symmetry of the material. By comparing the first measured voltage and the second measured voltage, the computing device may determine whether the material includes a crack or other defect.

WO 2018/093882 A1

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VERIFYING STRUCTURAL INTEGRITY OF MATERIALS USING ONE OR MORE CURRENT INJECTION POINTS AND MULTIPLE CURRENT EXTRACTION POINTS

This application is related to U.S. Provisional Application number 62/423,142 filed November 16, 2016, and U.S. Provisional Application number 62/502,046 filed on May 5, 2017, which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The disclosure relates to techniques for verifying structural integrity of conductive or semiconductive materials.

BACKGROUND

Many materials are useful when their mechanical properties remain intact, but less useful when damaged, such as when cracked. Thus, detection whether these materials are damaged is important. As one example, ceramic body plating is used to protect soldiers, police officers, and other security personnel from projectiles. Ceramic body plating may be useful when undamaged, but may be replaced after being damaged, e.g., after cracking.

X-ray scanning, including X-ray radiography and X-ray computed tomography (CT scanning) may be used to detect cracks or other defects in materials. However, such techniques may utilize large and heavy scanners, which may not be easily portable. Further, X-ray scanning and X-ray CT scanning may be relatively expensive, relatively slow, or both.

SUMMARY

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include applying an electrical signal to a current injection electrode electrically coupled to the material. The current injection electrode may be positioned on a symmetry of the material. The method also may include extracting the electrical signal through a plurality of current extraction electrodes. The plurality of current extraction electrodes may be arranged symmetrically with reference to the symmetry of the material. The method may further include, while applying the electrical signal to the current injection electrode, determining a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode. The first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material. The method additionally may include determining whether the material includes a crack or other defect based on the voltage difference.

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include applying a first electrical signal to a first current injection electrode electrically coupled to the material. The first current injection electrode is positioned at a first location of the material. The method also may include extracting the first electrical signal through a plurality of current

extraction electrodes. The plurality of current extraction electrodes may be arranged symmetrically with reference to a symmetry of the material. The method additionally may include, while applying the first electrical signal to the first current injection electrode, determining a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode. The first and second measurement electrodes may be arranged symmetrically with reference to the symmetry of the material. The method further may include applying a second electrical signal to a second current injection electrode electrically coupled to the material. The second current injection electrode is positioned at a second location of the material, and the first and second locations may be symmetric with reference to the symmetry of the material. The method also may include extracting the second electrical signal through the plurality of current extraction electrodes, and, while applying the second electrical signal to the second current injection electrode, determining a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode. The method further may include determining whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

In some examples, the disclosure describes system including a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device. The computing device may be configured to cause the electrical signal source to apply an electrical signal to a current injection electrode. The current injection electrode may be positioned on a symmetry of the material and may be from the set of N electrodes. The computing device also may be configured to cause the electrical signal to be extracted through a plurality of current extraction electrodes. The plurality of current extraction electrodes may be arranged symmetrically with reference to the symmetry of the material and may be from the set of N electrodes. The computing device additionally may be configured to, while the electrical signal source is applying the electrical signal to the current injection electrode, determine a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode. The first and second measurement electrodes may be arranged symmetrically with reference to the symmetry of the material. The computing device further may be configured to determine whether the material includes a crack or other defect based on the voltage difference.

In some examples, the disclosure describes a system including a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device. The computing device may be configured to cause the electrical signal source to apply a first electrical signal to a first current injection electrode electrically coupled to the material. The first current injection electrode is positioned at a first location of the material and is from the set of N electrodes. The computing device also may be configured to cause the first electrical signal to be extracted through a plurality of current extraction electrodes. The plurality of current extraction electrodes may be arranged symmetrically with reference to a symmetry of the material and may be from the set of N electrodes. The computing device further may be configured to, while the electrical signal source is applying the first electrical signal to the first current injection electrode, determine a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode. The first and second measurement electrodes may be arranged symmetrically with reference to the symmetry of the material. The computing device additionally may be configured to cause the electrical signal source to apply a second electrical signal to a second current injection electrode electrically coupled to the material. The second current injection electrode is positioned at a second location of the material and is from the set of N electrodes, and the first and second locations may be symmetric with reference to the symmetry of the material. The computing device also may be configured to cause the second electrical signal to be extracted through the plurality of current extraction electrodes, and, while the electrical signal source is applying the second electrical signal to the second current injection electrode, determine a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode. The computing device additionally may be configured to determine whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a conceptual block diagram illustrating an example system for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes.

FIG. 2 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using a single current injection electrode and a plurality of current extraction electrodes.

FIG. 3 is a conceptual block diagram illustrating an example system for determining whether a material includes a crack or other defect using a single current injection electrode and a plurality of current extraction electrodes in a configuration including a single current injection electrode, two current extraction electrodes, and two measurement electrodes.

FIG. 4 is an equivalent circuit diagram of the system configuration shown in FIG. 3 in the absence of a crack or other defect.

FIG. 5 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using at least two current injection electrodes and a plurality of current extraction electrodes.

FIG. 6 is a conceptual block diagram illustrating an example system for determining whether a material includes a crack or other defect using at least two current injection electrodes and a plurality of current extraction electrodes in a first configuration including a first current injection electrode, two current extraction electrodes, and two measurement electrodes.

FIG. 7 is an equivalent circuit diagram of the system configuration shown in FIG. 6 in the absence of a crack or other defect.

FIG. 8 is a conceptual block diagram illustrating an example system for determining whether a material includes a crack or other defect using at least two current injection electrodes and a plurality of current extraction electrodes in a second configuration including a second current injection electrode, two current extraction electrodes, and two measurement electrodes.

FIG. 9 is an equivalent circuit diagram of the system configuration shown in FIG. 10 in the absence of a crack or other defect.

FIG. 10 is an equivalent circuit diagram of an example system configuration in which measurement voltages are measured with respect to a voltage reference derived from the electrical signal applied to the current injection electrode, in the absence of a crack or other defect.

FIGS. 11–14 are circuit diagrams of example system configurations including various locations of current sources for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes.

FIG. 15 is a circuit diagram of an example system configuration in which measurement voltages are measured with respect to a differential voltage reference derived from the electrical signal applied to the current injection electrode.

FIGS. 16A–16C are circuit diagrams of example system configurations for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes.

DETAILED DESCRIPTION

The disclosure describes systems and techniques for verifying structural integrity of a material. In some examples, a system may include a computing device and an electrical signal source. The techniques may include applying an electrical signal, such as a current, from the electrical signal source to a current injection electrode electrically coupled to a material and extracting the electrical signal through a plurality of current extraction electrodes. The material may include a symmetry. A symmetry is a point, a line, a plane, a curve, or a manifold, for which a single mathematical operation made with reference to the symmetry maps each respective point of the material to another respective point of the material. The plurality of current extraction electrodes may be arranged symmetrically with reference to the symmetry of the material. While the electrical signal is being applied to the material, the computing device may measure a first voltage using a first measurement electrode and a second voltage using a second measurement electrode. In some examples, the first measurement electrode and the second measurement electrode may be positioned symmetrically with reference to the symmetry of the material. By comparing the first measured voltage and the second measured voltage, the computing device may determine whether the material includes a crack or other defect.

In some examples, the current injection electrode may include a single current injection electrode, which may be positioned on the symmetry of the material, e.g., near an opposite side or end of the material as the plurality of current extraction electrodes. As the single current injection electrode is positioned on the symmetry of the material and the plurality of current extraction electrodes are positioned symmetrically with reference to the symmetry of the material, the respective currents flowing from the single current injection electrode to each respective current extraction electrode may be substantially the same (e.g., the same or nearly the same) in the absence or a crack or defect in the material. However, if material includes a crack or other defect, the respective currents flowing from the single current injection electrode to the respective current extraction electrodes may not be substantially the same, as the crack or other defect affects the resistance of the material to current flowing across the crack or other defect. Hence, if the first measured voltage and the second measured voltage are different, the computing device may determine that the material includes a crack or other defect.

In some examples, rather than using a single current injection electrode, at least two current injection electrodes may be used, one current injection electrode for each set of voltage measurements. A first current injection electrode may be positioned at a first position of the material, and a second current injection electrode may be positioned at a second position of the material. The first and second positions may be symmetric with reference to the symmetry of the material. In a first measurement set, the electrical signal source may apply a first electrical signal to the first current injection electrode, and the first electrical signal may be extracted through the plurality of current extraction electrodes. The computing device may measure a first measured voltage using the first measurement electrode and a second measured voltage using the second measurement electrode. The computing device may determine a first voltage difference between the first measured voltage and the second measured voltage.

In a second measurement set, the electrical signal source may apply a second electrical signal to the second current injection electrode, and the second electrical signal may be extracted through the plurality of current extraction electrodes. The computing device may measure a third measured voltage using the first measurement electrode and a fourth measured voltage using the second measurement electrode. The computing device may determine a second voltage difference between the third measured voltage and the fourth measured voltage. As the current injection electrodes are positioned symmetrically with reference to the symmetry of the material and the plurality of current extraction electrodes are positioned symmetrically with reference to the symmetry of the material, the first voltage difference and the second voltage difference are substantially the same (e.g., the same or nearly the same) in magnitude in the absence of a crack or other defect. However, if material includes a crack or other defect, the respective currents flowing from the current injection electrode to the respective current extraction electrodes may not be substantially the same, as the crack or other defect affects the resistance of the material to current flowing across the crack or other defect. This may result in the first voltage difference and the second voltage difference being different in magnitude. Hence, if the first voltage difference and the second voltage difference are different in magnitude, the computing device may determine that the material includes a crack or other defect.

In some examples, regardless of whether a single current injection electrode or at least two current injection electrodes is used, the computing device may measure respective voltages using more than two electrodes. For example, the computing device may measure respective voltages using a plurality of respective measurement electrode sets. For each of the plurality of respective measurement electrode sets, the computing device may determine a respective voltage difference between a first respective voltage measured using a respective first measurement electrode from the respective measurement electrode set and a second respective voltage measured using a respective second measurement electrode from the respective measurement electrode set. For each of the plurality of respective measurement electrode sets, the respective first measurement electrode and the respective second measurement electrode may be positioned symmetrically with reference to the symmetry of the material. The computing device may utilize voltage differences for each of the plurality of respective measurement electrode sets to determine whether the material includes a crack or other defect.

Utilizing comparisons between multiple voltage measurements from a material may allow determination of whether a material includes a crack or other defect without previous measurement of control voltages, which may simplify determination of whether the material includes the crack or other defect. Further, as the multiple voltage measurements are performed at substantially the same time (e.g., as part of a single set of measurements), the material may be expected to be at substantially the same temperature (e.g., the same temperature or nearly the same temperature). Thus, temperature may be less of a factor in the comparisons. This may be important for some materials, such as semiconductors, whose conductivity changes significantly as a function of temperature.

Other techniques also may be used to detect cracks in a material. For example, X-ray radiography or X-ray computed tomography (CT) may be used to detect cracks in a material. However, X-ray radiography and X-ray CT utilize relatively large, relatively expensive equipment to perform the crack detection. This may prevent X-ray radiography and X-ray CT from being portable, such as being used to test materials in the environments in which they are used. Moreover, X-ray radiography and X-ray CT may be relatively time consuming. In contrast, the techniques and systems described herein may smaller, less expensive, and quicker to operate that X-ray radiography and X-ray CT systems. In some examples, the techniques described herein may allow determination of whether a material includes a crack or other defect in the field, where the material is being used, rather than requiring the material to be transported to the X-ray radiography or X-ray CT system.

FIG. 1 is a conceptual block diagram illustrating an example system for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes. System 10 of FIG. 1 includes a computing device 12, an electrical signal source 14, a plurality of electrodes 18A–18V (collectively, "electrodes 18"), a switch network 20, and an optional reference electrode 22. Electrodes 18 are electrically coupled to material 16.

Material 16 may be any material for which detection of a potential crack or other defect is desired. In some examples, material 16 may be an electrically conductive or an electrically semiconductive material. For example, material 16 may include a metal, an alloy, a metalloid, a semiconductor, an electrically conductive or semiconductive ceramic, or the like. In some examples, material 16 may include a ceramic such as boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

Material 16 may be used in any one of a wide variety of applications. For example, material 16 may be a ceramic that has relatively high hardness, a relatively high Young's modulus, a relatively high tensile strength, and may be used in ceramic armor plating. Ceramic armor plating may be used in body armor for military and police personnel, vehicle armor, or the like. Example materials for ceramic armor plating include boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

Material 16 may define any geometry, and the geometry of material 16 may be based at least in part on the intended use for material 16. For example, ceramic armor plating may have a geometry defined by the surface that the armor plating will be applied to. Example geometries for material 16 include, but are not limited to, polygonal solids, such as rectangular solids or solids with more sides.

In some examples, material 16 may define a geometry that has a symmetry, i.e., is symmetric. As used herein, a symmetry is a point, line, plane, curve, or manifold, with reference to which a single mathematical operation maps each point of material 16 to another point of material 16. In the example of FIG. 1, material 16 includes a plane of symmetry 24, across which there is mirror symmetry. As described in further detail below, in some examples in which material 16 includes a symmetry, computing device 12 may compare voltages measured using electrodes or electrode pairs that are symmetrical with reference to the symmetry, e.g., plane of symmetry 24, to determine whether material 16 includes a crack or other defect.

Electrical signal source 14 may include any device configured to output an electrical signal to electrodes 18. The electrical signal may include an alternating current (AC) signal or a direct current (DC) signal. In some examples, electrical signal source 14 may output a current signal; in other examples, electrical signal source 14 may output a voltage signal. In some examples, electrical signal source 14 may include a power source, such as a battery, a capacitor, a supercapacitor, a transformer electrically connected to a mains voltage, or the like. In some examples, in addition to the power source, electrical signal source 14 may include analog or digital circuitry configured to receive the electrical signal from the power source and modify the electrical signal into a format suitable for output to electrodes 18.

Switch network 20 includes a plurality of inputs and a plurality of outputs, with respective inputs electrically coupled to each respective output by the network of switches. For example, switch network 20 may include a pair of inputs electrically coupled to electrical signal source 14, and at least a pair of inputs electrically coupled to computing device 12. Switch network 20 may include at least as many outputs are there are electrodes 18 and 22. For example, in the example shown in FIG. 1, system 10 includes twenty-three electrodes, and switch network 20 thus includes at least twenty-three outputs. Each electrode of electrodes 18 and reference electrode 22 is electrically coupled to a respective output of switch network 20.

Computing device 12 is configured to control operation of system 10, including electrical signal source 14 and switch network 20. Computing device 12 may include any of a wide range of devices, including computer servers, desktop computers, notebook (i.e., laptop) computers, tablet computers, and the like. In some examples, computing device 12 may include a processor. The processor may include one or more microprocessors, digital signal processors (DSP), application specific integrated circuits (ASIC), field programmable gate arrays (FPGA), or other digital logic circuitry. In some examples, computing device 12 may include an analog-to-digital converter (ADC), or system 10 may include an ADC separate from computing device 12. In examples in which the ADC is separate from computing device 12, the ADC may be electrically coupled between a selected measurement electrode and computing device 12. The ADC may measure the voltage using the selected measurement electrode, e.g., under control of computing device 12.

Computing device 12 is communicatively coupled to electrical signal source 14 and electrically coupled to switch network 20, e.g., either directly or indirectly via an external device, such as an ADC. Computing device 12 may be configured to control electrical signal source 14 to output an electrical signal, and may be configured to control switch network 20 to connect a selected electrode of electrodes 18 to electrical signal source 14 to serve as a current injection electrode, such that the electrical signal output by electrical signal source 14 is output to the current injection electrode.

Computing device 12 is also configured to cause switch network 20 to connect a selected plurality of electrodes 18 to computing device 12 to serve as a plurality of current extraction electrodes through which the electrical signal is extracted, e.g., to ground. Further, computing device 12 is configured to cause switch network 20 to connect selected electrodes either individuals or in pairs to computing device 12 to serve as a measurement electrode or pair of measurement electrodes. In this way, computing device 12 may determine a voltage using a measurement electrode or a pair of measurement electrodes in response to the electrical signal output by electrical signal source 14.

Electrodes 18 include a plurality of electrodes electrically coupled to material 16. In some examples, as shown in FIG. 1, each electrode of electrodes 18 is also electrically coupled to switch network 20. Each of electrodes 18 may be electrically connected to material 16 using any suitable type of electrical coupling, including, for example, an electrically conductive adhesive, an electrically conductive solder, embedding electrodes 18 in material 16, a dielectric coupling via capacitive coupling, or the like.

Electrodes 18 may be attached to any surface of material 16. The surface to which electrodes 18 are attached may affect the direction in which the electrical field extends and current flows within material 16. Cracks or other defects may affect the magnitude of the voltage more significantly when the electrical field and current flow extends across a plane of the crack (e.g., normal to a surface of the crack). As such, in some examples, the likely locations of cracks or other defects and the likely orientation of cracks or other defects within material 16 may be predicted based on the use for material 16. In some of these examples, electrodes 18 may then be attached to material 16 so that the electrical field and current flow within material 16 extends substantially normal to a predicted orientation of the crack or other defect.

In some examples, rather than predicting a location of the crack or other defect within material 16 and placing electrodes 18 based on the prediction, electrodes 18 may be attached to more than one surface of material 16. For example, if material 16 is in the shape of a cube, electrodes 18 may be attached to three orthogonal surfaces of the cube. By attaching a respective electrode of electrodes 18 to three orthogonal surfaces, the electrical field and current flow may be caused to extend in one of three orthogonal directions depending on the electrodes 18 through which the electrical signal is applied. This may increase the likelihood that the induced electrical field and current flow will extend within material 16 normal to the plane of any crack in material 16. Other examples are possible for other shapes. In some examples, electrodes 18 are distributed across a surface area of material 16, as shown in FIG. 1. In other examples, electrodes 18 are distributed around a perimeter of material 16. In some examples, plurality of electrodes 18 may be referred to as a set of N electrodes 18.

In some examples, electrodes 18 may be positioned on material 16 according to a selected geometric relationship. For example, electrodes 18 may be positioned on material 16 so that each electrode of electrodes 18 is substantially symmetric to another one of electrodes 18 with reference to the symmetry of material 16. In the example of FIG. 1, first electrode 18A is substantially symmetric to seventh electrode 18G with reference to plane of symmetry 24, second electrode 18B is substantially symmetric to sixth electrode 18F with reference to plane of symmetry 24, third electrode 18C is substantially symmetric to fifth electrode 18E with reference to plane of symmetry 24, and so on.

As another example, electrodes 18 may be positioned on material 16 so that a respective pair of electrodes is substantially symmetric to another respective pair of electrodes 18 with reference to the symmetry of material 16. For example, a first pair of electrodes may include first electrode 18A and twenty-second electrode 18V and a second pair of electrodes may include seventh electrode 18G and eighth electrode 18H. The first pair of electrodes is symmetric to the second pair of electrodes with reference to plane of symmetry 24.

In some examples, electrodes 18 may be positioned on material 16 so that each respective pair of electrodes is substantially symmetric to another respective pair of electrodes 18 with reference to the symmetry of material 16. This may be accomplished in examples in which each electrode of electrodes 18 is substantially symmetric to another one of electrodes 18 with reference to the symmetry of material 16, and a respective electrode of two symmetric electrodes is used in each respective pair of electrodes in a symmetric pair of electrodes.

Further, in some examples, two electrodes may be positioned on the symmetry of material 16, e.g., on plane of symmetry 24 shown in FIG. 1. For example, fourth electrode 18D and fifteenth electrode 18O are positioned on plane of symmetry 24. In other examples, electrodes are not positioned on the symmetry of material 16.

In some examples, positioning electrodes 18 to be exactly symmetrical may be difficult to achieve in practice. Hence, electrodes 18 may be positioned to be substantially symmetrical. As used here, substantially symmetrical means that the electrodes are placed approximately symmetrical with reference to a symmetry of material 16, e.g., within about 0.5 mm of being symmetric, within about 0.2 mm of being symmetric or within about 0.1 mm of being symmetric.

In some examples, system 10 may optionally include reference electrode 22, which may not be electrically coupled to material 16 and may be used for single-ended voltage measurements between one electrode of plurality of electrodes 18 and reference electrode 22. Reference electrode 22 may be at a selected voltage, such a ground or an offset voltage. In some examples, computing device 12 may use the single-ended voltages in the techniques described herein to determine whether material 16 includes a crack or other defect. In other examples, computing device 12 may determine differential voltages between two electrodes electrically coupled to material 16 by comparing (e.g., subtracting) single ended voltages associated with the two electrodes, and computing device 12 may use these differential voltages in the techniques described herein to determine whether material 16 includes a crack or other defect. In still other examples, computing device 12 may determine a voltage between two of electrodes 18 directly, e.g., without first determining two single-ended voltages.

Computing device 12 may be configured to cause electrical signal source 14 to apply an electrical signal to a current injection electrode electrically coupled to material 16 and cause the electrical signal to be extracted through a plurality of current extraction electrodes by causing the switch network to electrically couple to the plurality of current extraction electrodes. The current injection electrode may include at least one of electrodes 18. Similarly, the plurality of current extraction electrodes may include at least one of electrodes 18, and the at least one current injection electrode may be different from the plurality of current extraction electrodes.

The plurality of current extraction electrodes may be arranged symmetrically with reference to the symmetry of material 16, e.g., with reference to plane of symmetry 24. The plurality of current extraction electrodes may include at least two current extraction electrodes, and may include any number of current extraction electrodes greater than two. For example, the plurality of current extraction electrodes may include an even number of current extraction electrodes. For each respective pair of the even number of current extraction electrodes, a first electrode of the pair may be positioned symmetrically to the second electrode of the pair with reference to the symmetry of material 16, e.g., plane of symmetry 24. For example, the plurality of current extraction electrodes may include twelfth electrode 18L, thirteenth electrode 18M, seventeenth electrode 18Q, and eighteenth electrode 18R. Twelfth electrode 18L is positioned symmetrically to eighteenth electrode 18R with reference to plane of symmetry 24 and thirteenth electrode 18M is positioned symmetrically to seventeenth electrode 18Q with reference to plane of symmetry 24.

Computing device 12 may cause switch network 20 to connect the current injection electrode and the plurality of current extraction electrodes so that a current source (e.g., included in electrical signal source 14) injects the injection current is through a high side or a low side with reference to a voltage source. Examples of different high side current source and low side current source configurations are shown and described with reference to FIGS. 4, 7, and 9–16C.

While electrical signal source 14 is applying the electrical signal to material 16 using the at least one current injection electrode and the plurality of current extraction electrodes, computing device 12 may determine a first measured voltage using a first measurement electrode and a second measured voltage using a second measurement electrode. In some examples, the first measurement electrode and the second measurement electrode may be positioned symmetrically with reference to the symmetry of material 16, e.g., plane of symmetry 24. For example, the first electrode may be any one of electrodes 18A, 18B, 18C, 18V, 18U, 18T, 18S, 18R, 18Q, or 18P, and the second electrode may be a corresponding one of electrodes 18G, 18F, 18E, 18H, 18I, 18J, 18K, 18L, 18M, or 18N. In some examples, the measurement electrodes may be different than the current extraction electrodes. In other examples, the measurement electrodes may be the same as the current extraction electrodes. In still other examples, the measurement electrodes may not be electrically coupled to material 16. For example, the measurement electrodes may include a first electrode measuring a voltage at a location between a first current extraction electrode and switch network 18 and a second electrode measuring a voltage at a location between a second current extraction electrode and switch network 18. By comparing the first measured voltage and the second measured voltage, computing device 12 may determine whether material 16 includes a crack or other defect.

In some examples, computing device 12 may measure respective voltages using more than two measurement electrodes. For example, computing device 12 may measure respective voltages using a plurality of respective measurement electrode sets. For each of the plurality of respective measurement electrode sets, computing device 12 may determine a respective voltage difference between a first respective voltage measured using a respective first measurement electrode from the respective measurement electrode set and a second respective voltage measured using a respective second measurement electrode from the respective measurement electrode set. For each of the plurality of respective measurement electrode sets, the respective first measurement electrode and the respective second measurement electrode may be positioned symmetrically with reference to the symmetry of the material. For example, a first measurement electrode set may include first electrode 18A and seventh electrode 18G, a second measurement electrode set may include twenty-second electrode 18V and eighth electrode 18H, and so on. Computing device may utilize voltage differences for each of the plurality of respective measurement electrode sets to determine whether material 16 includes a crack or other defect.

Utilizing comparisons between multiple voltage measurements from material 16 may allow determination of whether material 16 includes a crack or other defect without previous measurement of control voltages, which may simplify determination of whether material 16 includes the crack or other defect. Further, as the multiple voltage measurements are performed at substantially the same time (e.g., as part of a single set of measurements), material 16 may be expected to be at substantially the same temperature (e.g., the same temperature or nearly the same temperature). Thus, temperature may be less of a factor in the comparisons. This may be important for some materials, such as semiconductors, whose conductivity changes significantly as a function of temperature.

In some examples, the at least one current injection electrode utilized for the voltage measurements may include a single current injection electrode, which may be positioned on the symmetry of material 16, e.g., on plane of symmetry 24. FIG. 2 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using a single current injection electrode and a plurality of current extraction electrodes. The technique of FIG. 2 will be described with concurrent reference to system 10 of FIG. 3, but it will be understood that other systems that include more or fewer components than system 10 may perform the technique of FIG. 2 (e.g., a system that includes only computing device 12), and that system 10 may be used to perform other techniques (e.g., the techniques of FIG. 5, among other techniques). FIG. 3 is a conceptual block diagram illustrating an example system 10 for determining whether a material 16 includes a crack or other defect using a single current injection electrode and a plurality of current extraction electrodes in a configuration including a single current injection electrode 18D, two current extraction electrodes 18Q and 18M, and two measurement electrodes 18V and 18H. Aside from the configuration of electrodes 18, system 10 in FIG. 3 is similar to or substantially the same as system 10 illustrated in FIG. 1.

The technique of FIG. 2 may include applying an electrical signal to a current injection electrode located on a symmetry of material 16, e.g., on plane of symmetry 24 (32). For example, computing device 12 may cause switch network 20 to electrically couple an electrode of electrodes 18 to electrical signal source 14 as the current injection electrode. As shown in FIG. 3, the single current injection electrode may be fourth electrode 18D (referred to as current injection electrode 18D with reference to FIGS. 2 and 3), which is located on plane of symmetry 24. Computing device 12 then may cause electrical signal source 14 to apply the electrical signal to the current injection electrode, fourth electrode 18D.

The technique of FIG. 2 also includes extracting the electrical signal through a plurality of current extraction electrodes (34). For example, computing device 12 may cause switch network 20 to electrically couple a plurality of electrodes from electrodes 18 to electrical signal source 14 or to ground as the plurality of current extraction electrodes. As described above, the plurality of current extraction electrodes may include at least two current extraction electrodes. In the example shown in FIG. 3, the plurality of current extraction electrodes includes two current extraction electrodes, thirteenth electrode 18M and seventeenth electrode 18Q (referred to as current extraction electrodes 18M and 18Q with reference to FIGS. 2 and 3). In general, any number of electrodes 18 may be coupled to switch network 20 as current extraction electrodes, as long as the arrangement of the current extraction electrodes is symmetrical with reference to a symmetry of material 16, e.g., plane of symmetry 24. For example, any of electrodes 18A–18V other than the electrode being used as the current injection electrode may be used as a current extraction electrode.

In some examples, as shown in FIG. 3, current extraction electrodes 18M and 18Q may be positioned near an opposite side or end of material 16 as current injection electrode 18D. This may result in more even current flow through the volume of material 16, e.g., compared to current extraction electrodes positioned nearer to current injection electrode 18D, such as electrodes 18C and 18D. This may improve a likelihood that a crack or other defect present in material 16 is detected by the technique of FIG. 2.

The technique of FIG. 2 also includes determining a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode (36). For example, computing device 12 may cause switch network 20 to electrically couple a first electrode to computing device 12 to be the first measurement electrode and to electrically couple a second electrode to computing device 12 to be the second measurement electrode.

In some examples, computing device 12 may be configured to select the first and second measurement electrodes from electrodes 18. For example, as shown in FIG. 3, eighth electrode 18H may be the first measurement electrode and twenty-second electrode 18V may be the second measurement electrode. In other examples, computing device 12 may select the current extraction electrodes to be the measurement electrodes, e.g., first current extraction electrode 18M may be the first measurement electrode and second current extraction electrode 18Q may be the second measurement electrode. In still other examples, computing device 12 may be configured to select the first and second measurement electrodes from electrodes other than electrodes 18. For example, computing device 12 may be configured to select an electrode located between first current extraction electrode 18M and switch network 20 as the first measurement electrode and to select an electrode located between second current extraction electrode 18Q and switch network 20 as the second measurement electrode. An example of this configuration is shown and described below with reference to FIG. 4. Regardless of which electrodes computing device 12 selects as the first and second measurement electrodes, the first and second measurement electrodes may be positioned symmetric to each other with reference to a symmetry of material 16, e.g., plane of symmetry 24.

Computing device 12 may be configured to measure the first measured voltage between the first measurement electrode and a third measurement electrode. In some examples, the third measurement electrode may be another electrode from electrodes 18, such that the first measured voltage is a differential voltage between the first measurement electrode and the third measurement electrode. In other examples, the third measurement electrode may be reference electrode 22, and the first measured voltage may be a single-ended voltage.

Similarly, computing device 12 may be configured to measure the second measured voltage between the second measurement electrode and a fourth measurement electrode. In some examples, the fourth measurement electrode may be another electrode from electrodes 18, such that the second measured voltage is a differential voltage between the second electrode and the fourth measurement electrode. In other examples, the fourth electrode may be reference electrode 22, and the second measured voltage may be a single-ended voltage. In examples in which the third and fourth measurement electrodes are not reference electrode 22, the third and fourth measurement electrodes may be positioned symmetric to each other with reference to a symmetry of material 16, e.g., plane of symmetry 24.

Once computing device 12 measures the first measured voltage using the first measurement electrode and measures the second measured voltage using the second measurement electrode, computing device 12 may determine a voltage difference between the first measured voltage and the second measured voltage (36). For example, computing device 12 may be configured to subtract the first measured voltage from the second measured voltage or subtract the second measured voltage from the first measured voltage.

In some examples, the technique of FIG. 2 optionally includes determining whether additional voltage differences are to be determined using additional measurement electrodes (38). For example, computing device 12 may be configured to determine respective voltage differences for each respective measurement electrode set of a plurality of respective measurement electrode sets. Each respective measurement electrode set may include a respective first measurement electrode and a respective second measurement electrode. Each respective first and second measurement electrodes may be positioned symmetric to each other with reference to a symmetry of material 16, e.g., plane of symmetry 24. Further, computing device 12 may be configured to measure the respective first voltage using the respective first measurement electrode and a respective third measurement electrode, which may be reference electrode 22 or another electrode of electrodes 18. Similarly, computing device 12 may be configured to measure the respective second voltage using the respective second measurement electrode and a respective fourth measurement electrode, which may be reference electrode 22 or another electrode of electrodes 18.

For each of the plurality of respective measurement electrode sets, computing device 12 may determine a respective voltage difference between a first respective voltage measured using the respective first measurement electrode and a second respective voltage measured using the respective second measurement electrode.

Hence, computing device 12 may be configured to determine whether additional voltage differences are to be determined using additional measurement electrodes (38). In response to determining that additional voltage differences are to be determined using additional measurement electrodes (the "YES" branch of decision block 38), computing device 12 may determine a respective voltage difference between a respective first voltage measured using a respective first measurement electrode and a respective second voltage measured using a respective second measurement electrode (36). For example, computing device 12 may cause switch network 20 to electrically couple selected electrodes from electrodes 18, reference electrode 22, or the like to computing device 12, may measure the respective first voltage using the respective first electrode, may measure the respective second voltage using the respective second electrode, and may determine a respective voltage difference between the respective first voltage and the respective second voltage (36). Computing device 12 may iterate this process until computing device 12 determines that no additional voltage differences are to be determined using additional measurement electrodes (the "NO" branch of decision block 38).

In response to determining that no additional voltage differences are to be determined using additional measurement electrodes (the "NO" branch of decision block 38), computing device 12 may determine whether material 16 includes a crack or other defect based on the respective voltage differences (40). In order to make this determination, computing device 12 may be configured to determine that a non-zero voltage difference (or a voltage difference that is greater than a threshold value) indicates a presence of a crack or other defect, and a voltage difference of zero (or a voltage difference that is less than a threshold value) indicates that material 16 does not include a crack or other defect.

To understand why this is the case, FIG. 4 is an equivalent circuit diagram of a system configuration similar to that shown in FIG. 3 in the absence of a crack or other defect. As shown in FIG. 4, a high side current source 42 outputs a test current $I_T = 2*I$ to a current injection electrode 44 that is located on a symmetry of material 46. Once the test current I_T enters material 46, the test current I_T splits and conducts through material 46 to first current extraction electrode 48 and second current extraction electrode 50. A first current I_r flows to first current extraction electrode 48 through an equivalent resistance R. A second current I_k flows to second current extraction electrode 50 through an equivalent resistance K*R. Equivalent resistances R and K*R represent the resistances of the portions of material 46 through which the first current I_r and the second current I_k flow. A portion of current I_c also may flow through equivalent resistance P*R within material 46. In the absence of cracks or defects in material 46, the magnitudes of currents I_k and I_r will be approximately proportional to the relative distances between current injection electrode 44 and first current extraction electrode 48 and between current injection electrode 44 and second current extraction electrode 50. K represents this proportionality. In the example of FIG. 4, as current injection electrode 44 is on the symmetry of material 46 and first and second current extraction electrodes 48 are positioned symmetric with reference to the symmetry, K = 1. The respective currents through the respective current extraction electrodes 48 and 50 pass through equal resistors with equivalent resistances of M*R, are combined, and pass through a resistance R1, at which a voltage V_{R1} may be measured.

By examination of FIG. 4 and with K=1:

$$R*I_r + V_r = R*I_k + V_l \qquad (1)$$

$$I_r + I_k = 2*I = I_p + I_n \qquad (2)$$

$$I_c = (V_l - V_r) / (P*R) \qquad (3)$$

$$M*R*I_p + V_r = M*R*I_n + V_l \qquad (4)$$

Rearranging equation (1) yields:

$$\Delta V = (V_l - V_r) = (I_r - I_k)*R \qquad (5)$$

$$I_r = P*I_c + I_k \qquad (6)$$

From equation (5), it is clear that the magnitude of the difference between V_l and V_r is proportional to the mismatch between the extracted currents. As current injection electrode 44 is positioned on the symmetry of material 46 and the first and second current extraction electrodes 48 and 50 are positioned symmetrically with reference to the symmetry of material 46, the respective extracted currents will be substantially the same (e.g., the same or nearly the same) in the absence or a crack or defect in material 46. As used here, substantially the same means voltages are within a threshold amount of each other. The threshold amount may be a predetermined percentage of the measured voltage, such as, for example, 20%, 10%, 5%, or 1%.

However, a crack or other defect increase the equivalent resistance of the portion of material 46 in which the crack or defect is located. This will cause an imbalance in the equivalent resistances K*R and R, causing the extracted currents to no longer be equal. As the magnitude of the difference between V_l and V_r is proportional to the mismatch between the extracted currents, unequal extracted currents, and thus unequal equivalent resistances, may be detected by measuring V_l and V_r. Hence, if the first measured voltage (e.g., V_l) and the second measured voltage (V_r) are different or are different by more than a threshold amount, computing device 12 may determine that material 16 or 46 includes a crack or other defect.

Returning now to FIG. 2, computing device 12 may determine whether material 16 includes a crack or other defect based on the respective voltage differences (40). For example, computing device 12 may determine that a voltage difference that is non-zero or whose magnitude or absolute value is greater than a threshold value indicates that material 16 includes a crack or other defect. On the other hand, computing device 12 may determine that a voltage difference that is zero or whose magnitude or absolute value is less than a threshold value indicates that material 16 does not include a crack or other defect.

In some examples in which computing device 12 determines a plurality of respective voltage differences, computing device 12 may compare each respective voltage difference to a threshold value and determine a number of voltage differences that is greater than the threshold value. Computing device 12 then may compare this number to a threshold number and determine whether material 16 includes a crack or other defect based on if the number of voltage differences that indicate a crack or other defect is greater than the threshold number.

In other examples in which computing device 12 determines a plurality of respective voltage differences, computing device 12 may mathematically manipulate the respective voltage differences to arrive at a single score for material 16. For example, computing device 12 may sum the respective voltage differences, square each respective voltage difference and sum the squares of the respective voltage differences, average the respective voltage differences, determine a weighted average of the respective voltage differences, or the like to determine a single score for material 16. Computing device 16 then may compare the single score to a threshold score value and determine that material 16 includes a crack or other defect if the single score is greater than the threshold score value.

In some examples, in addition to using the voltage differences to determine whether material 16 includes a crack or other defect, computing device 12 may utilize a control voltage difference or respective control voltage differences. The control voltage difference may represent the voltage difference determined for a give combination of measurement electrodes when material 16 does not include a crack or other defect. The control voltage difference may be based on material 16, a model, or an average of a plurality of materials that are similar to or substantially the same as material 16. For example, computing device 12 or another similar computing device may determine the control voltage difference at a time at which material 16 is manufactured, or a time at which an independent measurement (e.g., X-ray radiology or X-ray CT scan) may be used to verify that material 16 is intact, undamaged, or does not include a crack. Computing device 12 or the other similar computing device may determine the control voltage by applying the electrical signal to the current injection electrode 18D, extracting the electrical signal through the current extraction electrodes 18M and 18Q, and determining the control voltage difference using first and second measurement electrodes, e.g., electrodes 18H and 18V. In some examples, the control voltage difference(s) may be determined using similar or substantially the same combinations of current injection electrode, current extraction electrodes, and measurement electrodes as are used to determine the voltage difference(s) described above.

In other examples, the control voltage difference(s) may be determined using a model of the material in an intact (undamaged) state. For example, computing device 12 may execute the model of material 16 and determine the control voltage difference(s) based on the model. In some examples, the model may include a physics-based model of the electrical properties of material 16. In some other examples, the control voltage difference(s) may be determined as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged). This control voltage difference(s) may be stored (e.g., in a memory device associated with computing device 12) for later use.

In examples in which computing device 12 utilizes control voltage differences, computing device 12 may compare a respective voltage difference to a respective control voltage difference. The respective control voltage difference may be associated with the same combination of current injection electrode, current extraction electrodes, and measurement electrodes as the respective voltage difference. The comparison between the respective voltage difference and the respective control voltage difference may include subtracting the respective control voltage difference from the respective voltage difference or dividing by respective voltage difference by the respective control voltage difference. By utilizing control voltage differences in this manner, the technique may account for variations between the respective measured voltages that exist even in the absence of cracks or other defects. For example, material 16 may include inhomogeneities, different grain structures, or the like, which may cause the first and second measured voltages to not be exactly the same. Hence, there may still be variations between the first and second measured voltages even if the absence of cracks or other defects. As the control voltage differences represent electrical behavior of material 16 in the absence of cracks or other defects, the control voltage differences may help account for the variations in the first and second measured voltages.

After the respective voltage differences have been compared to the respective control voltage differences, the results of the respective comparisons (e.g., the differences or ratios) may be utilized to determine whether material 16 includes a crack or other defect according to the techniques described above.

In some examples, rather than utilizing a single current injection electrode, a technique for determining whether a material includes a crack or other defect may utilize at least two current injection electrodes, each current injection electrode being utilized for a separate set of measurements. FIG. 5 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using at least two current injection electrodes and a plurality of current extraction electrodes. The technique of FIG. 5 will be described with concurrent reference to system 10 of FIGS. 6 and 8, but it will be understood that other systems that include more or fewer components than system 10 may perform the technique of FIG. 5 (e.g., a system that includes only computing device 12), and that system 10 may be used to perform other techniques (e.g., the techniques of FIG. 2, among other techniques). FIG. 6 is a conceptual block diagram illustrating an example system 10 for determining whether material 16 includes a crack or other defect using at least two current injection electrodes and a plurality of current extraction electrodes. FIG. 6 illustrates system 10 in a first configuration including a first current injection electrode 18C, two current extraction electrodes 18M and 18Q, in which voltage measurements are made at current extraction electrodes 18M and 18Q. FIG. 8 illustrates system 10 in a second configuration including a second current injection electrode 18E, two current extraction electrodes 18M and 18Q, in which voltage measurements are made at current extraction electrodes 18M and 18Q. Aside from the configuration of electrodes 18, system 10 in FIGS. 6 and 8 is similar to or substantially the same as system 10 illustrated in FIG. 1.

The technique of FIG. 5 includes applying a first electrical signal to a first current injection electrode electrically coupled to material 16 at a first position or location (52). For example, computing device 12 may cause switch network 20 to electrically couple an electrode of electrodes 18 to electrical signal source 14 as the first current injection electrode. As shown in FIG. 6, the first current injection electrode may be third electrode 18C (referred to as first current injection electrode 18C with reference to FIGS. 5, 6, and 8). Computing device 12 then may cause electrical signal source 14 to apply the first electrical signal to first current injection electrode 18C.

The technique of FIG. 5 also includes extracting the first electrical signal through a plurality of current extraction electrodes (54) and determining a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, which may be current extraction electrodes 18M and 18Q in FIG. 6 (56). In some examples, the technique of FIG. 5 optionally includes determining whether additional voltage differences are to be determined using additional measurement electrodes (58). Steps (54), (56), and (58) may be similar to or substantially the same as steps (34), (36), and (38), respectively described above with reference to FIG. 2.

In response to determining that no additional voltage differences are to be determined using additional measurement electrodes (the "NO" branch of decision block 58), computing device 12 may be configured to apply a second electrical signal to a second current injection electrode electrically coupled to material 16 at a second position or location (60). For example, computing device 12 may cause switch network 20 to electrically couple an electrode of electrodes 18 to electrical signal source 14 as the second current injection electrode. As shown in FIG. 8, the second current injection electrode may be fifth electrode 18E (referred to as second current injection electrode 18E with reference to FIGS. 5, 6, and 8). Second current injection electrode 18E is positioned symmetrically to first current injection electrode 18C with reference to plane of symmetry 24 of material 16. In other words, the location of second current injection electrode 18E is symmetric to the location of first current injection electrode 18C with reference to a symmetry of material 16, e.g., plane of symmetry 24. Computing device 12 then may cause electrical signal source 14 to apply the second electrical signal to second current injection electrode 18E.

The technique of FIG. 5 also includes extracting the second electrical signal through the plurality of current extraction electrodes (62) and determining a voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode (64). The measurement electrodes may be current extraction electrodes 18M and 18Q. In some examples, the technique of FIG. 5 optionally includes determining whether additional voltage differences are to be determined using additional measurement electrodes (66). Steps (62), (64), and (66) may be similar to or substantially the same as steps (34), (36), and (38), respectively described above with reference to FIG. 2.

Although FIGS. 5, 6, and 8 illustrate a technique that utilizes two current injection electrodes 18C and 18E for two measurement sets, in other examples, a technique may utilize any number of current injection electrodes for a corresponding number of sets, as long as the arbitrary number of current injection electrodes are symmetrically positioned with respect to a symmetry of material 16, e.g., plane of symmetry 24.

In response to determining that no additional voltage differences are to be determined using additional measurement electrodes (the "NO" branch of decision block 66), computing device 12 may be configured to determine whether material 16 includes a crack or other defect based on the respective voltage differences (68). In order to make this determination, computing device 12 may be configured to determine that a non-zero difference (or a difference that is greater than a threshold value) between two voltage differences associated with the same measurement electrodes and different current injection electrodes indicates a presence of a crack or other defect, and a difference of zero (or a difference that is less than a threshold value) between two voltage differences associated with the same measurement electrodes and different current injection electrodes indicates that material 16 does not include a crack or other defect.

To understand why this is the case, FIG. 7 is an equivalent circuit diagram of a system configuration similar to that shown in FIG. 6 in the absence of a crack or other defect. As shown in FIG. 7, a high side current source 72 outputs a test current $I_T = 2*I$ to a first current injection electrode 74 that is at a first position of material 76. Once the test current I_T enters material 76, the test current I_T splits and conducts through material 76 to first current extraction electrode 78 and second current extraction electrode 80. A first current I_r flows to first current extraction electrode 78 through an equivalent resistance K*R. A second current I_k flows to second current extraction electrode 80 through an equivalent resistance R. Equivalent resistances R and K*R represent the resistances of the portions of material 76 through which the first current I_r and the second current I_k flow. A portion of current I_c also may flow through equivalent resistance P*R within material 76. In the absence of cracks or defects in material 76, the magnitudes of currents I_k and I_r will be approximately proportional to the relative distances between first current injection electrode 74 and first current extraction electrode 78 and between first current injection electrode 74 and second current extraction electrode 80. K represents this proportionality. The respective currents through the respective current extraction electrodes 78 and 80 pass through equal resistors with equivalent resistances of M*R, are combined, and pass through a resistance R1, at which a voltage V_{R1} may be measured.

FIG. 9 is an equivalent circuit diagram of a system configuration similar to that shown in FIG. 8 in the absence of a crack or other defect. As shown in FIG. 9, high side current source 72 outputs a test current $I_T = 2*I$ to a second current injection electrode 82 that is at a second position of material 76. The first position and the second position are symmetric with reference to a symmetry of material 76. Once the test current I_T enters material 76, the test current I_T splits and conducts through material 76 to first current extraction electrode 78 and second current extraction electrode 80. A first current I_r flows to first current extraction electrode 78 through an equivalent resistance R. A second current I_k flows to second current extraction electrode 80 through an equivalent resistance K*R. Equivalent resistances R and K*R represent the resistances of the portions of material 76 through which the first current I_r and the second current I_k flow. A portion of current I_c also may flow through equivalent resistance P*R within material 76. In the absence of cracks or defects in material 76, the magnitudes of currents I_k and I_r will be approximately proportional to the relative distances between second current injection electrode 82 and first current extraction electrode 78 and between second current injection electrode 82 and second current extraction electrode 80. K represents this proportionality. The respective currents through the respective current extraction electrodes 78 and 80 pass through equal resistors with equivalent resistances of M*R, are combined, and pass through a resistance R1, at which a voltage V_{R1} may be measured.

By examination of FIG. 9:

$$R*I_r + V_r = K*R*I_k + V_l \qquad (7)$$

$$I_r + I_k = 2*I = I_p + I_n \qquad (8)$$

$$I_c = (V_l - V_r) / (P*R) \qquad (9)$$

$$M*R*I_p + V_r = M*R*I_n + V_l \qquad (10)$$

Rearranging equation (7) yields:

$$\Delta V = (V_l - V_r) = (I_r - K*I_k)*R \qquad (11)$$

$$I_r = P*I_c + K*I_k \qquad (12)$$

From equation (11), it is clear that the magnitude of the difference between V_l and V_r is proportional to the mismatch between the extracted currents. If the current source is connected to first source contact 74, as in FIG. 7, by symmetry, the difference between V_l and V_r with have the same magnitude and opposite sign (in the absence of crack or other defect). As such, in the absence of a crack or other defect in material 76, a sum of the voltage difference (V_l – Vr) determined using first current injection electrode 74 and the voltage difference (V_l – Vr) determined using second current injection electrode 82 will be approximately zero (e.g., zero or nearly zero). In other words, in the absence of a crack or other defect in material 76, a magnitude or absolute value of the voltage difference (V_l – Vr) determined using first current injection electrode 74 will be substantially the same (e.g., the same or nearly the same) as the voltage difference (V_l – Vr) determined using second current injection electrode 82. As used here, substantially the same means voltages are within a threshold amount of each other.

The threshold amount may be a predetermined percentage of the measured voltage, such as, for example, 20%, 10%, 5%, or 1%.

However, a crack or other defect increases the equivalent resistance of the portion of material 76 in which the crack or defect is located. This will change the proportionality between equivalent resistances K*R and R. Further, this imbalance will not be symmetrical, so a magnitude or absolute value of the voltage difference (V_l – Vr) determined using first current injection electrode 74 (a first voltage difference) will no longer be substantially the same (e.g., the same or nearly the same) as the voltage difference (V_l – Vr) determined using second current injection electrode 82 (a second voltage difference). Hence, if a magnitude or absolute value of the first voltage difference and a magnitude or absolute value of the second voltage difference are different or are different by more than a threshold amount, computing device 12 may determine that material 16 or 76 includes a crack or other defect.

Returning now to FIG. 5, computing device 12 may determine whether material 16 includes a crack or other defect based on the respective voltage differences (40). For example, in response to a difference between a first voltage difference associated with the first current injection electrode 18C and a measurement electrode set and a second voltage difference associated with the second current injection electrode 18E and the measurement electrode set being a non-zero value or greater than a threshold value, computing device 12 may determine that material 16 includes the crack or other defect. As another example, in response to a difference between an absolute value of the first voltage difference associated with the first current injection electrode 18C and a measurement electrode set and an absolute value of the second voltage difference associated with the second current injection electrode 18E and the measurement electrode set being a non-zero value or greater than a threshold value, computing device 12 may determine that material 16 includes the crack or other defect.. On the other hand, in response to a difference between a first voltage difference associated with the first current injection electrode 18C and a measurement electrode set and a second voltage difference associated with the first current injection electrode 18C and a measurement electrode set being zero or less than a threshold value, computing device 12 may determine that material 16 does not include a crack or other defect.

In some examples in which computing device 12 determines a plurality of differences between respective voltage differences associated with the same measurement electrode set, computing device 12 may compare each respective difference between the voltage differences associated with the same measurement electrode set to a threshold value and determine a number of differences that is greater than the threshold value. Computing device 12 then may compare this number to a threshold number and determine whether material 16 includes a crack or other defect based on if the number of differences that indicate a crack or other defect is greater than the threshold number.

In other examples in which computing device 12 determines a plurality of differences between respective voltage differences associated with the same measurement electrode set, computing device 12 may mathematically manipulate the respective differences to arrive at a single score for material 16. For example, computing device 12 may sum the respective differences, square each respective difference and sum the squares of the respective differences, average the respective differences, determine a weighted average of the respective differences, or the like to determine a single score for material 16. Computing device 16 then may compare the single score to a threshold score value and determine that material 16 includes a crack or other defect if the single score is greater than the threshold score value.

In some examples, in addition to using the respective differences between voltage differences to determine whether material 16 includes a crack or other defect, computing device 12 may utilize a control voltage difference or respective control voltage differences, as described above with reference to FIG. 2.

In examples in which computing device 12 utilizes control voltage differences, computing device 12 may compare a respective voltage difference to a respective control voltage difference. The respective control voltage difference may be associated with the same combination of current injection electrode, current extraction electrodes, and measurement electrodes as the respective voltage difference. The comparison between the respective voltage difference and the respective control voltage difference may include subtracting the respective control voltage difference from the respective voltage difference or dividing by respective voltage difference by the respective control voltage difference. By utilizing control voltage differences in this manner, the technique may account for variations between the respective measured voltages that exist even in the absence of cracks or other defects. For example, material 16 may include inhomogeneities, different grain structures, or the like, which may cause the first and second measured voltages to not be exactly the same. Hence, there may still be variations between the first and second measured voltages even if the absence of cracks or other defects. As the control voltage differences represent electrical behavior of material 16 in the absence of cracks or other defects, the control voltage differences may help account for the variations in the first and second measured voltages.

After the respective voltage differences have been compared to the respective control voltage differences, the results of the respective comparisons (e.g., the differences or ratios) may be utilized to determine whether material 16 includes a crack or other defect according to the techniques described above.

In some examples, for any of the techniques described herein, voltages may be measured with respect to a voltage reference derived from the measurement current I_T. FIG. 10 is an equivalent circuit diagram of a system configuration in which measurement voltages are measured with respect to a voltage reference derived from the electrical signal applied to the current injection electrode, in the absence of a crack or other defect. In the circuit shown in FIG. 10, a high side current source 92 outputs a current to current injection electrode 94. The current splits between two equivalent resistances, R_{eql} and R_{eqr}, with values (1-K)*I through R_{eql} and K*I through R_{eqr}. The two currents are summed through resistors R_m into a current of 2*I which returns to ground through resistor R_l; as before in FIGS. 4, 7, and 9, $V_{Rl} = 2*I*R_l$. If V_{Rl} is measured using a reference electrode coupled to the non-grounded node of R_l and is used as the reference for an ADC, then the digitized value for any differential voltage pair is given by the following:

$$\Delta V[M] = (1-K)*I*R_{eql}-K*I*R_{eqr} \quad (13)$$

$$= I*((1-K)*R_{eql}-K*R_{eqr}) \quad (14)$$

$$ADC(\Delta V[M]) = \Delta V[M]*([2\text{^}A]-1)/V_{Rl} = I*((1-K)*R_{eql}-K*R_{eqr})*([2\text{^}A]-1)/2*I*R_l$$

$$= ((1-K)*R_{eql}-K*R_{eqr})*([2\text{^}A]-1)/2*R_l$$

Where R_{eql} = The equivalent resistance between the left voltage node and the current injection node

R_{eqr} = The equivalent resistance between the right voltage node and the current injection node

A = The ADC resolution in bits

K = Splitting factor and $K \leq 1$

Note that the digitized value for the measured differential voltage is not dependent on the source current $I_T = 2*I$, so current source noise is effectively cancelled from the measurement.

FIGS. 11–14 are circuit diagrams of example system configurations including various locations of current sources for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes. FIG. 11 illustrates an example system 100 that includes a high side current source 102 connected between a supply voltage, VS, and a material 104. High side current source 102 is configured to output a test current, I_T, equal to 2*I, to a current injection electrode 106 electrically coupled to material 104 on a plane of symmetry of material 104. System 100 also includes a plurality of measurement electrodes 1L–5L and 1R–5R electrically coupled to material 104, which may be used to measure single-ended or differential voltages associated with material 104. In other examples, system 100 may include more or fewer measurement electrodes.

The test current I_T enters material 104 through current injection electrode 106 and travels through material 104 to a first current extraction electrode 108A and a second current extraction electrode 108B. Assuming that material 104 does not include a crack or other defect, a first extracted current, I_n, extracted through first current extraction electrode 108A and a second extracted current, I_p, extracted through second current extraction electrode 108B are substantially the same. In some examples, respective voltages, V_L and V_R, may be measured at first current extraction electrode 108A and second current extraction electrode 108B. V_L and V_R may be used to determine whether material 104 includes a crack or other defect.

The respective extracted currents 108A and 108B conduct through equal resistors with equivalent resistances of M*R, are combined, and pass through a summing resistance R_1. A reference voltage V_{R1} may be measured between the summing point and Ground.

FIGS. 12 illustrates an example system 110 that includes a low side current source 112 connected between a summing resistor R_1 and Ground. Low side current source 112 is configured to output a test current, I_T, equal to 2*I. The injection current passes through a supply voltage source VS into material 114 at a current injection electrode 116 electrically coupled to material 114 on a plane of symmetry of material 114. System 110 also includes a plurality of measurement electrodes 1L–5L and 1R–5R electrically coupled to material 114, which may be used to measure single-ended or differential voltages associated with material 114. In other examples, system 110 may include more or fewer measurement electrodes.

The test current I_T enters material 114 through current injection electrode 116 and travels through material 114 to a first current extraction electrode 118A and a second current extraction electrode 118B.

Assuming that material 114 does not include a crack or other defect, a first extracted current, I_n, extracted through first current extraction electrode 118A and a second extracted current, I_p, extracted through second current extraction electrode 118B are substantially the same. In some examples, respective voltages, V_L and V_R, may be measured at first current extraction electrode 118A and second current extraction electrode 118B. V_L and V_R may be used to determine whether material 114 includes a crack or other defect.

The respective extracted currents 118A and 118B conduct through equal resistors with equivalent resistances of M*R, are combined, and pass through a summing resistance R_1. A differential reference voltage V_{R1} may be measured between the summing point and low side current source 112.

FIG. 13 illustrates an example system 120 that includes a high side current source 122 connected between a voltage source VS and a switch 129. High side current source 122 is configured to output a test current, I_T, equal to 2*I. Depending on the position of switch 129, the injection current passes through either a first current injection electrode 126A or a second current injection electrode 126B into material 124. First current injection electrode 126A and second current injection electrode 126B are positioned on material 124 symmetrically with reference to the plane of symmetry of material 124. System 120 also includes a plurality of measurement electrodes 1L–5L and 1R–5R electrically coupled to material 124, which may be used to measure single-ended or differential voltages associated with material 124. In other examples, system 120 may include more or fewer measurement electrodes, more of fewer current injection electrodes positioned in symmetrical pairs with reference to the plane of symmetry, or both.

The test current I_T enters material 124 through the selected current injection electrode 126A or 126B and travels through material 124 to a first current extraction electrode 128A and a second current extraction electrode 128B. Assuming that material 124 does not include a crack or other defect, a first extracted current, I_n, extracted through first current extraction electrode 128A and a second extracted current, I_p, extracted through second current extraction electrode 128B are proportional, and the proportion is substantially opposite when the other of first current injection electrode 126A and a second current injection electrode 126B is used to inject current into material 124. In some examples, respective voltages, V_L and V_R, may be measured at first current extraction electrode 128A and second current extraction electrode 128B. V_L and V_R may be used to determine whether material 124 includes a crack or other defect.

The respective extracted currents 128A and 128B conduct through equal resistors with equivalent resistances of M*R, are combined, and pass through a summing resistance R_1. A reference voltage V_{R1} may be measured between the summing point and Ground.

FIG. 14 illustrates an example system 130 that includes a low side current source 132 connected between a summing resistor R_1 and Ground. Low side current source 132 is configured to output a test current, I_T, equal to 2*I. Depending on the position of switch 139, the injection current passes through a supply voltage source VS, through either a first current injection electrode 136A or a second current injection electrode 136B, and into material 134. First current injection electrode 136A and second current injection electrode 136B are positioned on material 134 symmetrically with reference to the plane of symmetry of material 134. System 130 also includes a plurality of measurement electrodes 1L–5L and 1R–5R electrically coupled to material 134, which may be used to measure single-ended or differential voltages associated with material 134. In other examples, system 130 may include more or fewer measurement electrodes.

The test current I_T enters material 134 through the selected current injection electrode 136A or 136B and travels through material 134 to a first current extraction electrode 138A and a second current extraction electrode 138B. Assuming that material 134 does not include a crack or other defect, a first extracted current, I_n, extracted through first current extraction electrode 138A and a second extracted current, I_p, extracted through second current extraction electrode 138B are proportional, and the proportion is substantially opposite when the other of first current injection electrode 136A and a second current injection electrode 136B is used to inject current into material 134. In some examples, respective voltages, V_L and V_R, may be measured at first current extraction electrode 138A and second current extraction electrode 138B. V_L and V_R may be used to determine whether material 134 includes a crack or other defect.

The respective extracted currents 138A and 138B conduct through equal resistors with equivalent resistances of M*R, are combined, and pass through a summing resistance R_I. A differential reference voltage V_{RI} may be measured between the summing point and low side current source 132.

FIG. 15 is a circuit diagram of an example system configuration in which measurement voltages are measured with respect to a differential voltage reference derived from the electrical signal applied to the current injection electrode. FIG. 15 includes a similar configuration to that shown in FIG. 11. However, unlike system 100 shown in FIG. 11, system 140 shown in FIG. 15 includes a reference resistor R_I between current source 142 and a current injection electrode 146. The reference voltage, V_{RI}, is derived by a differential voltage measurement across R_I.

FIGS. 16A–16C are circuit diagrams of example system configurations for determining whether a material includes a crack or other defect using at least one current injection electrode and a plurality of current extraction electrodes. FIG. 15 includes a similar configuration to that shown in FIG. 11. However, unlike system 100 shown in FIG. 11, in system 150 shown in FIG. 16A, the resistors connected to extraction electrodes (M*R in FIG. 11) are replaced with two identical Current sources 157A and 157B with magnitude 1*I (which is one half of the current injected by high side current source 152 via current injection electrode 156). The extraction currents I_p and I_n are given current paths I_R and I_L, respectively, such that if $I_p = I_n = 1*I$, no current will flow in I_R or I_L. If I_p is unequal to I_n, then difference currents will flow in I_R and I_L. For example, if $I_p>I_n$, then I_R will flow away from the junction of I_p and the right current source 157B and I_L will flow into the junction of I_n and the left current source 157A. If $I_p<I_n$, the directions of the currents are reversed.

FIG. 16B illustrates an example by which the current flow may be measured using a differential load. If a load resistor R_d is placed between the current sources 157A and 157B, as shown in the FIG.

16B, then the magnitude and sign of the differential voltage across R_d indicates the mismatch of the extraction currents I_p and I_n.

FIG. 16C illustrates an example by which the current flow may be measured using single ended loads. If load resistors R_s are placed between the current sources 157A and 157B and connected to Ground, as shown in FIG. 16C, the magnitude and sign of the difference of single ended voltages V_R and V_L indicates the mismatch of the extraction currents I_p and I_n.

Clause 1: A method for detecting a crack or defect in a material, the method comprising: applying an electrical signal to a current injection electrode electrically coupled to the material, wherein the current injection electrode is positioned on a symmetry of the material; extracting the electrical signal through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to the symmetry of the material; while applying the electrical signal to the current injection electrode, determining a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and determining whether the material includes a crack or other defect based on the voltage difference.

Clause 2: The method of clause 1, wherein: determining the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the electrical signal to current injection electrode, determining a voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material.

Clause 3: The method of clause 1 or 2, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first measurement electrode to the second measurement electrode.

Clause 4: The method of any one of clauses 1 to 3, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

Clause 5: The method of clause 4, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

Clause 6: The method of any one of clauses 1 to 5, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, and wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode.

Clause 7: The method of clause 6, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

Clause 8: The method of any one of clauses 1 to 7, wherein determining whether the material includes the crack or other defect based on the voltage difference comprises determining that the material includes the crack or other defect in response to the voltage difference being a non-zero value.

Clause 9: The method of clause 8, wherein determining that the material includes the crack or other defect in response to the voltage difference being a non-zero value comprises determining that the material includes the crack or other defect in response to an absolute value of the voltage difference being greater than a threshold voltage value.

Clause 10: The method of any one of clauses 1 to 9, wherein: determining the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the electrical signal to the current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set; for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrode are arranged symmetrically with reference to the symmetry of the material; and determining whether the material includes a crack or other defect based on the respective voltage differences.

Clause 11: The method of clause 10, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

Clause 12: The method of any one of clauses 1 to 11, wherein determining whether the material includes the crack or other defect based on the voltage difference comprises: determining an adjusted voltage difference based on the voltage difference and a control voltage difference associated with the first and second measurement electrodes; and determining whether the material includes the crack or other defect based on the adjusted voltage difference.

Clause 13: A method for detecting a crack or defect in a material, the method comprising: applying a first electrical signal to a first current injection electrode electrically coupled to the material, wherein the first current injection electrode is positioned at a first location of the material; extracting the first electrical signal through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to a symmetry of the material; while applying the first electrical signal to the first current injection electrode, determining a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; applying a second electrical signal to a second current injection electrode electrically coupled to the material, wherein the second current injection electrode is positioned at a second location of the material, wherein the first and second locations are symmetric with reference to the symmetry of the material; extracting the second electrical signal through the plurality of current extraction electrodes; while applying the second electrical signal to the second current injection electrode, determining a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode; and determining whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

Clause 14: The method of clause 13, wherein: determining the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the first electrical signal to first current injection electrode, determining the first voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material; and determining the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode comprises, while applying the second electrical signal to second current injection electrode, determining a second voltage difference between a third differential voltage determined using the first measurement electrode and the third measurement electrode and a fourth differential voltage determined using the second measurement electrode and the fourth measurement electrode.

Clause 15: The method of clause 13 or 14, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

Clause 16: The method of any one of clauses 13 to 15, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

Clause 17: The method of clause 16, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

Clause 18: The method of any one of clauses 13 to 17, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode, wherein the third voltage is a third single-ended voltage measured using the first measurement electrode and the reference electrode, and wherein the fourth voltage is a fourth single-ended voltage measured using the second measurement electrode and the reference electrode.

Clause 19: The method of clause 18, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

Clause 20: The method of any one of clauses 13 to 19, wherein determining whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference comprises determining that the material includes the crack or other defect in response to a difference between the first voltage difference and the second voltage difference being a non-zero value.

Clause 21: The method of clause 20, wherein determining that the material includes the crack or other defect in response the voltage difference being a non-zero value comprises determining that the material includes the crack or other defect in response to an absolute value of the difference between the first voltage difference and the second voltage difference being greater than a threshold voltage value.

Clause 22: The method of any one of clauses 13 to 21, wherein: determining the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the first electrical signal to the first current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective first voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set; for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; determining the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode comprises, while applying the second electrical signal to the second current injection electrode, determining, for each respective measurement electrode set of the plurality of respective measurement electrode sets, a respective third voltage difference between a respective third voltage measured using the respective first measurement electrode from the respective measurement electrode set and a respective fourth voltage measured using the respective second measurement electrode from the respective measurement electrode set; and determining whether the material includes a crack or other defect based on the respective voltage differences.

Clause 23: The method of clause 22, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

Clause 24: The method of any one of clauses 13 to 23, wherein determining whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference comprises: determining a first adjusted voltage difference based on the first voltage difference and a control voltage difference associated with the first and second measurement electrodes and the first current injection electrode; determining a second adjusted voltage difference based on the second voltage difference and a control voltage difference associated with the first and second measurement electrodes and second current injection electrode; and determining whether the material includes the crack or other defect based on the first adjusted voltage difference and the second adjusted voltage difference.

Clause 25: A system comprising: a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device configured to: cause the electrical signal source to apply an electrical signal to a current injection electrode, wherein the current injection electrode is positioned on a symmetry of the material and is from the set of N electrodes; cause the electrical signal to be extracted through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to the symmetry of the material and are from the set of N electrodes; while the electrical signal source is applying the electrical signal to the current injection electrode, determine a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and determine whether the material includes a crack or other defect based on the voltage difference.

Clause 26: The system of clause 25, wherein: the computing device is configured to determine the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the electrical signal to the current injection electrode, determining a voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material.

Clause 27: The system of clause 25 or 26, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

Clause 28: The system of any one of clauses 25 to 27, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

Clause 29: The system of clause 28, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

Clause 30: The system of any one of clauses 25 to 29, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, and wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode.

Clause 31: The system of clause 30, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

Clause 32: The system of any one of clauses 25 to 31, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the voltage difference by at least determining that the material includes the crack or other defect in response to the voltage difference being a non-zero value.

Clause 33: The system of clause 32, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the voltage difference being a non-zero value by at least determining that the material includes the crack or other defect in response to an absolute value of the voltage difference being greater than a threshold voltage value.

Clause 34: The system of any one of clauses 25 to 33, wherein: the computing device is configured to determine the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the electrical signal to the current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set; for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and the computing device is configured to determine whether the material includes a crack or other defect based on the respective voltage differences.

Clause 35: The system of clause 34, wherein the set of N electrodes are distributed around a perimeter of the material, and wherein the set of N electrodes includes the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

Clause 36: The system of any one of clauses 25 to 35, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the voltage difference by at least: determining an adjusted voltage difference based on the voltage difference and a control voltage difference associated with the first and second measurement electrodes; and determining whether the material includes the crack or other defect based on the adjusted voltage difference.

Clause 37: A system comprising: a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device configured to: cause the electrical signal source to apply a first electrical signal to a first current injection electrode electrically coupled to the material, wherein the first current injection electrode is positioned at a first location of the material and is from the set of N electrodes; cause the first electrical signal to be extracted through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to a symmetry of the material and are from the set of N electrodes; while the electrical signal source is applying the first electrical signal to the first current injection electrode, determine a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; cause the electrical signal source to apply a second electrical signal to a second current injection electrode electrically coupled to the material, wherein the second current injection electrode is positioned at a second location of the material and is from the set of N electrodes, and wherein the first and second locations are symmetric with reference to the symmetry of the material; cause the second electrical signal to be extracted through the plurality of current extraction electrodes; while the electrical signal source is applying the second electrical signal to the second current injection electrode, determine a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode; and determine whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

Clause 38: The system of clause 37, wherein: the computing device is configured to determine the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the first electrical signal to the first current injection electrode, determining the first voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material and are from the set of N electrodes; and the computing device is configured to determine the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the second electrical signal to second current injection electrode, determining a second voltage difference between a third differential voltage determined using the first measurement electrode and the third measurement electrode and a fourth differential voltage determined using the second measurement electrode and the fourth measurement electrode.

Clause 39: The system of clause 37 or 38, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

Clause 40: The system of any one of clauses 37 to 39, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

Clause 41: The system of clause 40, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

Clause 42: The system of any one of clauses 37 to 41, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode, wherein the third voltage is a third single-ended voltage measured using the first measurement electrode and the reference electrode, and wherein the fourth voltage is a fourth single-ended voltage measured using the second measurement electrode and the reference electrode.

Clause 43: The system of clause 42, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

Clause 44: The system of any one of clauses 37 to 43, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference by at least determining that the material includes the crack or other defect in response to a difference between the first voltage difference and the second voltage difference being a non-zero value.

Clause 45: The system of clause 44, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the voltage difference being a non-zero value by at least determining that the material includes the crack or other defect in response to an absolute value of the difference between the first voltage difference and the second voltage difference being greater than a threshold voltage value.

Clause 46: The system of any one of clauses 37 to 45, wherein: the computing device is configured to determine the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the first electrical signal to the first current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective first voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set; for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; the computing device is configured to determine the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the second electrical signal to the second current injection electrode, determining, for each respective measurement electrode set of the plurality of respective measurement electrode sets, a respective third voltage difference between a respective third voltage measured using the respective first measurement electrode from the respective measurement electrode set and a respective fourth voltage measured using the respective second measurement electrode from the respective measurement electrode set; and the computing device is configured to determine whether the material includes a crack or other defect based on the respective voltage differences.

Clause 47: The system of clause 46, wherein the set of N electrodes are distributed around a perimeter of the material, and wherein the set of N electrodes includes the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

Clause 48: The system of any one of clauses 37 to 47, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference by at least: determining a first adjusted voltage difference based on the first voltage difference and a control voltage difference associated with the first and second measurement electrodes and the first current injection electrode; determining a second adjusted voltage difference based on the second voltage difference and a control voltage difference associated with the first and second measurement electrodes and second current injection electrode; and determining whether the material includes the crack or other defect based on the first adjusted voltage difference and the second adjusted voltage difference.

Various examples have been described. These and other examples are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method for detecting a crack or defect in a material, the method comprising:

applying an electrical signal to a current injection electrode electrically coupled to the material, wherein the current injection electrode is positioned on a symmetry of the material;

extracting the electrical signal through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to the symmetry of the material;

while applying the electrical signal to the current injection electrode, determining a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and

determining whether the material includes a crack or other defect based on the voltage difference.

2. The method of claim 1, wherein:

determining the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the electrical signal to current injection electrode, determining a voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material.

3. The method of claim 1, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first measurement electrode to the second measurement electrode.

4. The method of claim 1, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

5. The method of claim 4, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

6. The method of claim 1, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, and wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode.

7. The method of claim 6, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

8. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the voltage difference comprises determining that the material includes the crack or other defect in response to the voltage difference being a non-zero value.

9. The method of claim 8, wherein determining that the material includes the crack or other defect in response the voltage difference being a non-zero value comprises determining that the material includes the crack or other defect in response to an absolute value of the voltage difference being greater than a threshold voltage value.

10. The method of claim 1, wherein:

determining the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the electrical signal to the current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set;

for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrode are arranged symmetrically with reference to the symmetry of the material; and

determining whether the material includes a crack or other defect based on the respective voltage differences.

11. The method of claim 10, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

12. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the voltage difference comprises:

determining an adjusted voltage difference based on the voltage difference and a control voltage difference associated with the first and second measurement electrodes; and

determining whether the material includes the crack or other defect based on the adjusted voltage difference.

13. A method for detecting a crack or defect in a material, the method comprising:

applying a first electrical signal to a first current injection electrode electrically coupled to the material, wherein the first current injection electrode is positioned at a first location of the material;

extracting the first electrical signal through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to a symmetry of the material;

while applying the first electrical signal to the first current injection electrode, determining a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material;

applying a second electrical signal to a second current injection electrode electrically coupled to the material, wherein the second current injection electrode is positioned at a second location of the material, wherein the first and second locations are symmetric with reference to the symmetry of the material;

extracting the second electrical signal through the plurality of current extraction electrodes;

while applying the second electrical signal to the second current injection electrode, determining a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode; and

determining whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

14. The method of claim 13, wherein:

determining the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the first electrical signal to first current injection electrode, determining the first voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material; and

determining the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode comprises, while applying the second electrical signal to second current injection electrode, determining a second voltage difference between a third differential voltage determined using the first measurement electrode and the third measurement electrode and a fourth differential voltage determined using the second measurement electrode and the fourth measurement electrode.

15. The method of claim 13, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

16. The method of claim 13, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

17. The method of claim 16, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

18. The method of claim 13, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode, wherein the third voltage is a third single-ended voltage measured using the first measurement electrode and the reference electrode, and wherein the fourth voltage is a fourth single-ended voltage measured using the second measurement electrode and the reference electrode.

19. The method of claim 18, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

20. The method of claim 13, wherein determining whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference comprises determining that the material includes the crack or other defect in response to a difference between the first voltage difference and the second voltage difference being a non-zero value.

21. The method of claim 20, wherein determining that the material includes the crack or other defect in response the voltage difference being a non-zero value comprises determining that the material includes the crack or other defect in response to an absolute value of the difference between the first voltage difference and the second voltage difference being greater than a threshold voltage value.

22. The method of claim 13, wherein:

determining the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode comprises, while applying the first electrical signal to the first current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective first voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set;

for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material;

determining the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode comprises, while applying the second electrical signal to the second current injection electrode, determining, for each respective measurement electrode set of the plurality of respective measurement electrode sets, a respective third voltage difference between a respective third voltage measured using the respective first measurement electrode from the respective measurement electrode set and a respective fourth voltage measured using the respective second measurement electrode from the respective measurement electrode set; and

determining whether the material includes a crack or other defect based on the respective voltage differences.

23. The method of claim 22, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

24. The method of claim 13, wherein determining whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference comprises:

determining a first adjusted voltage difference based on the first voltage difference and a control voltage difference associated with the first and second measurement electrodes and the first current injection electrode;

determining a second adjusted voltage difference based on the second voltage difference and a control voltage difference associated with the first and second measurement electrodes and second current injection electrode; and

determining whether the material includes the crack or other defect based on the first adjusted voltage difference and the second adjusted voltage difference.

25. A system comprising:

a set of N electrodes electrically coupled to a material;

an electrical signal source; and

a computing device configured to:

cause the electrical signal source to apply an electrical signal to a current injection electrode, wherein the current injection electrode is positioned on a symmetry of the material and is from the set of N electrodes;

cause the electrical signal to be extracted through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to the symmetry of the material and are from the set of N electrodes;

while the electrical signal source is applying the electrical signal to the current injection electrode, determine a voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and

determine whether the material includes a crack or other defect based on the voltage difference.

26. The system of claim 25, wherein:

the computing device is configured to determine the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the electrical signal to the current injection electrode, determining a voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material.

27. The system of claim 25, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

28. The system of claim 25, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

29. The system of claim 28, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

30. The system of claim 25, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, and wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode.

31. The system of claim 30, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

32. The system of claim 25, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the voltage difference by at least determining that the material includes the crack or other defect in response to the voltage difference being a non-zero value.

33. The system of claim 32, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the voltage difference being a non-zero value by at least determining that the material includes the crack or other defect in response to an absolute value of the voltage difference being greater than a threshold voltage value.

34. The system of claim 25, wherein:

the computing device is configured to determine the voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the electrical signal to the current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set;

for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material; and

the computing device is configured to determine whether the material includes a crack or other defect based on the respective voltage differences.

35. The system of claim 34, wherein the set of N electrodes are distributed around a perimeter of the material, and wherein the set of N electrodes includes the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

36. The system of claim 25, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the voltage difference by at least:

determining an adjusted voltage difference based on the voltage difference and a control voltage difference associated with the first and second measurement electrodes; and

determining whether the material includes the crack or other defect based on the adjusted voltage difference.

37. A system comprising:

a set of N electrodes electrically coupled to a material;

an electrical signal source; and

a computing device configured to:

cause the electrical signal source to apply a first electrical signal to a first current injection electrode electrically coupled to the material, wherein the first current injection electrode is positioned at a first location of the material and is from the set of N electrodes;

cause the first electrical signal to be extracted through a plurality of current extraction electrodes, wherein the plurality of current extraction electrodes are arranged symmetrically with reference to a symmetry of the material and are from the set of N electrodes;

while the electrical signal source is applying the first electrical signal to the first current injection electrode, determine a first voltage difference between a first voltage measured using a first measurement electrode and a second voltage measured using a second measurement electrode, wherein the first and second measurement electrodes are arranged symmetrically with reference to the symmetry of the material;

cause the electrical signal source to apply a second electrical signal to a second current injection electrode electrically coupled to the material, wherein the second current injection electrode is positioned at a second location of the material and is from the set of N electrodes, and wherein the first and second locations are symmetric with reference to the symmetry of the material;

cause the second electrical signal to be extracted through the plurality of current extraction electrodes;

while the electrical signal source is applying the second electrical signal to the second current injection electrode, determine a second voltage difference between a third voltage measured using the first measurement electrode and a fourth voltage measured using the second measurement electrode; and

determine whether the material includes a crack or other defect based on the first voltage difference and the second voltage difference.

38. The system of claim 37, wherein:

the computing device is configured to determine the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the first electrical signal to the first current injection electrode, determining the first voltage difference between a first differential voltage determined using the first measurement electrode and a third measurement electrode and a second differential voltage determined using the second measurement electrode and a fourth measurement electrode, wherein the third measurement electrode and the fourth measurement electrode are arranged symmetrically with reference to the symmetry of the material and are from the set of N electrodes; and the computing device is configured to determine the second voltage difference between the third voltage measured using the first measurement electrode and the second voltage measured using the fourth measurement electrode by at least, while the electrical signal source is applying the second electrical signal to second current injection electrode, determining a second voltage difference between a third differential voltage determined using the first measurement electrode and the third measurement electrode and a fourth differential voltage determined using the second measurement electrode and the fourth measurement electrode.

39. The system of claim 37, wherein the symmetry of the material is a point, a line, a plane, a curve, or a manifold, and wherein a single mathematical operation made with reference to the symmetry maps the first electrode to the second electrode.

40. The system of claim 37, wherein the plurality of current extraction electrodes is a first current extraction electrode and a second current extraction electrode.

41. The system of claim 40, wherein the first measurement electrode is the first current extraction electrode and the second measurement electrode is the second current extraction electrode.

42. The system of claim 37, wherein the first voltage is a first single-ended voltage measured using the first measurement electrode and a reference electrode, wherein the second voltage is a second single-ended voltage measured using the second measurement electrode and the reference electrode, wherein the third voltage is a third single-ended voltage measured using the first measurement electrode and the reference electrode, and wherein the fourth voltage is a fourth single-ended voltage measured using the second measurement electrode and the reference electrode.

43. The system of claim 42, wherein the reference electrode is electrically connected to a non-grounded node of a resistor electrically connected between the plurality of current extraction electrodes and electrical ground.

44. The system of claim 37, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference by at least determining that the material includes the crack or other defect in response to a difference between the first voltage difference and the second voltage difference being a non-zero value.

45. The system of claim 44, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the voltage difference being a non-zero value by at least determining that the material includes the crack or other defect in response to an absolute value of

the difference between the first voltage difference and the second voltage difference being greater than a threshold voltage value.

46. The system of claim 37, wherein:

the computing device is configured to determine the first voltage difference between the first voltage measured using the first measurement electrode and the second voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the first electrical signal to the first current injection electrode, determining, for each respective measurement electrode set of a plurality of respective measurement electrode sets, a respective first voltage difference between a respective first voltage measured using a respective first measurement electrode from the respective measurement electrode set and a respective second voltage measured using a respective second measurement electrode from the respective measurement electrode set;

for each respective measurement electrode set, the respective first measurement electrode and the respective second measurement electrodes are arranged symmetrically with reference to the symmetry of the material;

the computing device is configured to determine the second voltage difference between the third voltage measured using the first measurement electrode and the fourth voltage measured using the second measurement electrode by at least, while the electrical signal source is applying the second electrical signal to the second current injection electrode, determining, for each respective measurement electrode set of the plurality of respective measurement electrode sets, a respective third voltage difference between a respective third voltage measured using the respective first measurement electrode from the respective measurement electrode set and a respective fourth voltage measured using the respective second measurement electrode from the respective measurement electrode set; and

the computing device is configured to determine whether the material includes a crack or other defect based on the respective voltage differences.

47. The system of claim 46, wherein the set of N electrodes are distributed around a perimeter of the material, and wherein the set of N electrodes includes the current injection electrode, the plurality of current extraction electrodes, and the plurality of respective measurement electrode sets.

48. The system of claim 37, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first voltage difference and the second voltage difference by at least:

determining a first adjusted voltage difference based on the first voltage difference and a control voltage difference associated with the first and second measurement electrodes and the first current injection electrode;

determining a second adjusted voltage difference based on the second voltage difference and a control voltage difference associated with the first and second measurement electrodes and second current injection electrode; and

determining whether the material includes the crack or other defect based on the first adjusted voltage difference and the second adjusted voltage difference.

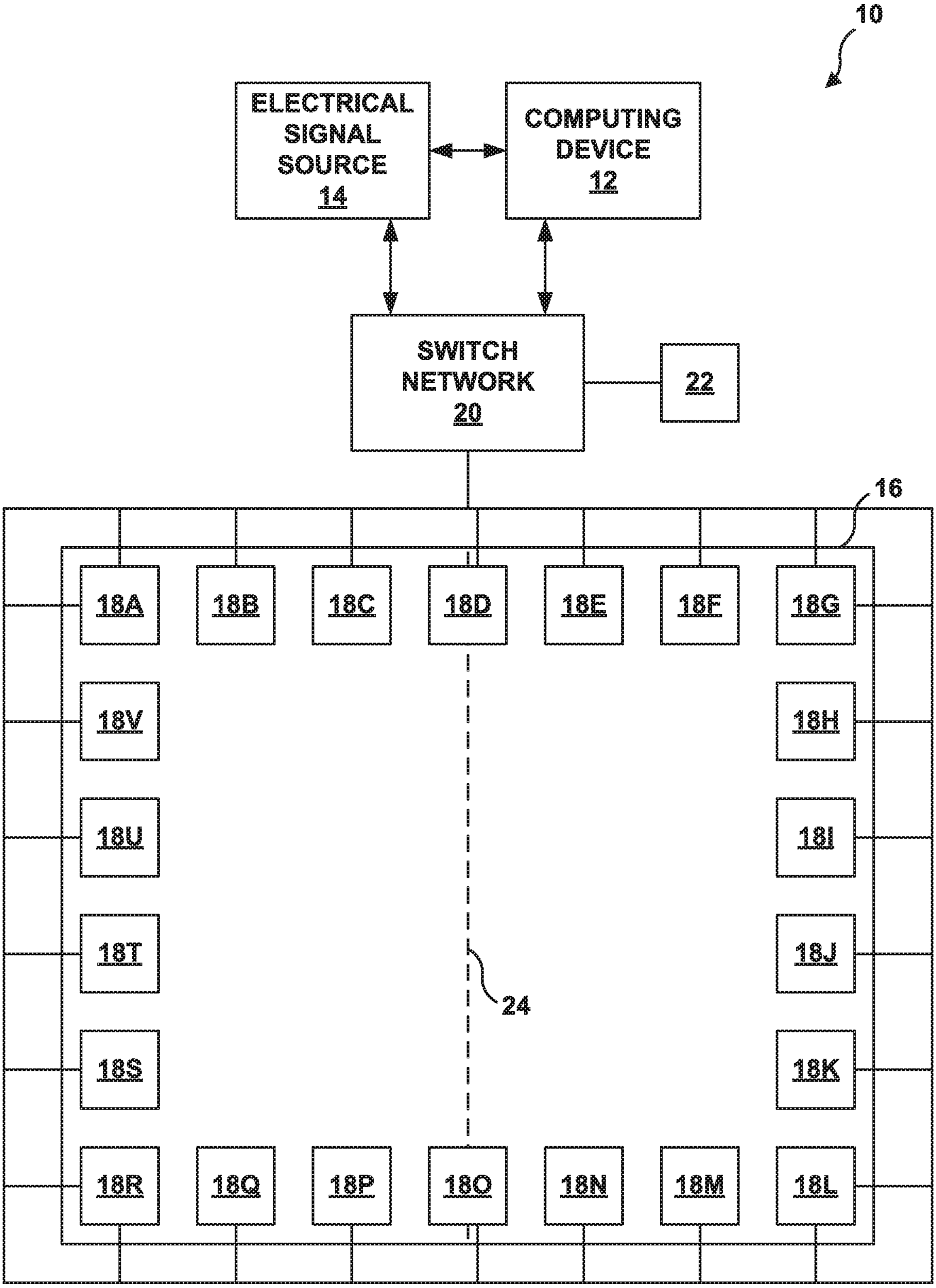

10
ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 12
SWITCH NETWORK 20
22
16
18A
18B
18C
18D
18E
18F
18G
18V
18H
18U
18I
18T
18J
24
18S
18K
18R
18Q
18P
18O
18N
18M
18L

FIG. 1

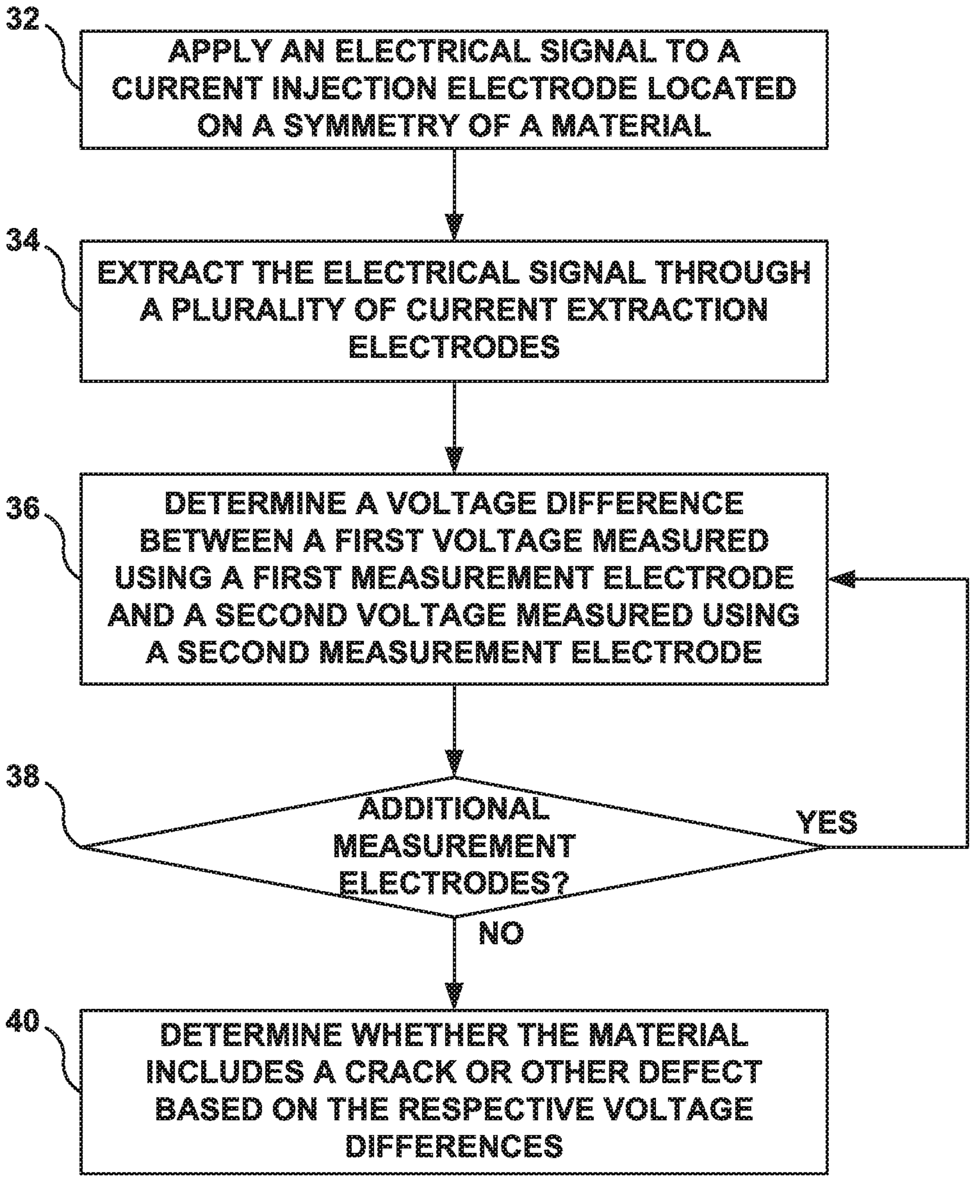

32
APPLY AN ELECTRICAL SIGNAL TO A CURRENT INJECTION ELECTRODE LOCATED ON A SYMMETRY OF A MATERIAL
34
EXTRACT THE ELECTRICAL SIGNAL THROUGH A PLURALITY OF CURRENT EXTRACTION ELECTRODES
36
DETERMINE A VOLTAGE DIFFERENCE BETWEEN A FIRST VOLTAGE MEASURED USING A FIRST MEASUREMENT ELECTRODE AND A SECOND VOLTAGE MEASURED USING A SECOND MEASUREMENT ELECTRODE
38
ADDITIONAL MEASUREMENT ELECTRODES?
YES
NO
40
DETERMINE WHETHER THE MATERIAL INCLUDES A CRACK OR OTHER DEFECT BASED ON THE RESPECTIVE VOLTAGE DIFFERENCES

FIG. 2

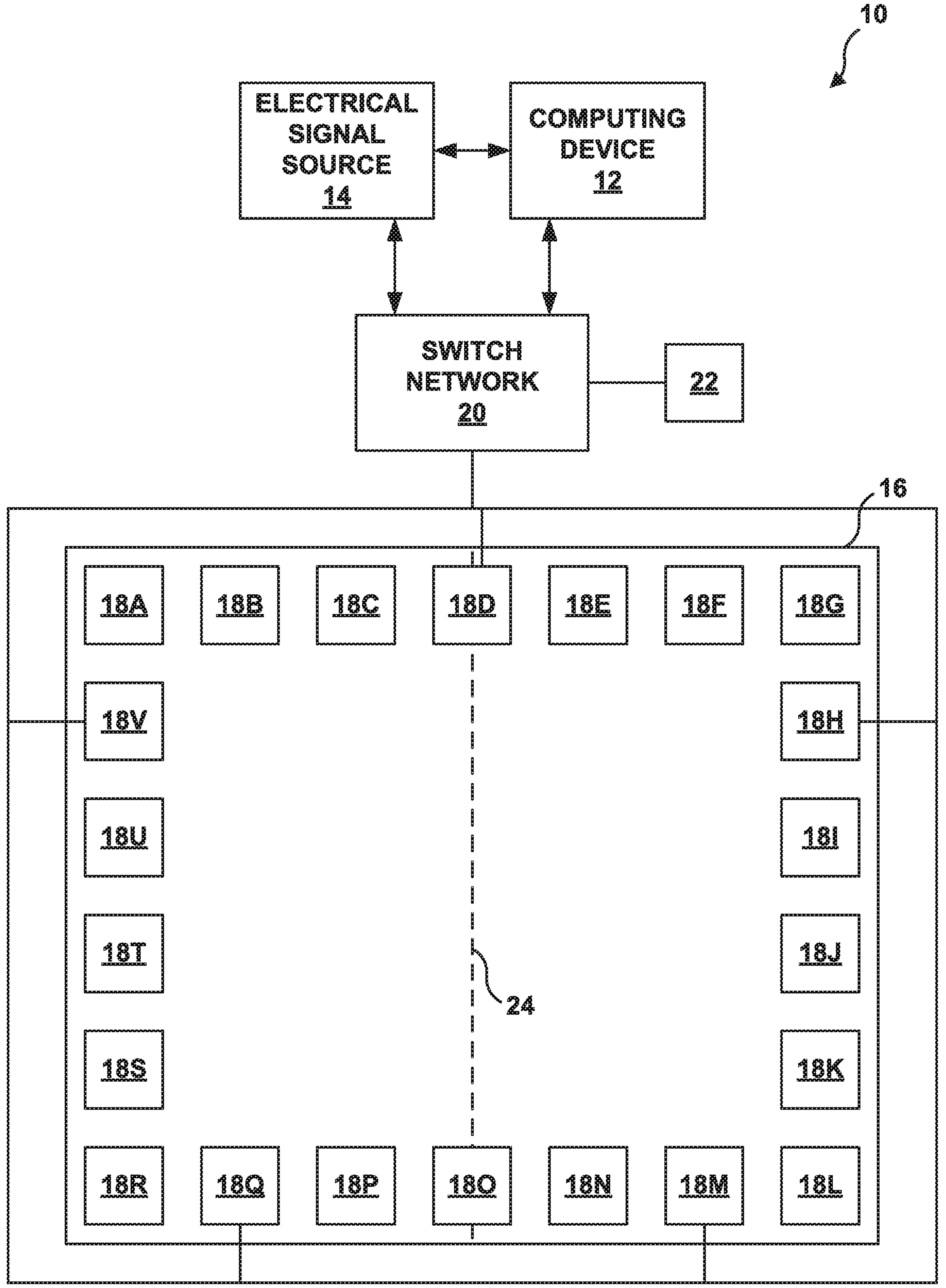

10
ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 12
SWITCH NETWORK 20
22
16
18A
18B
18C
18D
18E
18F
18G
18V
18H
18U
18I
18T
18J
24
18S
18K
18R
18Q
18P
18O
18N
18M
18L

FIG. 3

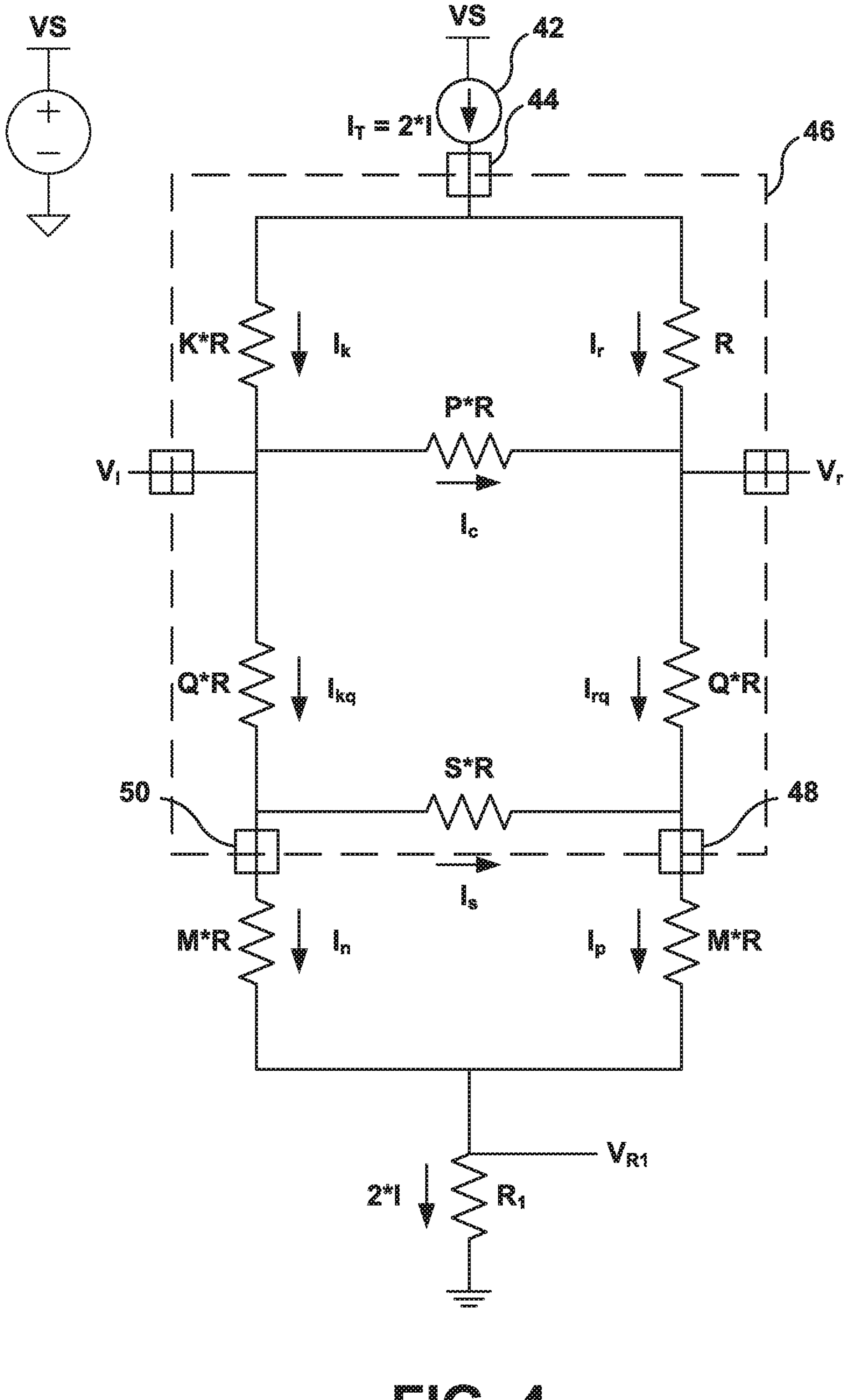

VS
VS
42
44
$I_T = 2*I$
46
K*R
I_k
I_r
R
P*R
V_l
V_r
I_c
Q*R
I_{kq}
I_{rq}
Q*R
S*R
50
48
I_s
M*R
I_n
I_p
M*R
V_{R1}
2*I
R_1

FIG. 4

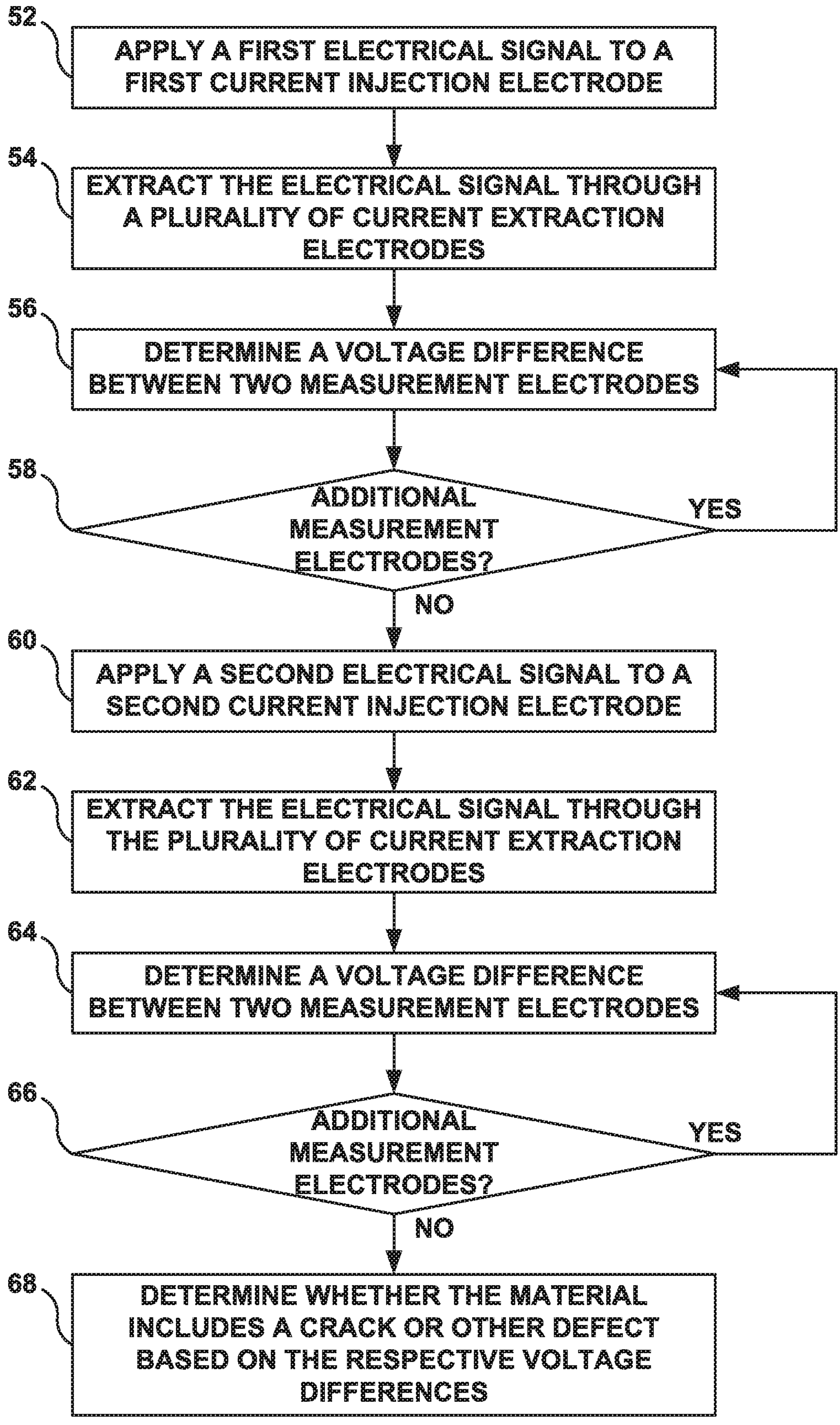
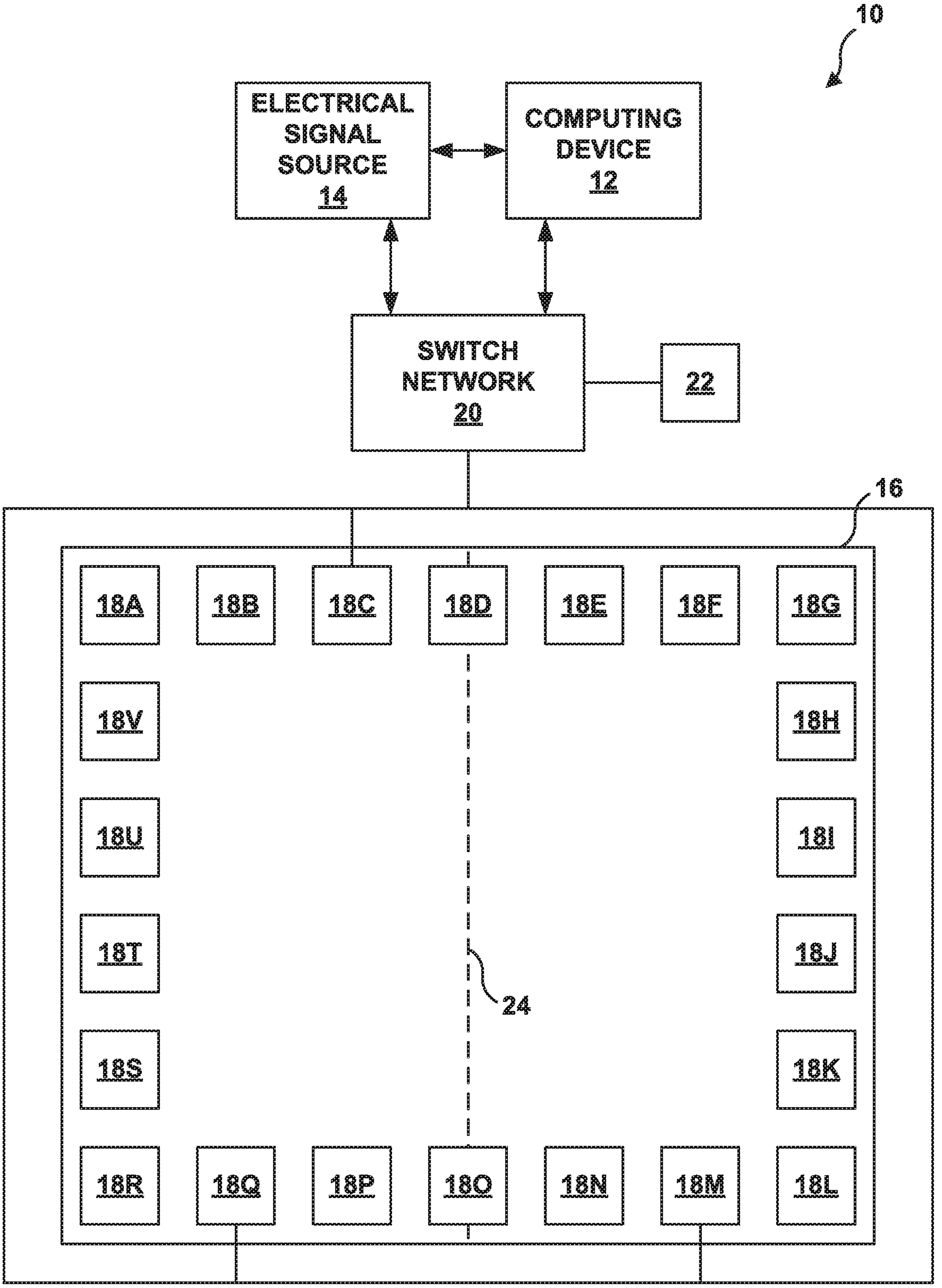

52
APPLY A FIRST ELECTRICAL SIGNAL TO A FIRST CURRENT INJECTION ELECTRODE
54
EXTRACT THE ELECTRICAL SIGNAL THROUGH A PLURALITY OF CURRENT EXTRACTION ELECTRODES
56
DETERMINE A VOLTAGE DIFFERENCE BETWEEN TWO MEASUREMENT ELECTRODES
58
ADDITIONAL MEASUREMENT ELECTRODES?
YES
NO
60
APPLY A SECOND ELECTRICAL SIGNAL TO A SECOND CURRENT INJECTION ELECTRODE
62
EXTRACT THE ELECTRICAL SIGNAL THROUGH THE PLURALITY OF CURRENT EXTRACTION ELECTRODES
64
DETERMINE A VOLTAGE DIFFERENCE BETWEEN TWO MEASUREMENT ELECTRODES
66
ADDITIONAL MEASUREMENT ELECTRODES?
YES
NO
68
DETERMINE WHETHER THE MATERIAL INCLUDES A CRACK OR OTHER DEFECT BASED ON THE RESPECTIVE VOLTAGE DIFFERENCES

FIG. 5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ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 12
SWITCH NETWORK 20
22
16
18A
18B
18C
18D
18E
18F
18G
18V
18H
18U
18I
18T
18J
24
18S
18K
18R
18Q
18P
18O
18N
18M
18L

FIG. 6

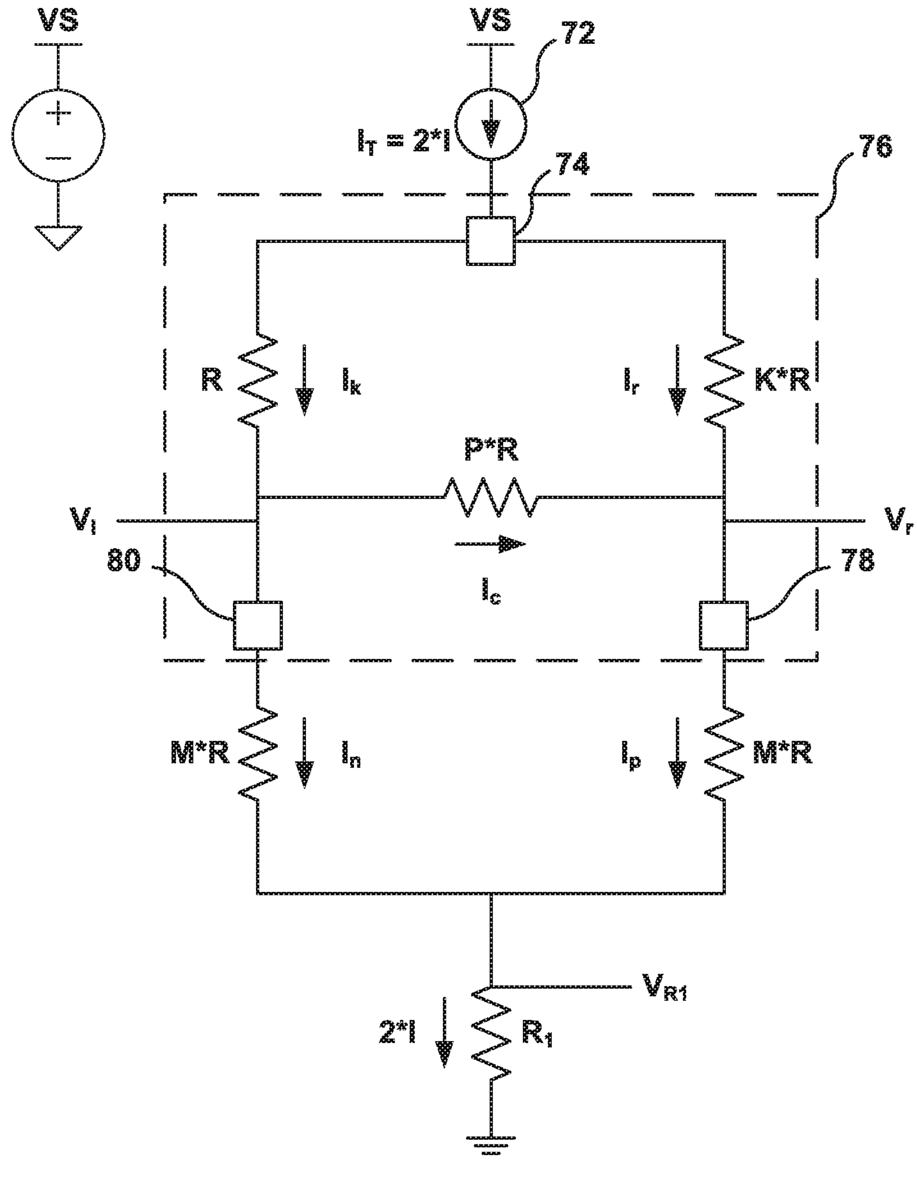
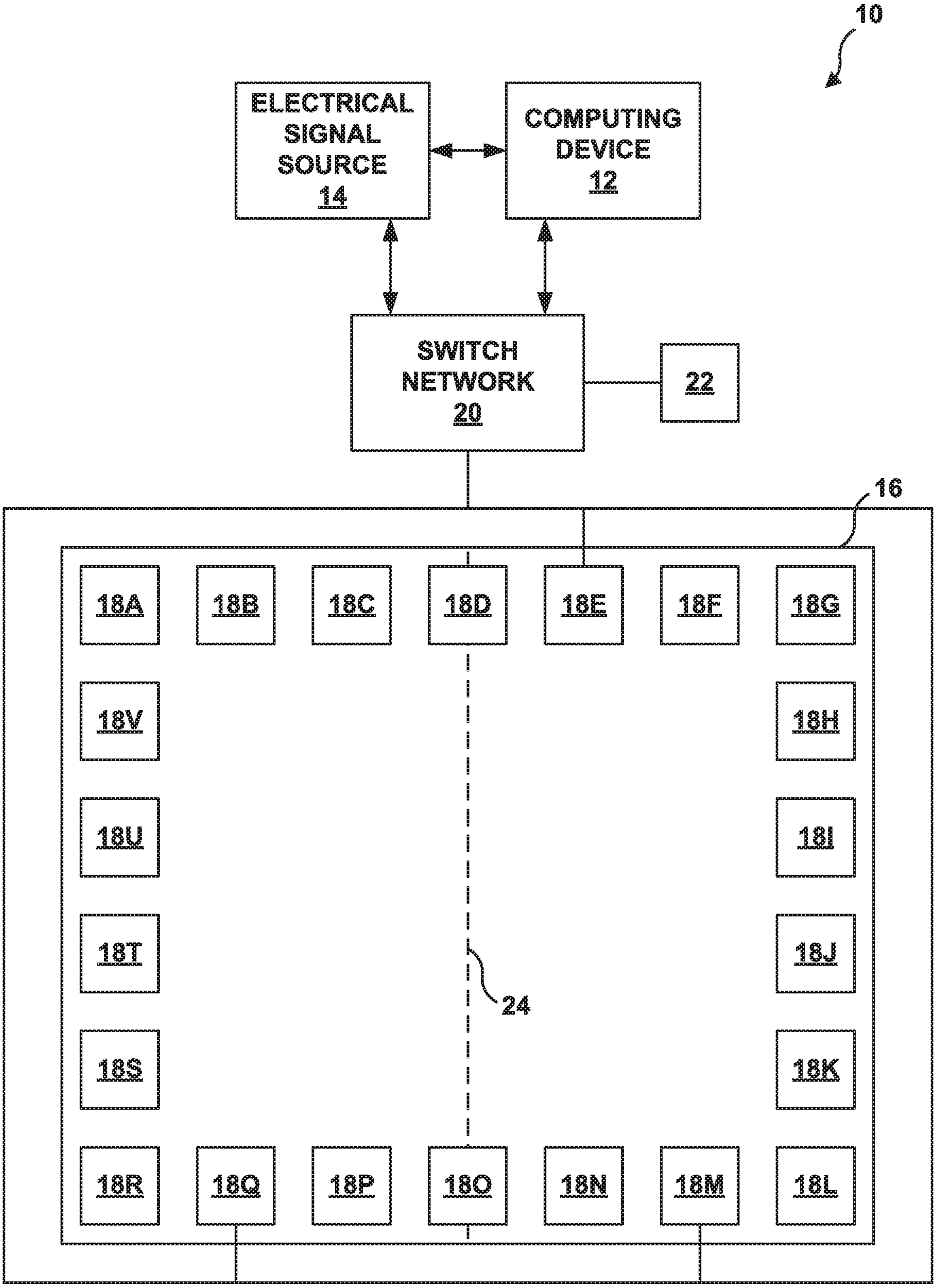


FIG. 7


10
ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 12
SWITCH NETWORK 20
22
16
18A
18B
18C
18D
18E
18F
18G
18V
18H
18U
18I
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18J
24
18S
18K
18R
18Q
18P
18O
18N
18M
18L

FIG. 8

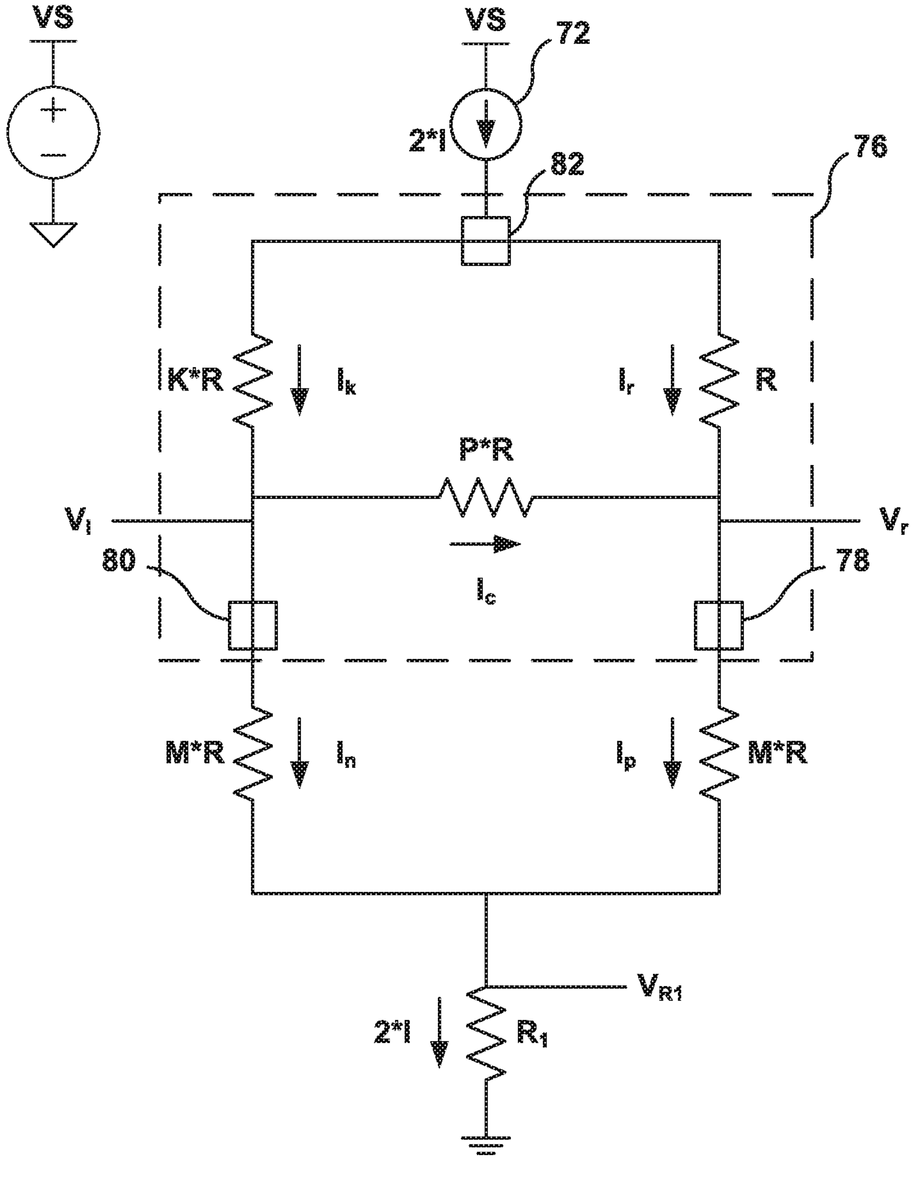


FIG. 9

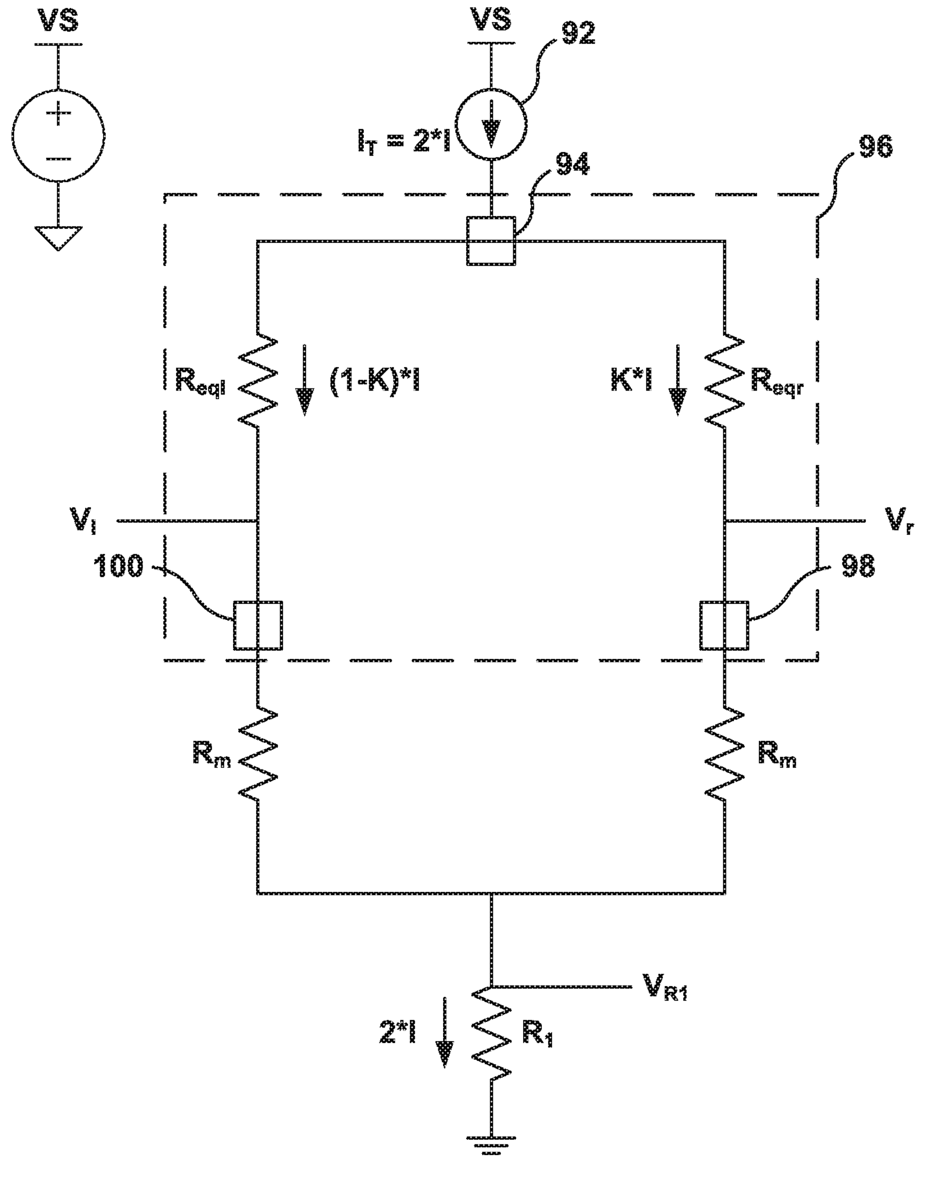


FIG. 10

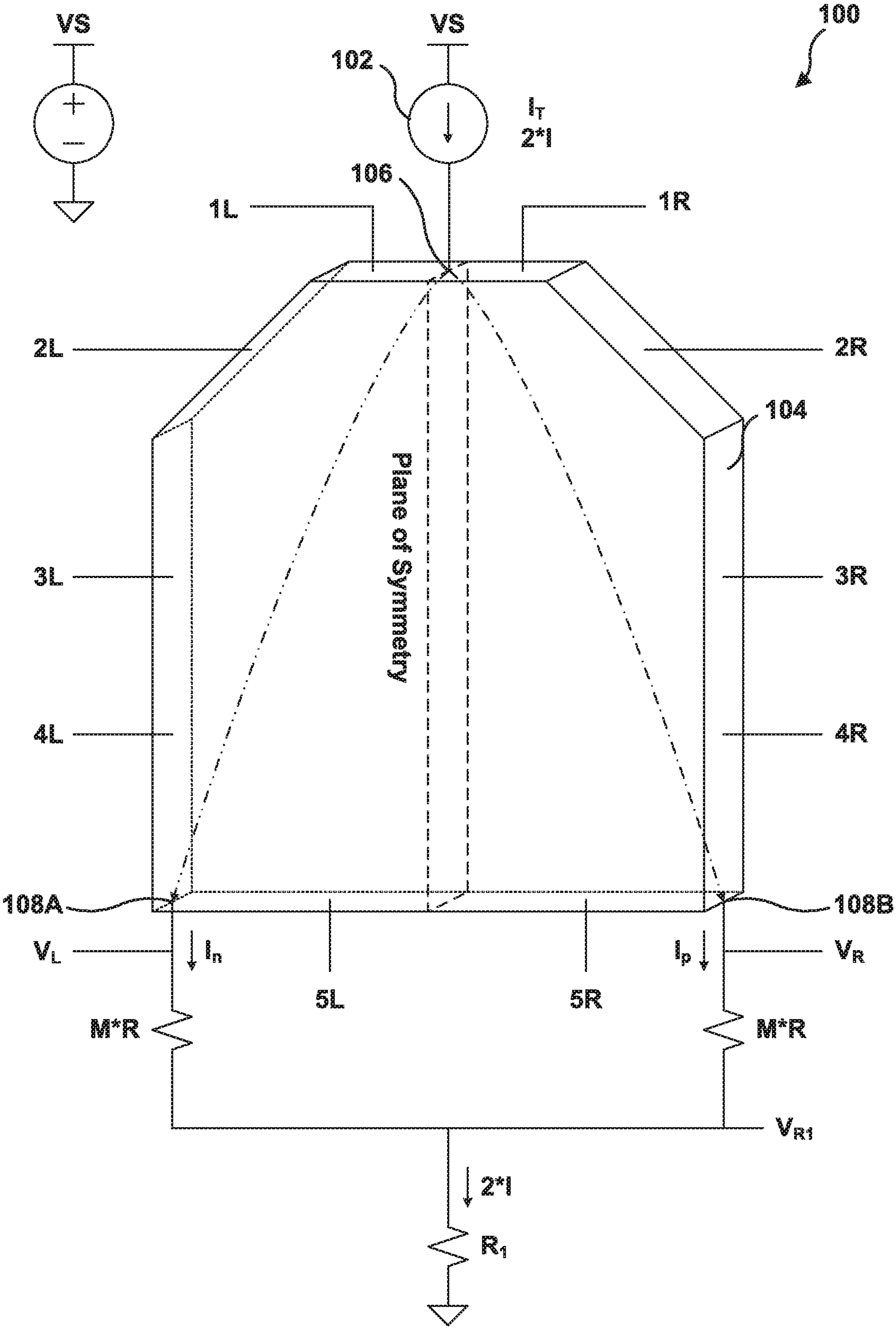
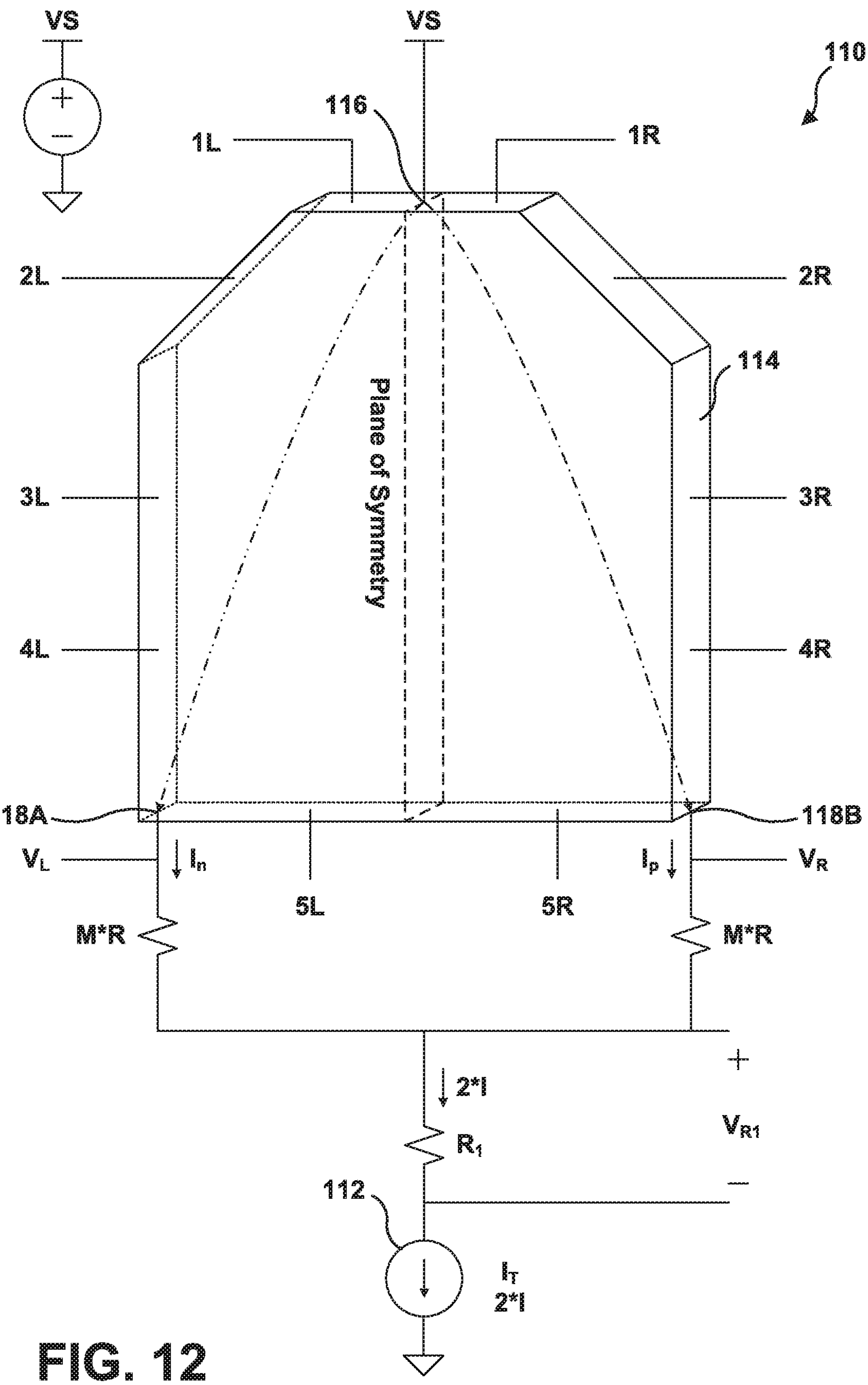

100
VS
VS
102
I_T
2*I
106
1L
1R
2L
2R
104
Plane of Symmetry
3L
3R
4L
4R
108A
108B
V_L
I_n
I_p
V_R
5L
5R
M*R
M*R
V_{R1}
2*I
R_1

FIG. 11



VS
VS
110
116
1L
1R
2L
2R
114
Plane of Symmetry
3L
3R
4L
4R
118A
118B
V_L
I_n
I_p
V_R
5L
5R
M*R
M*R
+
2*I
V_{R1}
R_1
112
−
I_T
2*I

FIG. 12

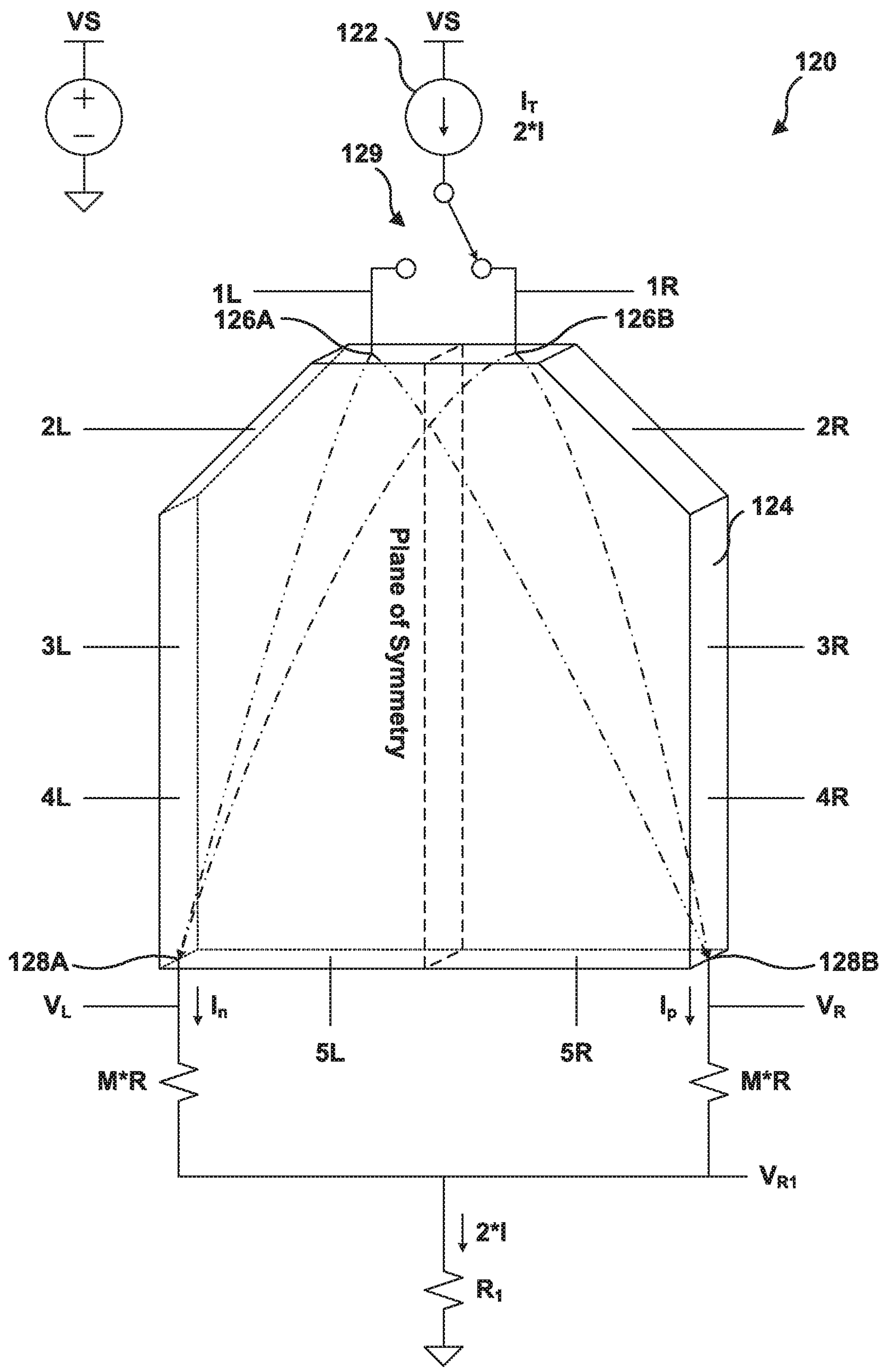

VS
VS
122
120
IT
2*I
129
1L
1R
126A
126B
2L
2R
124
Plane of Symmetry
3L
3R
4L
4R
128A
128B
VL
In
5L
5R
Ip
VR
M*R
M*R
VR1
2*I
R1

FIG. 13

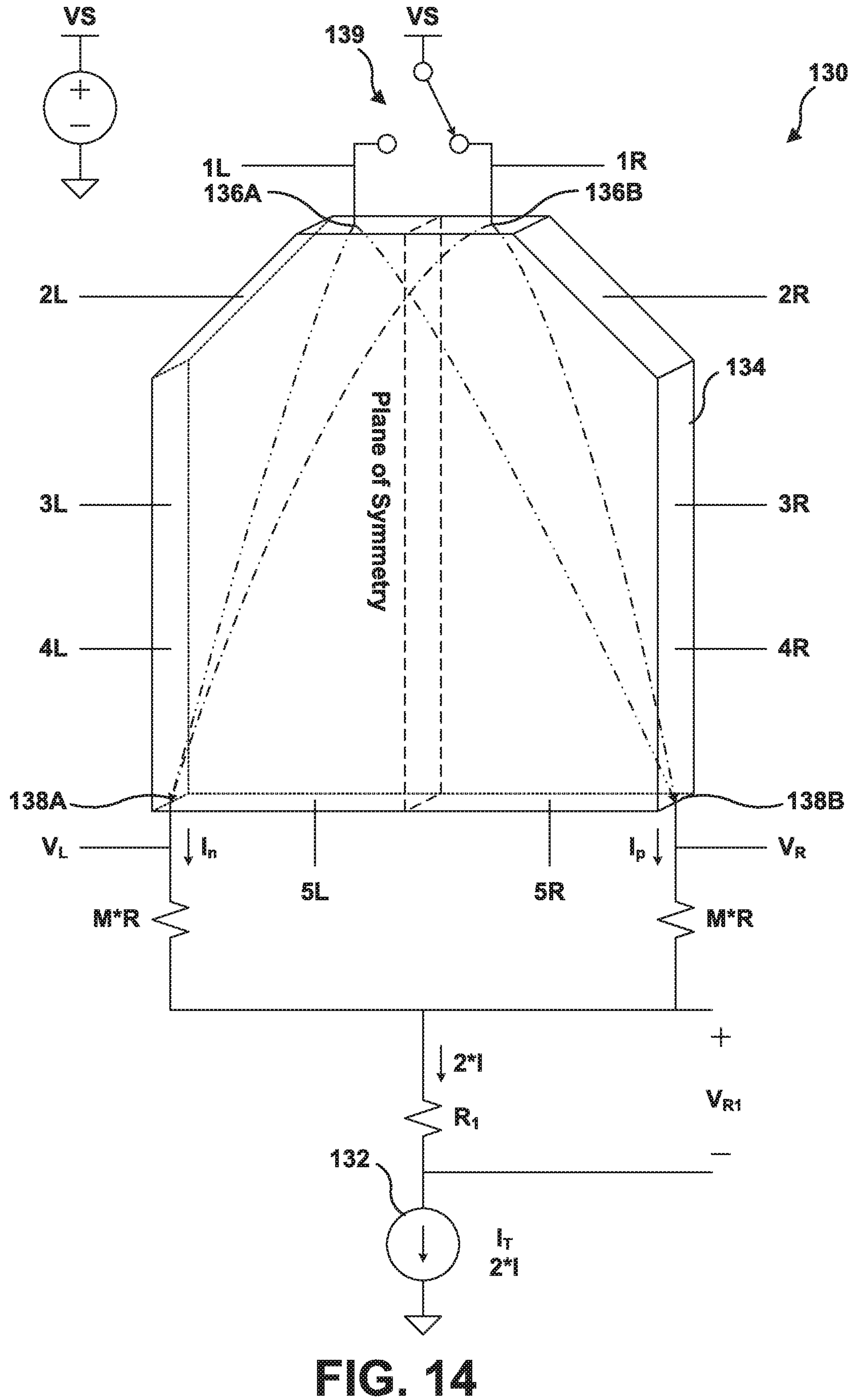
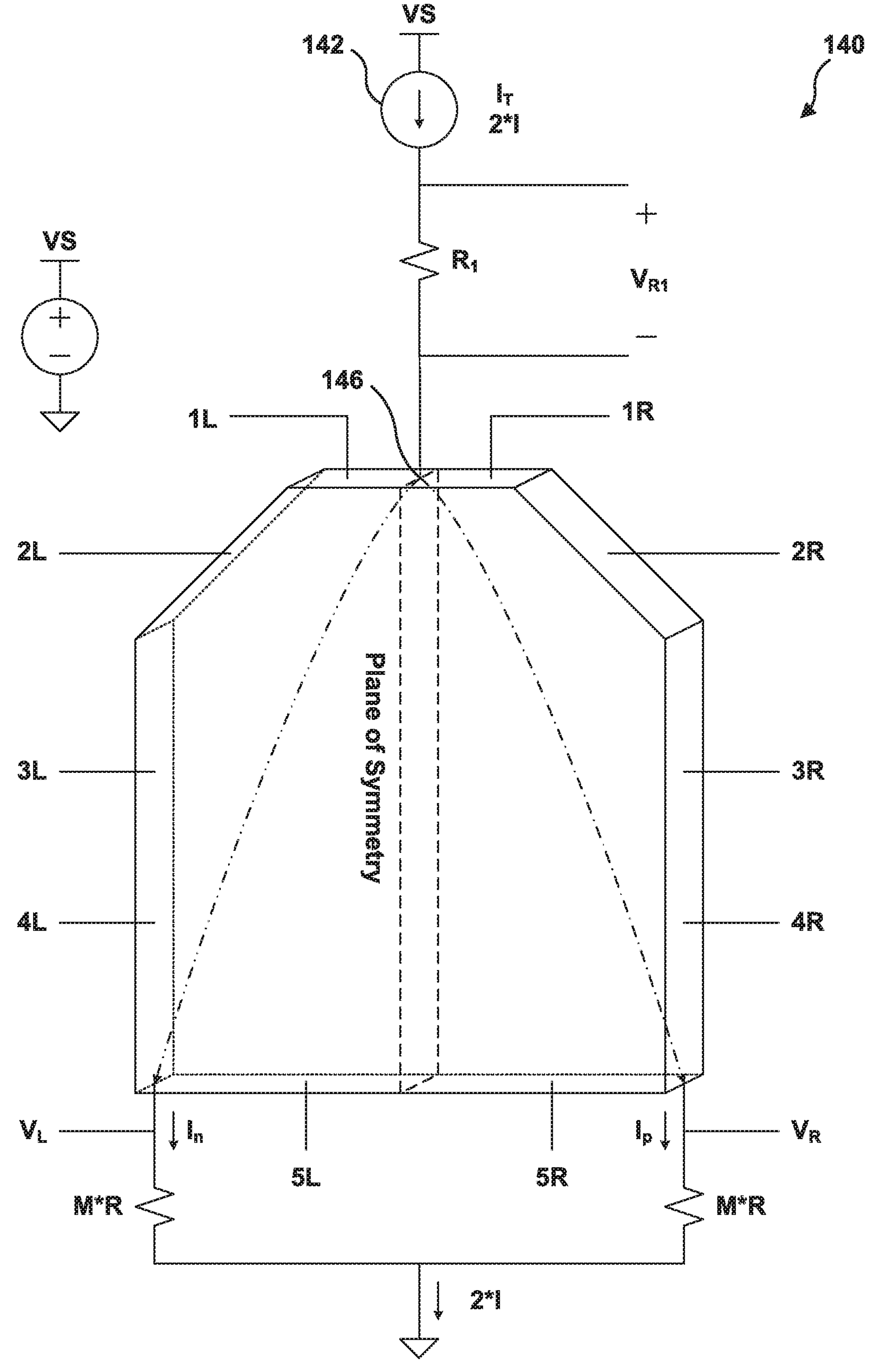

VS
VS
139
130
1L
1R
136A
136B
2L
2R
134
Plane of Symmetry
3L
3R
4L
4R
138A
138B
V_L
I_n
I_p
V_R
5L
5R
M*R
M*R
+
2*I
V_R1
R_1
–
132
I_T
2*I

FIG. 14



VS
142
140
I_T
2*I
+
R_1
V_{R1}
–
VS
+
–
146
1L
1R
2L
2R
Plane of Symmetry
3L
3R
4L
4R
V_L
I_n
I_p
V_R
5L
5R
M*R
M*R
2*I

FIG. 15

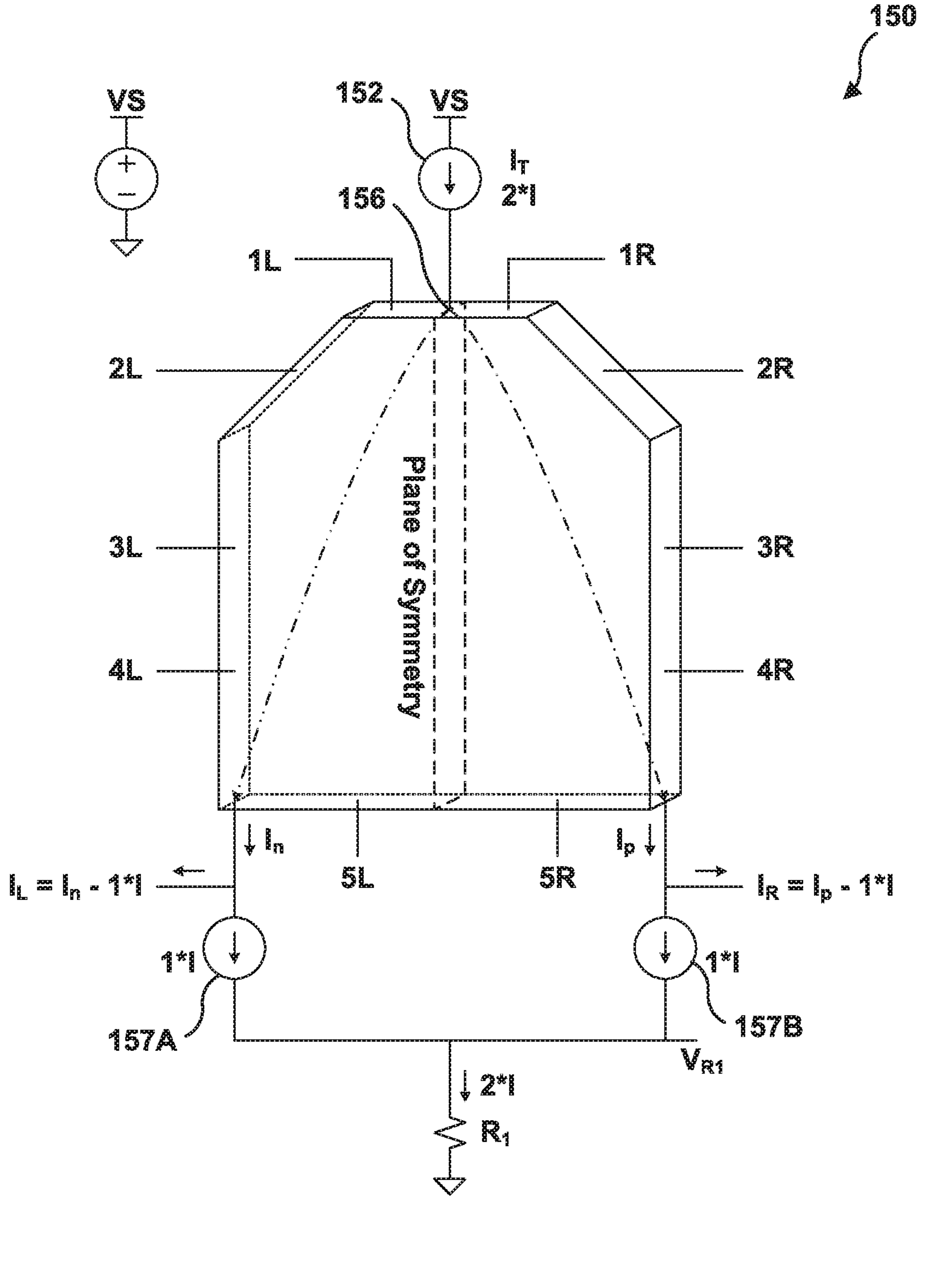

150
VS
152
VS
I_T
2*I
156
1L
1R
2L
2R
Plane of Symmetry
3L
3R
4L
4R
I_n
I_p
5L
5R
$I_L = I_n - 1*I$
$I_R = I_p - 1*I$
1*I
1*I
157A
157B
V_{R1}
2*I
R_1

FIG. 16A

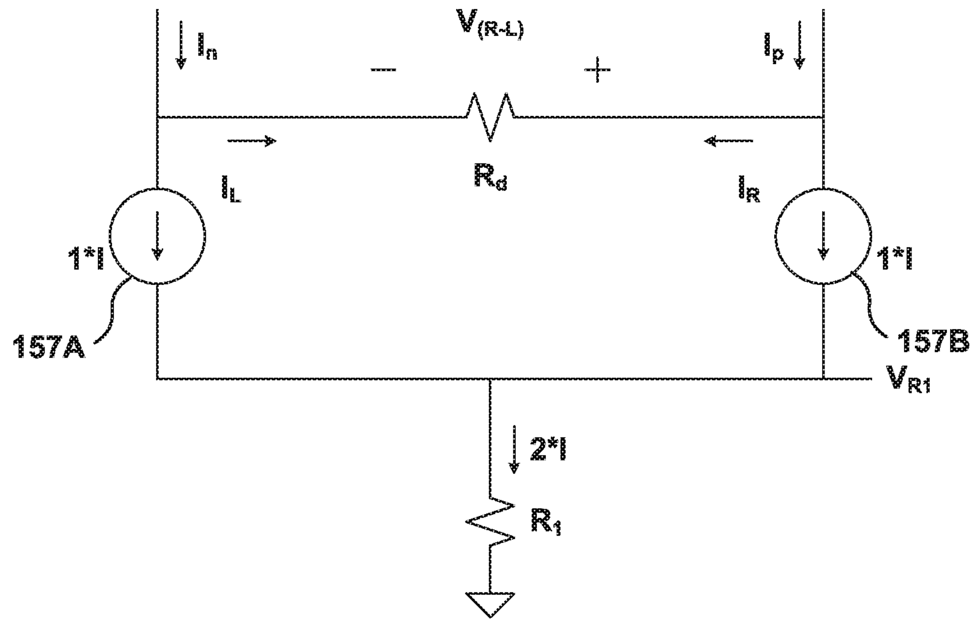


FIG. 16B

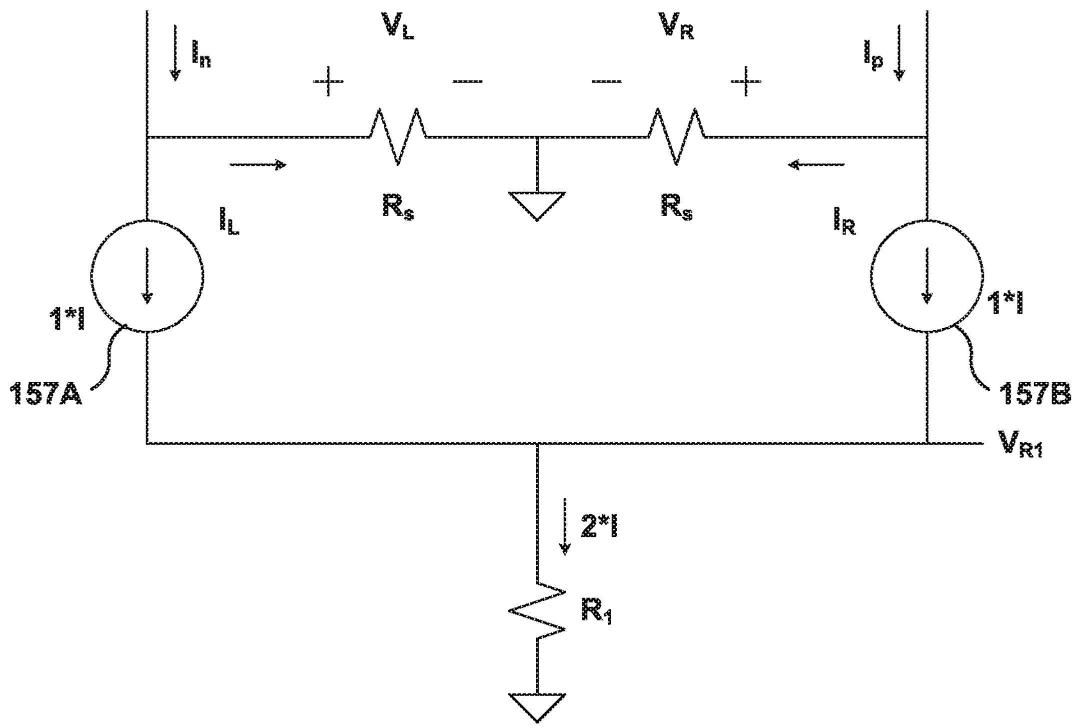


FIG. 16C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/061776

A. CLASSIFICATION OF SUBJECT MATTER

G01N 27/20(2006.01)i, G01N 27/04(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N 27/20; G01N 27/00; G01B 5/28; G01N 27/83; G01R 33/035; G01R 27/08; G01N 27/87; G01N 27/90; G01R 31/08; G01N 27/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: detect, crack, material, inject, extract, current, measure, voltage

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7443177 B1 (BOWLER, NICOLA) 28 October 2008 See column 1, lines 14-33, column 12, lines 3-6, column 13, lines 51-56 and claims 1-20.	1-4,6-16,18-28,30-40,42-48
A		5,17,29,41
A	US 7161356 B1 (CHIEN, RING-LING) 09 January 2007 See claims 1-2.	1-48
A	US 2005-0075800 A1 (BATZINGER et al.) 07 April 2005 See paragraphs [0018]-[0022] and figure 1.	1-48
A	WO 89-12833 A1 (ELECTRIC POWER RESEARCH INSTITUTE, INC.) 28 December 1989 See claims 1-15.	1-48
A	US 5258708 A (SADEGHI et al.) 02 November 1993 See claims 1-6.	1-48

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 January 2018 (31.01.2018)	**31 January 2018 (31.01.2018)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2017/061776

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 7443177 B1	28/10/2008	None	
US 7161356 B1	09/01/2007	None	
US 2005-0075800 A1	07/04/2005	CA 2538304 A1	21/04/2005
		CA 2538304 C	14/12/2010
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		EP 0422131 A4	16/10/1991
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US 5258708 A	02/11/1993	None	